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Documentation errors in instrumentation and electrical systems: Toward productivity improvement using System Information Modeling

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ABSTRACT

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. Considering this alarming statistic and the impact that poor quality documentation can have on productivity, the research presented in this paper classifies and quantifies errors in 106 drawings and the cable schedule used to document for the electrical package for an Iron Ore Stacker Conveyor. The research reveals that Computer Aided Design (CAD) used to produce the electrical drawings was ineffective, inefficient and costly to produce as they contained an array of errors. In addressing the need to eliminate documentation errors and improve productivity, the cable schedule is used to create a Systems Information Management to develop a 1:1 object orientated model using the software Dynamic Asset Documentation. As a result, of using this approach it is estimated that a 94% cost saving and a substantial improvement in productivity could have been attained in this particular case.

1. Introduction

Poor design and documentation has been repeatedly identified as a major factor that is contributing to the poor performance (e.g. cost and schedule overruns) and productivity of the construction industry [1–3]. The documentation that is produced by consultants often contains errors and omissions [3–5]. Complete design documentation is generally not available when a project goes to tender, and as a result very few projects are actually completed within the tendered price [6]. Accordingly Barrett and Barrett have stated, “projects that run over time and budget are often underpinned by faulty documentation that looks professional, but in fact does not properly describe the built solution” [7].

Client's fixed budgets and their requirement for earlier completion often result in unnecessary pressure being placed upon design and engineering organizations to meet their immediate demands and needs [7]. The use of competitive tendering by clients to acquire the services of design and engineering organizations may result in a de-emphasis being placed on the use of design audits, checks, verifications and reviews [8]. Consequently, the design documentation that is produced may contain incorrect dimensions, inadequate references to drawings, standards and building/engineering codes and conflicting specification [9]. Therefore, contractors and subcontractors are often required to raise ‘requests for information’ (RFI) for the purpose of clarifying, confirming or requiring additional information. Empirical studies have indicated that between 50% and 60% of change orders that occur in projects are attributable to poor quality design documentation [10,11]. Moreover, the costs of rectifying errors that arise from the design and documentation process can potentially increase a project's cost by 5% [12].

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 instrumentation and electrical (I&E) systems, which 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. Inconsistencies can manifest between the documents and therefore they must be re-edited and crosschecked before they can be issued for construction.

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Against this contextual backdrop, the research presented in this paper aims to develop an understanding of the nature of documentation errors and quantify their cost and impact on productivity. In addressing the issues of documentation error and information redundancy, System Information Model (SIM) using the Dynamic Asset Documentation (DAD) software, which builds a 1:1 relationship between the real world objects and the developed model, is compared to the atypical 1:n relations of the conventional CAD enabled documentation process.

2. Design and engineering documentation

The design and construction of projects is complex and challenging process, and its success is heavily reliant upon good communication between members of the design and construction teams. Good design is effective when it serves its intended purpose and is constructible within desired budget and time constraints and safely [13]. Furthermore, it has been suggested that documentation quality should be measured using the following criteria [14]:

- timeliness — be supplied when required so as not to cause delay to works;
- accuracy — free of errors, conflicts and inconsistencies;
- completeness — providing all information required (i.e. ensuring there are no omissions);
- coordination — through coordination between design disciplines; and
- conformance — meeting the requirements of performance standards and statutory regulations.

Considering the above criteria Tilley et al. define quality documentation as the ability to provide the contractor with all the information needed to enable construction to be carried out as required, efficiently and without hindrance [14]. Research has revealed that the number of RFIs being raised in Australian construction and engineering projects is an increasing problem and is indicative characteristic of the poor quality documentation being produced [14–19].

The communication of current design documentation, for example, typically consists of a set of 2D generated drawings showing the physical structure, along with specifications showing the production and installation process. This is also akin to the domain of I&E systems where design documentation consists of schematics, and cable schedule and specifications. As a result there is a proclivity for contractors to be supplied with incomplete, conflicting and erroneous documents and questions will be raised as and when needed to address these issues [14,15]. When a situation of this nature arises, the standard form of communication between the contractor and designers is to raise an RFI. According to WisDOT CMM the purpose of an RFI is to identify and resolve issues on-site that require resolution to avoid potential contract disputes and claims [20]. Moreover, CMM further suggests that RFIs are used to provide a systematic collection of the analysis and resolution of questions that arise before and during construction [20]. RFIs are typically used when [19]:

- 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 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 approved method to resolve conflict issues; and
- to confirm verbal understandings between an architect/engineer and the contractor related to any of the foregoing.

RFIs that require a 'yes' or 'no' answer should be avoided [20]. Furthermore, RFIs should not be used to address minor questions, but instead focus on addressing significant issues that may impact cost and schedule [20]. A response to an RFI needs to be provided on a timely basis so as to not impact a project's schedule [5,14,15,17,20]. 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 [20]. A number of issues, however, can impact the time it takes to respond to an RFI. For example, staff who were originally involved in the design and have intricate tacit knowledge of the project may have left the organization, been allocated to another project or be on holiday. As a result, an alternative or new engineer will be required to attend to the RFI that has been raised.

In Fig. 1, for example, the documentation and RFI process is represented for a hypothetical Engineering Procurement Construction Management (EPCM) contract that involves an I&E contractor. Such contract types are commonly used in resources and energy sectors. Essentially, a company is contracted to provide engineering, procurement and construction management services. Other companies are contracted by the client to provide construction services and they are usually managed by the EPCM contractor on behalf of the client.

Documentation is prepared by engineering consultants who are contracted to the EPCM contractor. The process of engineering design is iterative and requires engineers and CAD draftsman to work collaboratively to realize a design solution. Once all the necessary quality assurance (QA) approvals have been undertaken, documents will be provided to the selected I&E contractor for construction. Once on-site, and construction commences, anomalies (e.g., errors, omissions, conflicting information) in the schematics and cable schedule are identified and RFIs are raised and sent to the EPCM contractor.

Depending on the scale and nature of the RFI, site work may have to be temporarily suspended which results in non-productive time (e.g., waiting, idle time) being experienced. In fact, considerable non-productive time may also be experienced by the contractor as they aim to understand the nature of the schematics provided due to the considerable amount of information redundancy that is contained on them. 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 contractor, but also the consulting engineer and EPCM contractor as schematics and the like will need to be modified when 'changes' are required [17].

