School of Built Environment

Documentation Errors in Instrumentation and Electrical Systems

Toward System Information Modelling

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> “It is only an error in judgment to make a mistake, but it shows infirmity of character to adhere to it when discovered”

Christian Nevell Bovee

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The authors hope the research undertaken can make a difference to better understanding why productivity in the design and documentation process is being impacted. Moreover, the findings reported should stimulate thinking about the need to re-appraise and re-evaluate the current design and documentation process of instrumentation and electrical and systems in complex construction and engineering projects.

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Glossary of Key Terms

Change Order	The client's written order to the contractor, issued after execution of the construction contract, which authorizes a change in the construction work and contract time and/or amount
Cost Overrun	Difference between the original contract value and actual contract value at practical completion
Dynamic Asset Documentation (DAD)	Systems information model that provides a 1:1 digital representation of the physical system where components, connections and functions are linked to their physical counterparts
Engineering Procurement and Construction Management (EPCM)	Under this arrangement the client selects an EPCM contractor who manages the whole project and ensures it is completed on time and to budget
Error	The execution of a task that is either unnecessary or incorrectly carried out
Fast Tracking	A method of project delivery in which the sequencing of construction activities enables some portions of a project to begin before the design is completed.
Information Redundancy	Unneeded and/or duplicated information
Non-value Adding Activity	An activity that generates a zero or negative return on the investment of resources and can be eliminated without impairing a process (e.g., idle time, repeat work etc.)
Non-Productive Time	Time not directly associated with the operation o performance of a job or task
Object Database	An object database (also object-oriented database management system) is a database management system in which information is represented in the form of objects as used in object-oriented programming.
Productivity	Average direct labor hours to install a unit of material
Request for Information	The role of an RFI is to act as a tool to resolve conflicts, ambiguities
Rework	Unnecessary effort of re-doing a process or activity that was incorrectly implemented the first time
Schedule Overrun	Occurs when the original contract period specified at contract award is extended beyond what was agreed prior to the commencement of works on-site

Executive Summary

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, 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 report examines the nature of errors contained within electrical documentation produced for an Iron Ore Stacker Conveyor. Analyses of 106 drawings and the cable schedule used to document the design of a Stacker Conveyor revealed:

- seven different types of error: labeling mistakes, inconsistent labeling, omissions from drawings, omissions from the cable schedule, missing labels, wrong design and incorrect connections;
- omissions from drawings (51.3%) and cable schedule (42.98%) accounted for a significant proportion of all the errors identified;
- that the reconciliation process associated with addressing an omission error ranged from three to five hours;
- an additional 851.5 man-hours would have been required to address all the errors identified, which translates to an additional cost of $127,725 (when man-hours are charged at a rate of $150 per hour for electrical engineers); and
- the block, schematic and termination and layout drawings contained considerable information redundancy. For example, 357 items appeared twice on drawings documents with as many as 42 items appearing five times. The creation of the information redundancy contained within the 107 documents equates to 598 additional man-hours and a cost of $77,740 (when man-hours are charged at a rate of $130 per hour Computer Aided Design (CAD) draftsmen).

It is proffered that the use of CAD to produce the electrical drawings of the Stacker Conveyor were ineffective, inefficient and costly to produce. In addressing the need to eliminate documentation errors and improve productivity, the cable schedule is used to create a Systems Information Management by developing a 1:1 object orientated model for the Stacker Conveyor using the Dynamic Asset Documentation software. As a result, of using this approach, it is estimated that a 94% cost saving and with 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 [1,2,3]. The documentation that is produced by consultants often contains errors and omissions [3,4,5]. Complete design documentation is generally not available when a project goes to tender stage, 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 no properly describe the built solution" [7].

Client's fixed budgets and their requirement for earlier completion often results 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 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 numerous '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 overall project costs 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 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 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.

Against this contextual backdrop, the research presented in this report 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, Dynamic Asset Documentation (DAD), 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, time and safely objectives [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.

Furthermore Tilley *et al*. defined 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 a significant problem. Moreover, the number of RFIs is a potential indicator of poor quality documentation being produced [14-20].

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 Tadt *et al*. the purpose of an RFI is to identify and resolve issues on-site that require resolution to avoid potential contract disputes and claims [21]. 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 leave/holiday. As a result, an alternative or new engineer will be required to attend to the RFI that has been raised.

In Figure 1, for example, the documentation and RFI process is represented for a hypothetical EPCM contract that involves a I&E contractor. 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.

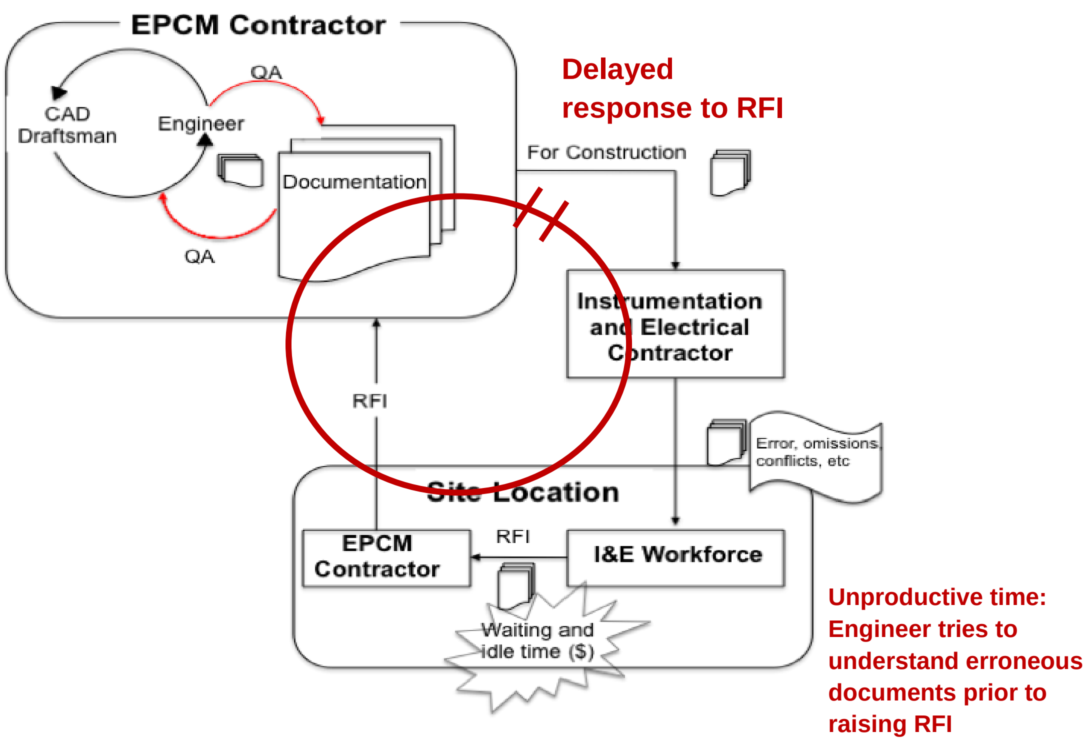


Figure 1. Documentation process and RFI

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 confined to the trade 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 McFallen 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 McFallen [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 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 the 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(n). 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 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 [30]. It has been suggested that when designers are selected on the basis of competition there is a tendency to 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]. 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].

3 Research Approach

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], 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 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 [3]. Active engagement from industry professionals who have intricate knowledge of the problem are needed to tackle this problem. With this in mind, participatory action research (PAR) approach was adopted [34-37]. 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 were 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 was unstructured interviews and documentary sources (Table 1). 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.

3.2.1 Interviews

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 minutes to two hours. 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.

Table 1. Summary of data collection methods used

Method	Advantages	Disadvantages
Interviews Open-ended based questions.	These were used to cover many topics and features of the documentation process; were modified between interviews as knowledge of the documentation process were acquired; used to convey empathy, build trust; and to provide an understanding of respondents view points and interpretations.	Sampling problems were experienced; respondent and interview bias; difficult to analyse and interpret responses to open-ended questions.
Documentary Sources Use of documents, files and reports	Non-reactive; often quantifiable; organizations staff assisted with analysing the data; independent sources; cheaper than gathering new data.	Access, retrieval, analysis, problems occurred due to time requirements; validity and reliability of sources; needed to analyse the data in context; data was limiting.

3.2.2 Documentary Sources

Documentary sources are commonly referred to as *unobtrusive measures* [43]. Such approaches are considered useful when conceptualised 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 a 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].

Content analysis was used as the primary research method and in conjunction with interviews, was used to quantify and determine the productivity impact of documentation errors. Data was extracted directly from the 'As Built' documentation that was provided for the Stacker Conveyor. A classification system for coding documentation errors that arose was developed. This process of coding is akin to previous studies that have examined the nature of design errors and omissions [46-48].