2.1. Project size and complexity

According to Tilley et al. as project size and complexity increases the quality of documentation provided by consultants' decreases, which results in an increase in the number of RFIs raised by contractors [14]. Moreover, Tilley et al. have suggested that procurement approaches may have an impact on the quality of documentation that is produced. Tilley and McFallan have 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 [1], which is akin to fast-tracking. There is, however, no empirical evidence available to support the suggestion proposed by Tilley and McFallan [1], 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 procurement method adopted [21–23].

As projects increase in size there is a propensity for design tasks to be undertaken concurrently, particularly in mega-projects in the

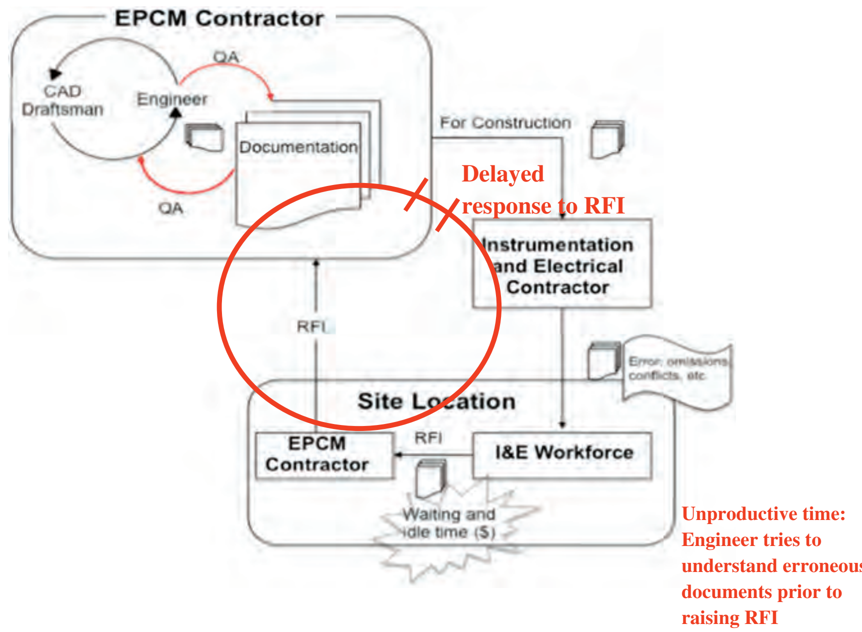

Fig. 1. Documentation process and RFI.

resource, energy and engineering sectors. 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 [24]. This approach is typically adopted to reduce design time and errors as well provide feedback to solve problems that may have manifested earlier [25,26]. Using preliminary information in overlapping design tasks often leads to information changes, which arise due to evolutions in design. Eastman asserts that the early release of information may cause unnecessary rework due to redundant data, and an increase time and effort to prepare for the release of information as checks and QA processes need to be implemented [27]. Furthermore, Terwiesch et al. [28] revealed that up to 50% of total engineering capacity is spent resolving rework issues as of early information release. Arundachawat et al. contend that a major source of rework arises from updating of preliminary information [26].

The updating of preliminary information can be a time-consuming process as the relevant information is likely to be contained within several documents. Fundamentally, there is a 1:n relationship where n is unknown. This becomes more of a problematic issue when CAD drawings need to be up-dated 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 the documents that contain the same or related information. Thus, documents need to be constantly checked every time, there is an amendment and repeated information must be identical to avoid the need for further clarification.

2.2. Contributors to poor documentation quality

A plethora of factors have been identified as to contributing to consultants producing poor quality documentation, which include poor project scope, lack of coordination between design disciplines, and lack of design audits, reviews and verifications [2,7,8,15,16]. Issues surrounding fee scales and the demand by clients to design and document in shorter periods of time have been identified as primary contributors to poor documentation quality [1–3]. According to DeFraites overall project quality is determined by the level of professional fees provided and that the quality of these services is determined by how the services are selected and how fees are negotiated [29,30]. It has been suggested that when designers are selected on the basis of competition there is a tendency for them to remove or modify particular services to maximize their fee [8]. Consequently, the documentation that they produce is often incomplete and may contain errors and omissions. Noteworthy, the legal standard of care for professional services does not require or expect perfection when creating design documentation prepared by design consultants [31–33]. From studies undertaken by the Construction Industry Institute and National Research Council a design error and omission rate in the range of 2% to 3% of construction cost is deemed to be an acceptable threshold level [14,15].

There has been limited research that has sought to quantify errors contained within design documentation, particularly in the context of I&E engineering. However, research propagated to date has enabled an underlying theoretical foundation to be established [2,3,5,8,17,32,33], though it requires further exploration before prescriptive laws can be formulated. Many organizations have been reluctant to allow researchers to examine firsthand the quality of documentation that has been provided to them due to reasons of commercial confidentiality and fear of potential litigation.

3. Research approach

Documentation errors are a chronic malaise and have become a 'norm' within the construction and engineering industry [3]. Active engagement from industry professionals who have intricate knowledge of the problem is needed to tackle this problem. With this in mind, a participatory action research (PAR) approach was adopted [34–39]. In brief, PAR is [38]:

- participatory;
- cooperative, 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 [34–37]. 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 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 issues of commercial confidentiality needed to be taken into account. Moreover, within any given I&E 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 System Information Model (SIM) known as DAD for the future life of the plant. The electrical package for a Stacker Conveyor (CV911) was selected as a complete set of drawings (106) and a cable schedule was readily available.

3.2. Data collection

Triangulation formed the basis for the data collection, which took place at the offices of the participating I&E organization. Triangulation involves the use of multiple research methods and/or measures of a phenomenon, in order to overcome problems of bias and validity [40,41]. The data collection methods used in this research were unstructured interviews and documentary sources. In addition to the active day-to-day involvement of the participating organization with a researcher in their offices, unstructured interviews with key personnel were also undertaken by a separate researcher who was not positioned within the office environment. This was undertaken to provide additional context to the problem and provide validity to the research process.

Unstructured interviews were used as a primary and secondary source 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 [42]. Interviews were undertaken with the Managing Director and Business Development Manager and varied in length from 30 min to 2 h. Interviews were open to stimulate conversation and breakdown 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.

Documentary sources are commonly referred to as unobtrusive measures [43]. Such approaches are considered useful when conceptualized as a complement to the use of other methods. The researcher was given access to drawings and documents for the selected project. In addition, the researcher was given access to documentation from other projects, such as lesson learned documents, to provide a contextual backdrop for the study. The analysis of documentary sources is commonly referred to as content analysis, which is non-reactive in nature [44]. In essence it is "a research technique for making replicable and valid inferences from data to their context" [45]. In its simplest format, content analysis is the extraction and categorization of information from documents. Inferences from the data extracted can only be drawn if the relationships with what the data means can be maintained between their institutional, societal or cultural contexts [45].

3.3. Case background

The Stacker Conveyor selected for this research was part of a $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 infrastructure to connect to mining operations
2. Mining operations and railway connections.

In the mine's first year of operation an estimated 27 million tons of iron was mined, railed, and shipped to customers in China. This increased to 40 million tons in 2011, and it anticipated that this will increase to 155 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 Fig. 2.

The Port expansion cost $486 million, with $59.3 million being dedicated to the EPCM, of which approximately 35% ($20.76 million) was expended on the electrical related design, and documentation.

4. Research findings

The 106 drawings and cable schedule for the iron ore conveyor used in this study were denoted as being 'As Built'. The 106 drawings can be classified into 4 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.

Analysis of these documents revealed that numerous errors and inconsistencies were prevalent even though they should reflect all the changes made in to the specifications and working drawings during the construction process as well as the exact location of all elements of work. If these documents were issued 'For Construction', then engineers on-site would spend considerable amounts of time trying to understand them and then would need to raise an RFI to confirm or clarify the issues that are identified. Moreover, engineers on-site cannot work without authorized drawings. They must submit their RFIs to the EPCM contractor on-site and wait for a response and the re-issue of new drawings. There may also be occasions when issues contained on the drawings cannot be understood by the engineer. In this particular case, the engineer may have to travel several kilometers from the workface to the site office to resolve the situation, which would result in considerable unproductive time being experienced.

Considering the errors contained in the 'As Built' drawings, it suggested that a significant amount of RFIs and non-productive time must have occurred during the actual installation process. Moreover, engineers on-site cannot work without authorized drawings. They must submit their RFIs to the EPCM contractor on-site and wait for a response and the re-issue of new drawings. It is not feasible to determine the non-productive time that occurred, but an estimate of productivity loss can be determined to attend to the 'As Built' drawings.

Fig. 2. Stacker Conveyor.

4.1. Error classification

The classification of error types provides a platform for their quantification [46–48]. The analysis of data derived from interviews and documentation for the selected case study enabled seven classifications of error to be identified and subsequently quantified (Table 1):

1. *Incorrect labeling*: The names of the cables or components are labeled incorrectly. For example, a cable name was labeled as MP46511-C-104 when it should be MP46511-C-105
2. *Inconsistent labeling*: The names of the same cables or components are not identical among different drawings. For example, in drawing 04900-EL-DR-2001_6, a pull wire switch was labeled as PW23, while in drawing 04900-EL-DR-2570_4, it was labeled PWS23.
3. *Drawings omission*: Cables and components were missing from some drawings. For example, a 400 V distribution board DB461L1 and its corresponding connection cable DB461L1-P-01 were found to be missing from the drawing.
4. *Incorrect connections*: Cables or components were connected to wrong connections (Fig. 3a).
5. *Cable schedule omissions*: Incomplete information contained within the cable schedule (Fig. 3b).
6. *Wrong design*: Cables and components are not meant to be designed on a particular drawing (Fig. 3c).
7. *Missing labels*: Cables or components are drawn on drawings but are not labeled (Fig. 3d).

Drawing omissions were the most prevalent form of error identified (53.90%). From the 106 drawings used to install the electrical system for the conveyor belt, 158 cables and 84 components were found to have been omitted. The cable schedule is typically used as the mechanism to extract materials and cable length and it was revealed that 94 cables and 20 components had been omitted (25.39%). If the contractor had simply relied upon the supplied cable schedule from the consultants, then their tender price would have been significantly 'incorrect'. Moreover, the omitted components and cables were deemed to have had long 'lead-in' times to procure. So, if the I&E service contractor did not identify these omissions, then the likelihood of a project delay would have been high.

Discussions with the participating organizations staff revealed that engineers on-site tended to spend varying amounts of time addressing different types of error. In the case of the iron ore conveyor, it was revealed that 'drawing omissions', 'cable schedule omissions' and 'wrong design' would require a considerable amount of time to address due to the complexity and lack of reference information available. It was assumed that 3 to 5 h would be required to attend to each specific problem identified in this instance.

To attend to issues such as 'labeling mistakes' and 'missing labels' it was suggested that 1 to 2 h would be required. 'Inconsistencies in labeling' and 'incorrect connections' can be dealt with by referring to the reference drawings. Such issues are deemed to be generally insignificant and can be readily addressed by experienced engineers. It is assumed that 15 min is required to address each problem found. For example, one cable was labeled MP46511-C-09D, when it should have been MP46511-C-09-D. Similarly, a component was labeled SS1, when it should have been SS01. The difficulty of addressing the 'inconsistent labeling' problem is that some labels found, which people thought are 'inconsistent', are actually consistent and referring to different devices. Thus, efforts are required to confirm this by comparing the information among the reference drawings. In some cases, several similar errors could appear on the same drawing and therefore can also be dealt with.

4.2. Quantification of unproductive time

The unproductive time associated with attending to the identified errors is quantified based upon estimates derived from the I&E contractor. Table 2 provides a summary of the man-hours allocated to each error type. A man-hour cost of $150 is used as this is

Table 1
Classification of error types.

Error types		Labeling mistake	Inconsistent labeling	Incorrect connection	Drawing omission	Omission from cable schedule	Missing label	Wrong design
Number of errors	Cables	38	16	0	158	94	5	10
	Components	7	13	1	84	20	0	3
Percentage of each type of errors		10.02%	6.46%	0.22%	53.90%	25.39%	1.11%	2.90%