4 Case Study 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 and estimated 27 million tons of iron were mined, railed, 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 Figure 2.

Figure 2. Stacker Conveyor

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.

5 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 kilometres from the workface to the site office to resolve the situation, which would result in considerable unproductive time being experienced.

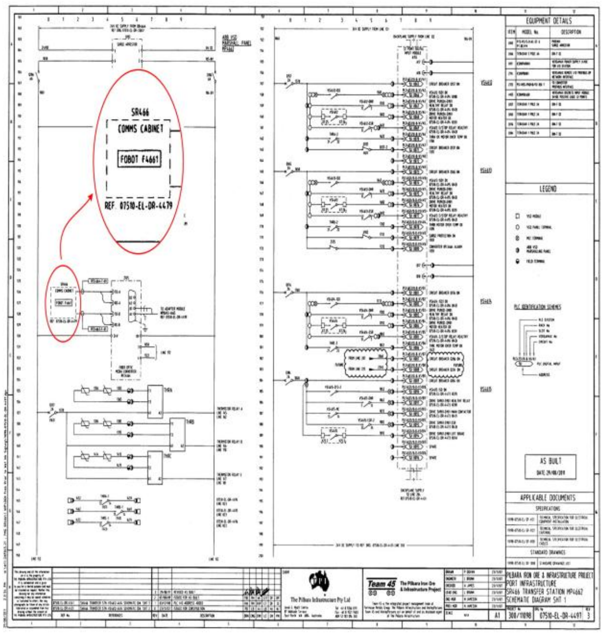
Considering the errors contained in the 'As Built' drawings, it suggested that a significant amount of RFIs and non-productive time must have occurred during the actual installation process. Moreover, engineers on-site cannot work without authorized drawings. They must submit their RFIs to the EPCM contractor 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

5.1 Error Classification

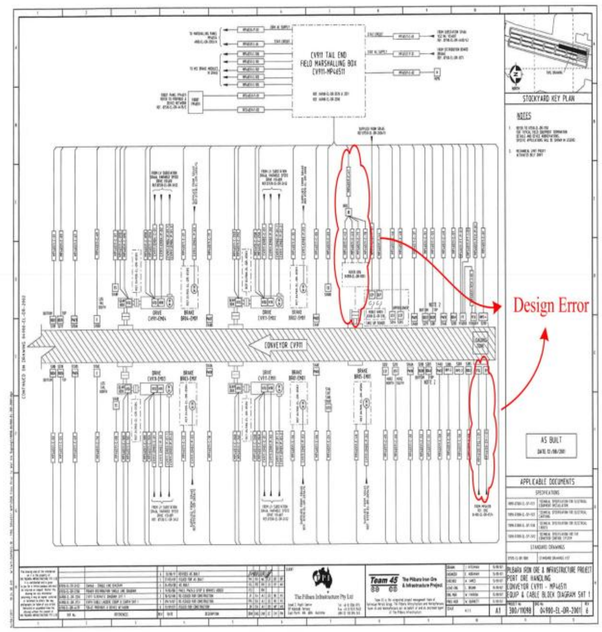
The classification of error types provides a platform for their quantification. The analysis of data derived from interviews and documentation for the selected case study enabled seven classifications of error to be identified and subsequently quantified (Table 2):

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 400V 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 (Figure 3a).
5. Cable schedule omissions: Incomplete information contained within the cable schedule (Figure 3b).
6. Wrong design: cables and components are not meant to be designed on a particular drawing (Figure 3c).
7. *Missing labels*: Cables or components are drawn on drawings but are not labeled (Figure 3d).