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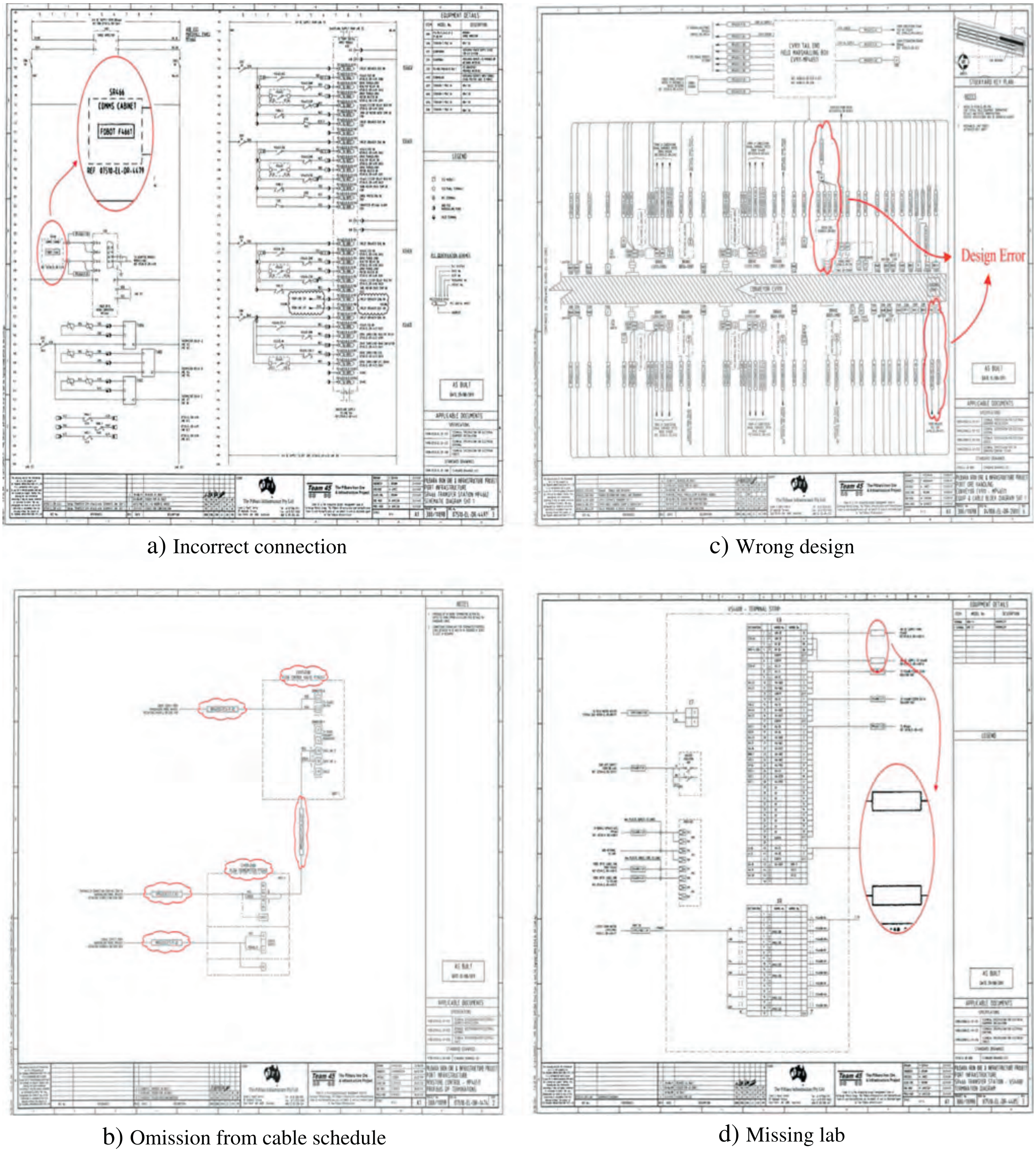

Fig. 3. Examples of errors.

considered to reflect market rates for an electrical engineer working on a remote mine site in WA.

A total of 859 man-hours have been calculated to deal with the errors identified on the 'As Built' drawings. It can be seen in Table 3 that an additional 437 man-hours (50.87%) is required to address the omission problems in the drawings. A total of 366 man-hours (42.61%) are required to address the omission problems identified in the cable schedule. Noteworthy, electrical engineers tend to install cables on site using information derived from the cable schedule as it provides the connection relationships between cables and components. Therefore, if information is missing from the cable schedule then work is unable to be completed.

It is estimated that 33.5 man-hours (3.90%) will be required to attend to labeling mistake issues. The man-hours required to attend to 'inconsistent labeling', 'incorrect connection', 'wrong designs' and 'missing labels' are insignificant 7.25 (0.84%), 0.25 (0.03%), 10 (1.16%) and 5 (0.58%)

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Table 2
Quantification of non-productive time on-site.

Error types	Labeling mistake	Inconsistent labeling	Incorrect connection	Drawing omission	Omission from cable schedule	Missing label	Wrong design	Total
Man-hours	33.5	7.25	0.25	437	366	5	10	859
Cost ($150/man-hour)	$5025	$1087.5	$37.5	$65,550	$54,900	$750	$1500	$128,850
Percentage (cost)	3.90%	0.84%	0.03%	50.87%	42.61%	0.58%	1.16%	

respectively. The estimated cost of 'unproductive time' for electrical engineers to attend to the errors contained in the 107 documents for the iron ore conveyor is calculated as follows:

$$C_E = \sum_{i=1}^{7} T_{Si} \times N_{Ei} \times R_{PE} \tag{1}$$

where,

T_{Si}, $i = 1,\ldots,7$ the average time for sorting out a single error,
N_{Ei}, $i = 1,\ldots,7$ number of errors among each type,
R_{PE} pay rate of the electrical engineer on site,
C_E cost on errors.

Average time to address an error for each type:

1. Labeling mistake = 0.74 h/error T_{S1}
2. Inconsistent labeling = 0.25 h/error T_{S2}
3. Incorrect connection = 0.25 h/error T_{S3}
4. Drawing omission = 1.81 h/error T_{S4}
5. Omission from cable schedule = 3.21 h/error T_{S5}
6. Missing label = 1 h/error T_{S6}
7. Wrong design = 0.77 h/error T_{S7}.

Substituting the data from Table 2 into Eq. (1), the cost associated with the unproductive time is calculated to be $128,850 to attend to all the errors contained within the 107 documents. This additional cost would be unrecoverable and have significant impact on a firm's profit margin. As noted above, the 107 documents represented only 5% of all the I&E drawings for the project. Thus, if an assumption is made that all the drawings were of a similar quality, then the total cost of unproductive time to address the problems is $2,577,000 (17,180 man-hours). This estimate is deemed to be conservative as it based upon 'As Built' and *not* the 'For Construction' drawings, which is suggested to contain a higher rate of error proneness.

4.3. Information redundancy

It was observed that equipment and cables appeared simultaneously in different CAD drawings. Repeating information is a costly and time consuming process and can lead to significant reductions in productivity. In the case of a large project, for example, a significant number of draftsmen will be required to work concurrently on the same set of drawings. As a result, cable or equipment may be drawn by separate draftsmen on different drawings using the same or dissimilar symbols, notations and labels. As a result the propensity for errors and omission increases and the drawings that are produced become difficult to understand and interpret.

A summary of the frequency of occurrences contained within the 107 documents for the cables and components of the iron ore conveyor is shown in Fig. 4. It can be seen that there are 357 cables and components appeared twice in the documents. 446 cables and components appeared three times. It also can be seen that the highest frequency of occurrence is 29. Fundamentally, two pieces of equipment appeared 28 times in the 106 drawings and once on the cable schedule.

When using CAD, each repeated cable or component in different drawings has to be manually drawn by the draftsman. Before doing so, a draftsman needs to determine the exact information that should be presented and the connection relationships between them for a particular drawing. Draftsmen also need to be aware that the labels for cables and component should be consistent with one another so as not to cause confusion and any misunderstanding from occurring.

Discussions with draftsmen of the I&E contractor suggest that each repeat of a single piece of cable or component drawn in CAD will take approximately 0.25 man-hours. Fig. 5 identifies the man-hours used for each redundant item contained within the documents. A total of 598 man-hours have been used to repeat cables and components within the drawings. The market rate of pay rate for draftsman in WA is $130/man-hour. Thus, the cost of the redundant information can be calculated using the following equation where:

$$C_R = \sum_{i=1}^{18} N_{CCi} \times (N_{Di} - 1) \times T_R \times R_{PE} \tag{2}$$

where,

N_{Di} number of documents, $i = 1,\ldots,18$,
N_{CCi} number of cables and components, $i = 1,\ldots,18$,
T_R time consumed on a single repeated cable or component,
R_{PE} pay rate of the draftsman using CAD,
C_R cost on redundancy.

As each cable or component has to appear once among the documents, hence in Eq. (2), $N_{Di} - 1$ and $T_R = 0.25$ h, $R_{PE} = \$130$/h. Substitute the corresponding values of N_{Di} and N_{CCi} derived from Fig. 3 into Eq. (2), the cost on redundancy for 107 documents is calculated to be $77,740. If the redundancy contained within the 107 is extrapolated to the entire I&E systems for the project, then a total of 11,960 man-hours would have accumulated at a cost of $1,554,800.

The assumptions used to quantify the man hours associated with unproductive time and redundancy are based upon objective estimates provided by personnel who have had extensive experience in the field and working within a CAD based environment. To prepare a conventional electrical CAD drawing may take between 20 and 100 h depending on the type of project and complexity of the installation systems. To prepare the 107 documents it is estimated that 4270 man-hours would have been used, which equates to a cost of $555,100. Thus, information redundancy included in the 'As Built' documents accounted for 14% of cost to prepare the documentation.

Table 3
CAD versus DAD to document Stacker Conveyor.

Methods	Number of documents	Average man-hours per drawing	Pay rate	Total man-hours	Total cost
CAD	107	39.91	$130/h	4270	$555,100
DAD	107	2	$150/h[a]	214	$32,100

[a] The market rate for a DAD draftsman as of July 2012.

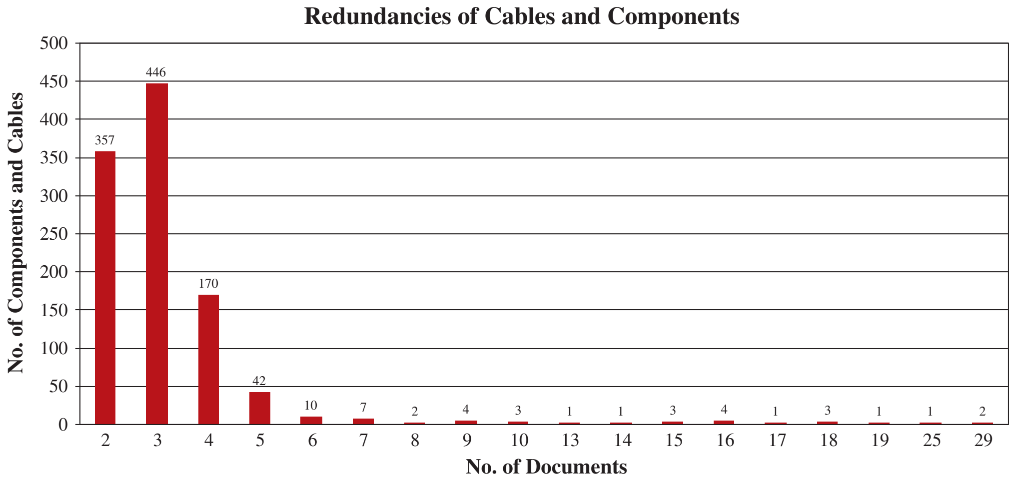

Fig. 4. Redundancy associated with cables and components.

5. Toward productivity improvement

The elimination of information redundancy requires a shift away from the traditional view of documentation production based on CAD generated drawings where there is typically a 1:n relationship between the real world and the documents. The findings indicate that documentation error and redundancy are costly and adversely impact productivity. The cost curve to produce documentation using CAD is presented in Fig. 6. Considering the traditional way documentation is produced and the time and cost constraints regularly imposed upon engineers and draftsmen, it would be unreasonable to assume that documentation is complete.

An alternative way to produce documentation for I&E is to produce an SIM object orientated model (OOM) where a 1:1 relationship between model and the real objects can be created. By constructing a 1:1 model, information redundancy can be eliminated, which will reduce the propensity for errors and omissions to be made.

DAD is software that has been developed to address issues surrounding documentation errors and information redundancy and was developed by the organization who participated in this research. The software has received numerous State and National awards for its ability to provide clients with significant cost and productivity savings [49]. A comparison between DAD and the traditional drawing and documentation production process is identified in Table 3.

For the Stacker Conveyor, the 'As Built' cable schedule was only required to produce the documentation in using DAD. Fig. 7a and b was produced in CAD and illustrates the single line diagrams of the motor control center MC465. A detailed examination of these two drawings revealed that a considerable amount of information had been omitted. The drawings were produced in DAD and were combined to form Fig. 7c, which denotes the connection relationship of MC465. It can be seen that all cables and components connected directly to the right hand side of MC465 have been omitted from Fig. 7a and b.

In Fig. 8a, it can be seen that in drawing 07510-EL-DR-4485-3, two cables were drawn without any labels and thus may potentially confuse electrical engineers on site. If the I&E document were originally documented in DAD, then this problem would never have arisen, as any cable or component that is created is provided with a name that has a 1:1 relationship (Fig. 8b). The connection relationship, the position and additional information can also be embedded in the model.

Essentially, there are two methods to build models in DAD:

1. Extract information direct from cable schedule, assuming it is correct
2. Manually, assuming the correct relationship between cables and components is established.