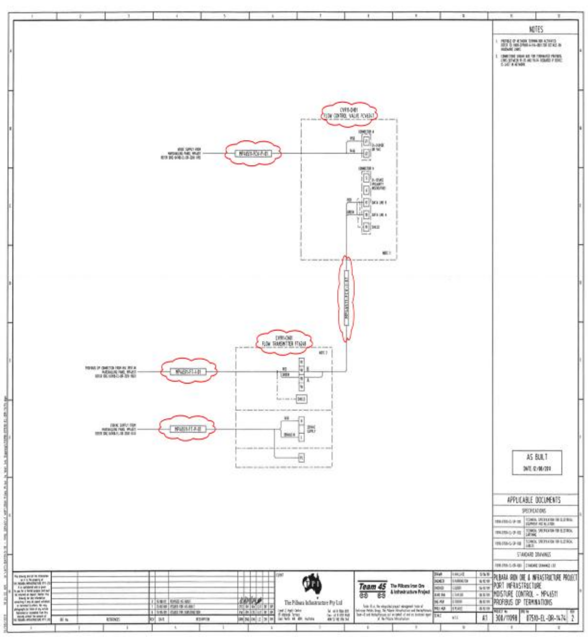
Drawing omissions were the most prevalent form of error identified (53.90%).From the 106 drawings used to install the electrical system for the conveyor belt, 158 cables and 84 components were found to have been omitted. The cable schedule is typically used as the mechanism to extract materials and cable 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 services contractor did not identify these omissions, then the likelihood of a project delay would have be high.



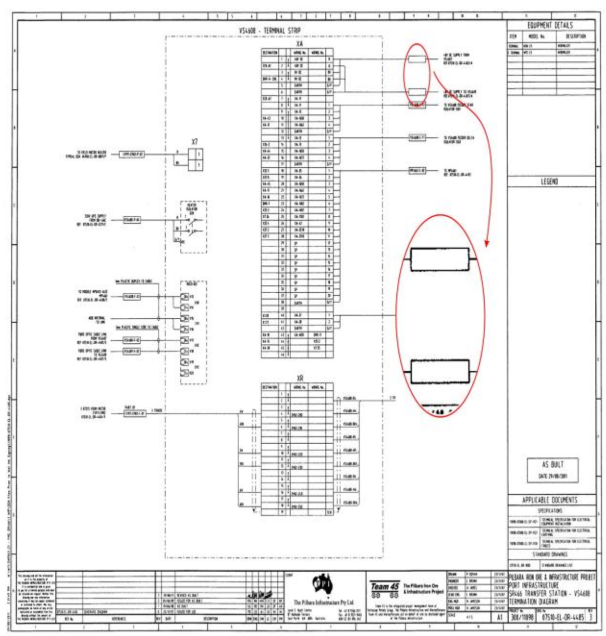
(a) Incorrect connection



(c) Wrong design



(b) Omission from cable schedule



(d) Missing label

Figure 3. Examples of errors

Table 2. 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 Total		10.02%	6.46%	0.22%	**53.90%**	**25.39%**	1.11%	2.90%

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 time address due the complexity and lack of reference information available. It was assumed that 3 to 5 hours 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 hours would be required. 'Inconsistencies in labeling' and 'incorrect connections' can be dealt with instantaneously by referring to the reference drawing. Such issues are deemed to be generally insignificant and can be readily addressed by experienced engineers. 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. In some cases, several similar errors could appear on the same drawing and therefore can also be dealt with.

5.2 Quantification of Unproductive Time

The unproductive time associated with attending to the identified is quantified based upon estimates derived from the I&E contractor. Table 3 provides a summary of the man-hours allocated to each error type. A man-hour cost of $150 is used as this is considered to reflect market rates for an electrical engineer working on a remote mine site in WA.

A total 851.5 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 (51.32%) are required to address the omission problems in the drawings. A total of 366 man-hours (42.98%) 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.

Table 3. 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	0	0	437	366	5	10	851.5
Cost ($150/man-hour)	$5,025	$0	$0	$65,550	$54,900	$750	$1,500	$127,725
Percentage (Total Cost)	3.93%	0%	0%	51.32%	42.98%	0.59%	1.17%	

It is estimated that 33.5 man-hours (3.93%) will be required to attend to labeling mistake issues. The man-hours required to attend to ‘wrong designs’ and ‘missing labels’ are insignificant 10 (1.17%) and 5 (0.59%) 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:

Average time to address an error for each type:

1. Labeling mistake = 0.74 hour/error T_{S1}
2. Inconsistent labeling = 0 hour/error T_{S2}
3. Incorrect connection = 0 hour/error T_{S3}
4. Drawing omission = 1.81 hour/error T_{S4}
5. Omission from cable schedule = 3.21hour/error T_{S5}
6. Missing label = 1hour/error T_{S6}
7. Wrong design = 0.77hour/error T_{S7}

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.

The direct cost for the electrical engineers to sort out the errors within the drawings can be calculated as:

$$C_E = \sum_{i=1}^{7} T_{Si} \times N_{Ei} \times R_{PE} \qquad \text{[Eq.1]}$$

Substituting the data from Table 2 into Equation (1), the cost associated with the unproductive time is calculated to be $127,725 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 $2,554,500 (17030 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.