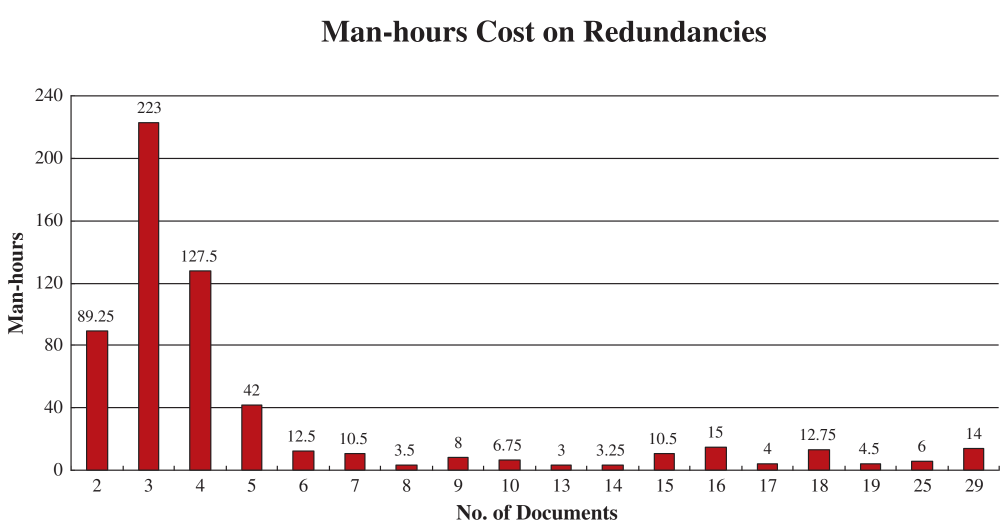

Fig. 5. Man-hour costs for information redundancy.

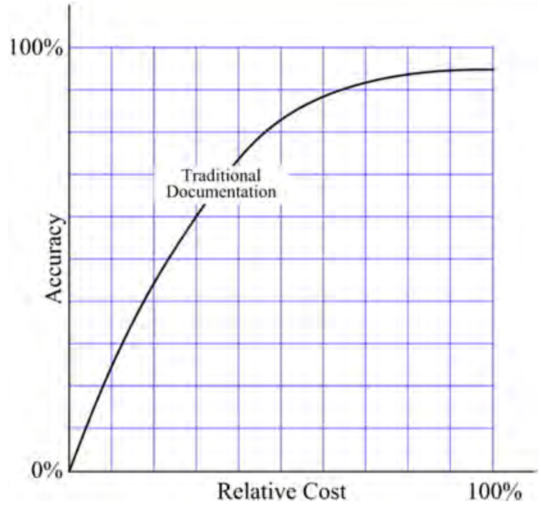

Fig. 6. Cost curve to prepare traditional documentation.

Once the object database is established within DAD, it can produce a variety of diagram types (e.g., Block, Schematic, Termination, and Layout). All the drawings share information from the constructed database and therefore design repetition for the same component or cable is eliminated. If some aspects of the systems design are required to be revised, then revisions can be undertaken by simply amending the database. Consequently, there is no need to individually revise drawings, which is often the case when using the conventional CAD based approach. Hence, man-hours are saved and documentation errors are reduced.

5.1. Quantifying the benefits of DAD

DAD was used to re-produce the 'As Built' drawings for the Stacker Conveyor using the cable schedule. The cable schedule was used as it is the only traditional document format that is able to provide a wide synopsis of the design as all cables and the devices that they join together are listed. The cable schedule also provides a summary of the complex information spread across all the other documents in a design package and usually produced in an. XLS file that can be imported to DAD.

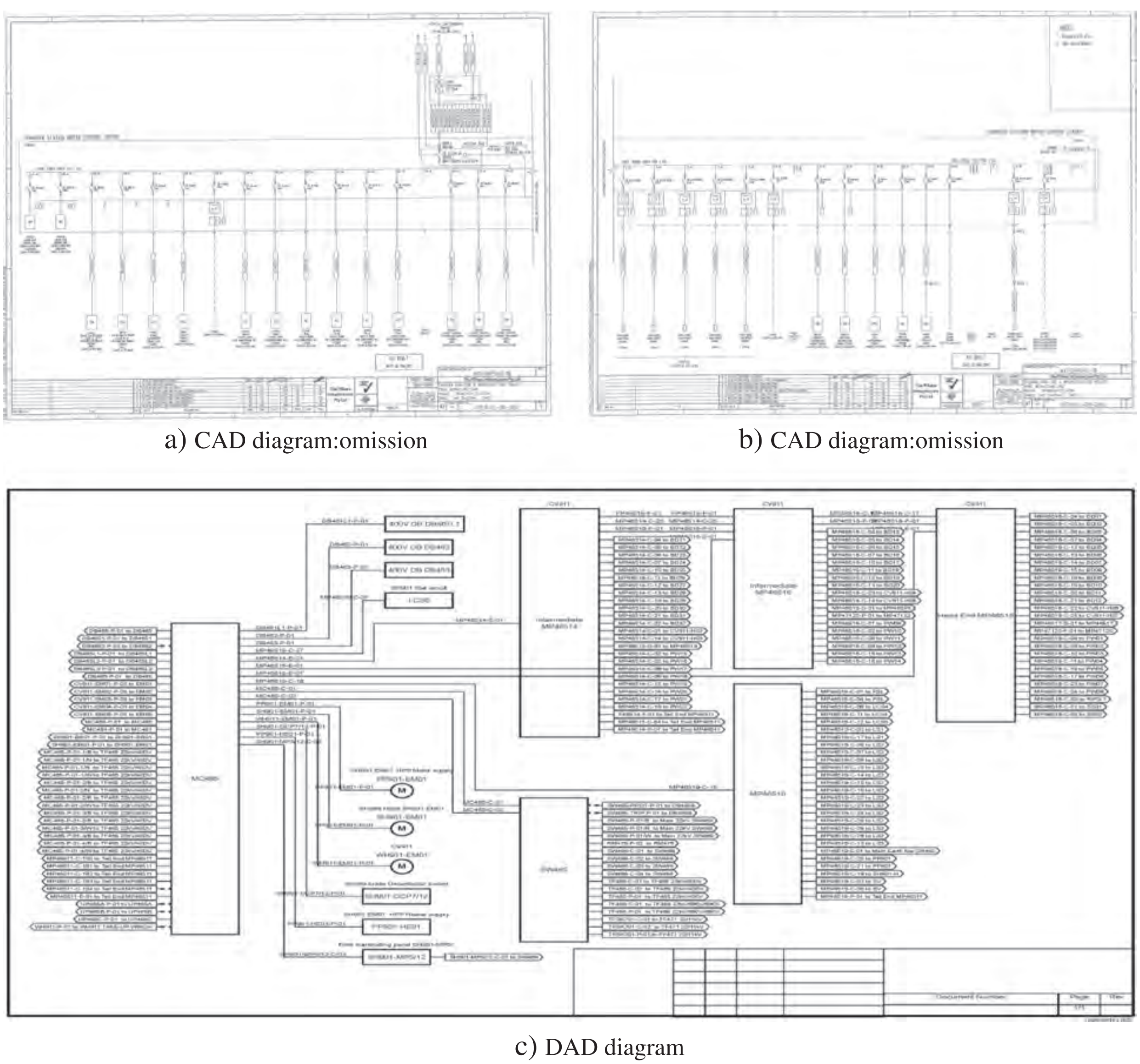

Fig. 7. Drawing omission identified in DAD.

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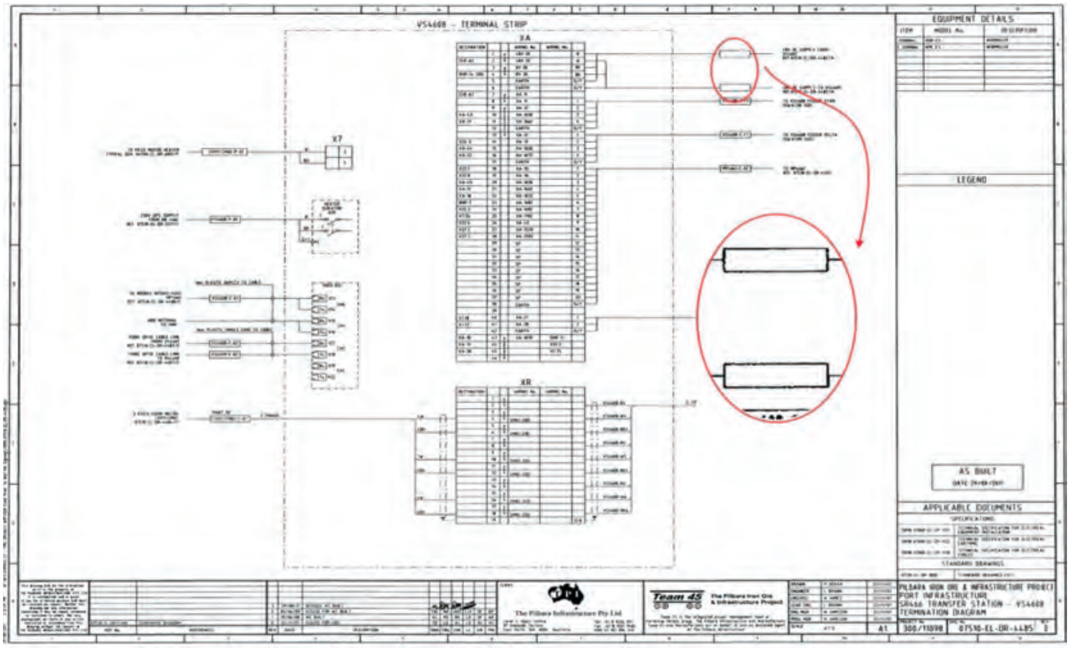
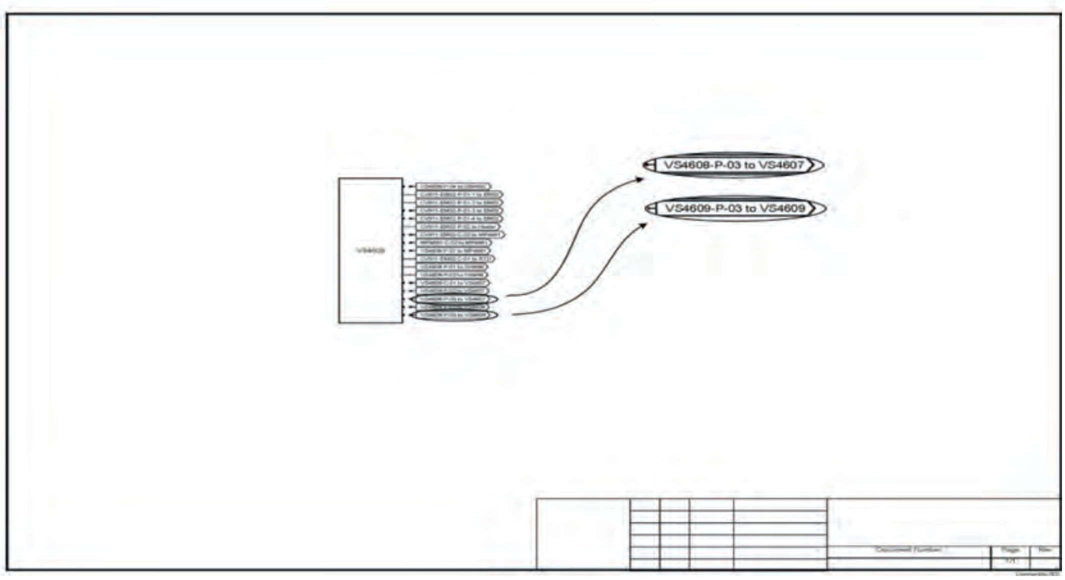


a) Missing Label in CAD drawing



b) Corresponding Labelsin DAD

Fig. 8. Missing labels identified in DAD.

The average time to produce a single drawing was 2 h. To produce the 107 documents consumed approximately 214 h. Thus, if a pay rate of $150/h is assumed, then the monetary cost by using DAD would have been $32,100. A comparison of using DAD against the traditional CAD drawing is shown in Table 3. It can be seen from Table 3 that by producing the 106 electrical drawings and cable schedule, the use of DAD could have saved 4056 man-hours (94.99% of the man-hour) and $523,000 (94.22% reduced cost). Figs. 9 and 10 graphically represent the productivity improvements of using DAD.

The determination of the unproductive time due to errors ($128,850) and redundancy ($77,740) can be used as a baseline to demonstrate the potential cost saving that DAD can offer to a project. As noted above, if it is assumed that the rate of documentation errors and redundancy was constant for all the electrical documentation produced then the estimated costs of unproductive time are $2,577,000 and redundancy $1,554,800. The budget for the electrical design and documentation was $20.76 million, which includes the cost of information redundancy. Costs associated with unproductive time are excluded as documentation errors are not identified until the installation of cables and components. The 'real' cost for the electrical design and documentation therefore would have been in the region of $23.337 million. The use of DAD in this instance would have eliminated information redundancy and provided a budget of $19,205,200. A total of $4,131,800 may have been saved using DAD. A comparison of the cost between traditional CAD drawing and DAD is depicted in Fig. 11.