5.3 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 Figure 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.

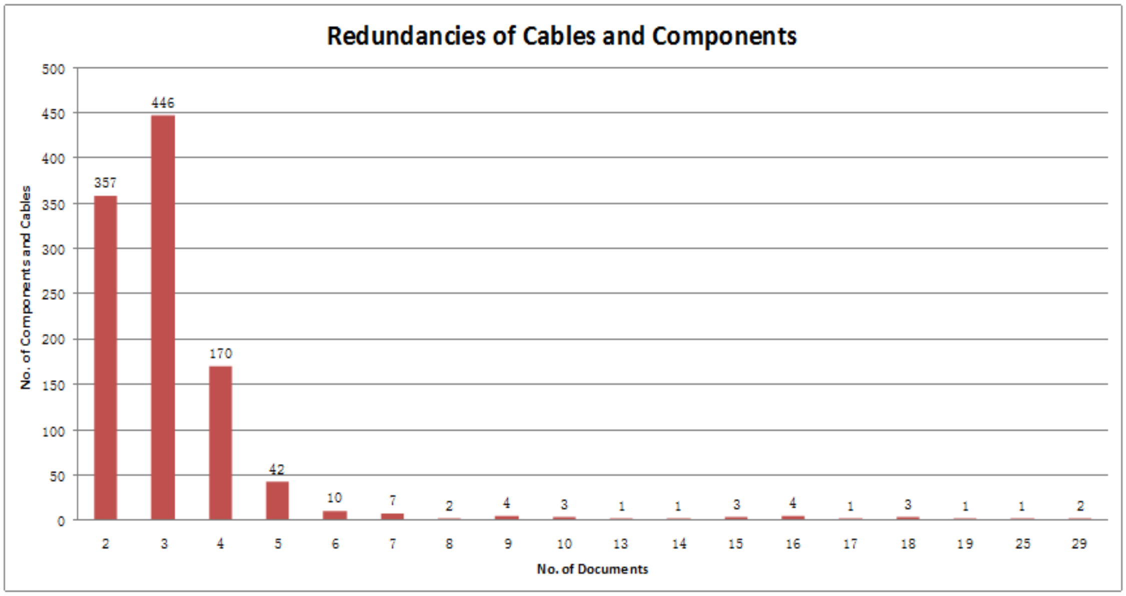


Figure 4. Redundancy associated with cables and components

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 on 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. Figure 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:

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.

The overall cost of the redundant information can be expressed as:

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

As each cable or component has to appear once among the documents, hence in Equation (2), N_{Di} - 1 and $T_R = 0.25$ hour, $R_{PE} = \$130$/hour. Substitute the corresponding values of N_{Di} and N_{CCi} derived from Figure 3 into Equation (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 11960 man-hours would have accumulated at a cost of $1,554,800.