6. Research limitations

The research adopted a PAR approach to quantify documentation errors in a set of electrical documents for a Stacker Conveyor. The

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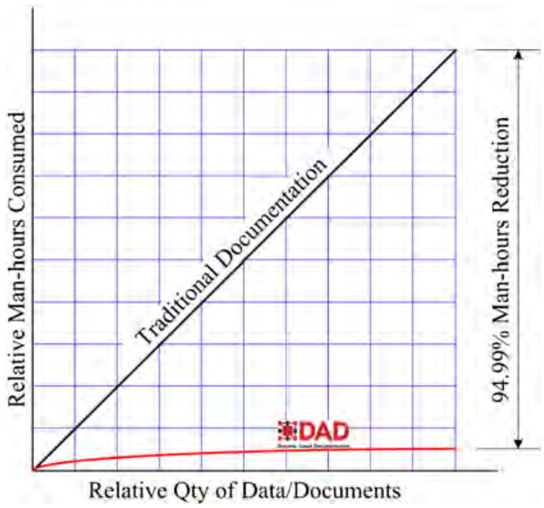

Fig. 9. Reduction in man-hours.

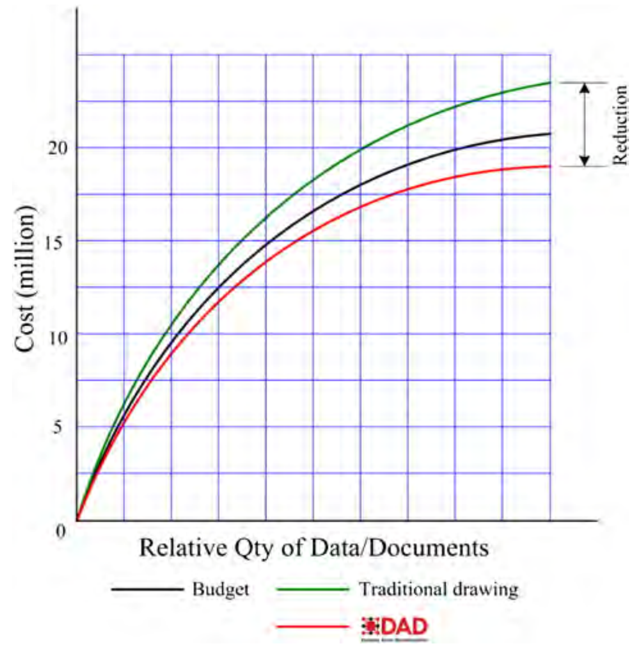

Fig. 11. Cost comparison between traditional CAD drawing and DAD.

active involvement of staff from the participating organization in the research process provided invaluable insights into the mechanisms used to produce electrical documentation. The study was exploratory and not definitive. The quantification process was time-consuming and only one case has been examined which limits the generalizability of the reported findings. In addition, 'As Built' drawings were used as the reference point, which did not truly reflect the extent of the problem at hand. As a result this may affect the internal and external validity of the study. Moreover, the research has examined the nature of documentation from the I&E contractor's perspective and therefore quality assurance processes of the EPCM contractor were not examined.

7. Conclusion

This research has demonstrated that electrical documentation for the Iron Ore Stacker Conveyor was produced inefficiently and contained significant errors, omissions and inconsistencies. There is a pressing need to re-evaluate the way in which I&E documentation is being produced if significant productivity and cost savings are to be achieved. The need is evident from the following results which have emerged from this initial study.

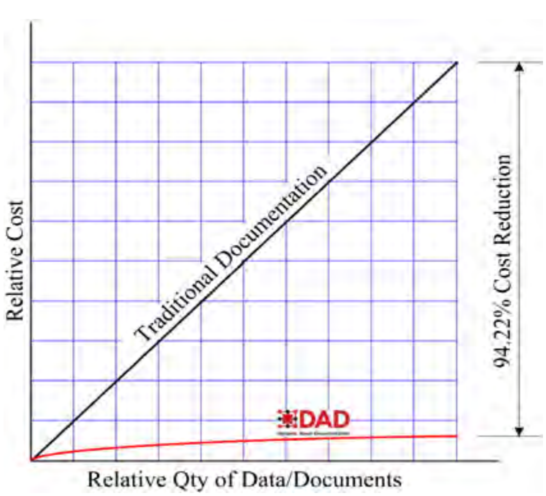

Fig. 10. Reduction in documentation cost.

Analysis of 106 'As Built' electrical drawings and a cable schedule for an Iron Stacker Conveyor revealed a variety of documentation errors manifested themselves as labeling mistakes, inconsistent labeling, drawing omissions, omissions from the cable schedule, missing labels, wrong design and incorrect connections. Omissions from drawings and the cable schedule accounted for 93% of all errors identified. It was revealed through in-depth discussions with staff from the participating organization that the reconciliation process of an omission ranged from 3 to 5 h before an RFI seeking clarification could be sent to the consult engineer. This non-productive time leads to losses productivity and increased costs. A total of 803 extra man-hours would have been needed to address the omissions at a cost of $120,450. In the case of all documentation errors at total of 859 extra man-hours would be required at a cost of $128,850.

During the analysis it was observed that there was considerable information redundancy contained within the 107 electrical documents. For example, 357 items appeared twice on drawing documents with as many as 42 items appearing five times. The creation of the information redundancy contained within the 107 documents equates to an additional 598 man-hours and a cost of $77,740.

The Iron Stacker Conveyor's 'As Built' cable schedule was converted into DAD to examine how it would eliminate documentation errors and information redundancy. The average time to produce a single drawing was 2 h compared to the estimated 39 h using CAD. It is suggested that producing the 106 electrical drawings and cable schedule, the use of DAD could have saved 4056 man-hours and $523,000. Therefore, a 94% cost saving and improvement in productivity could have been attained in this particular case.

A novel line of inquiry has been undertaken, which has provided the basis for further studies into this important and fertile area. More case studies are required to examine the extent of documentation error and information redundancy that prevails, particularly for those drawings that are issued 'For Construction'. An examination of the changes between 'For Construction' and 'As Built' drawings as well as nature and volume of RFIs generated by drawings produced in CAD in comparison to those in DAD would provide additional insights into the productivity benefits that it can be realized in documentation process.

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