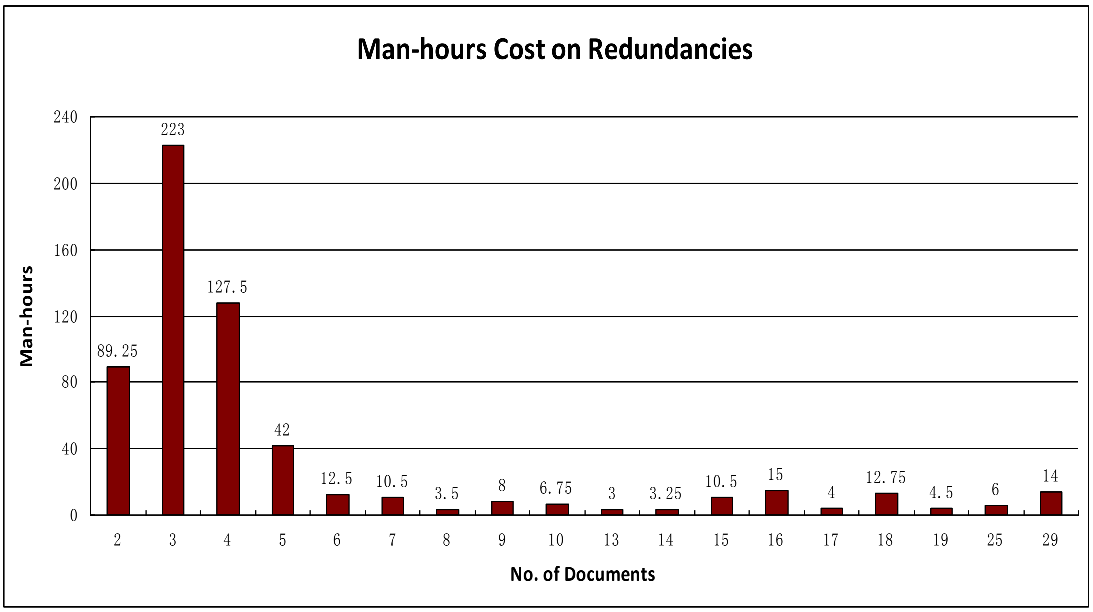


Figure 5. Man-hours cost for information redundancy

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 to 100 hours 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.

6 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 hypothetical cost curve to produce documentation using CAD is presented in Figure 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.

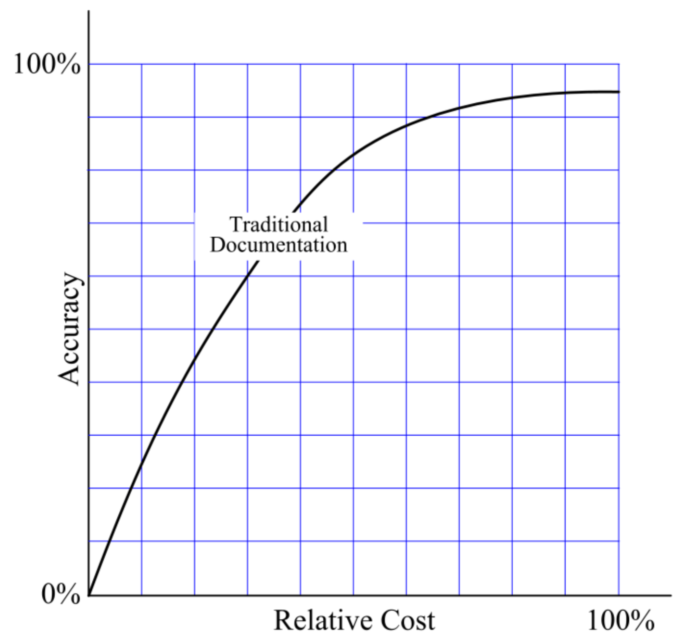
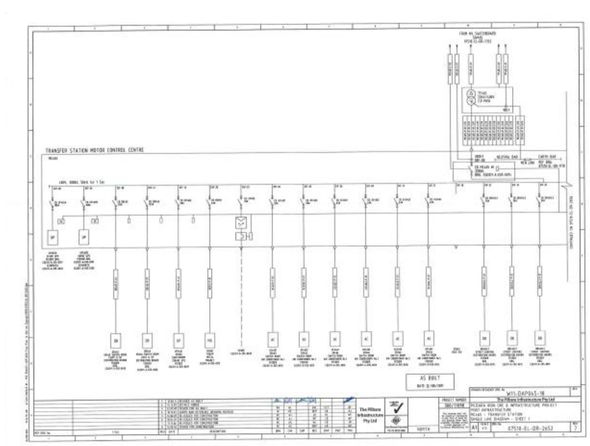


Figure 6. Cost curve to prepare traditional documentation

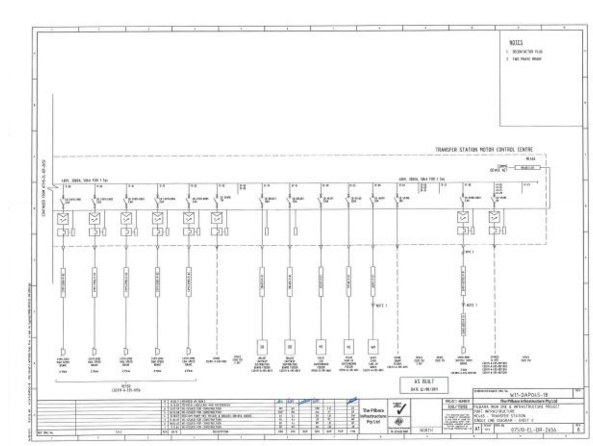
An alternative way to produce documentation for I&E is to produce a SIM object orientated model (OOM) where a 1:1 relationship between model and the real objects can be created. By constructing a 1:1 model, information redundancy can be eliminated, which will reduce the propensity for errors and omissions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

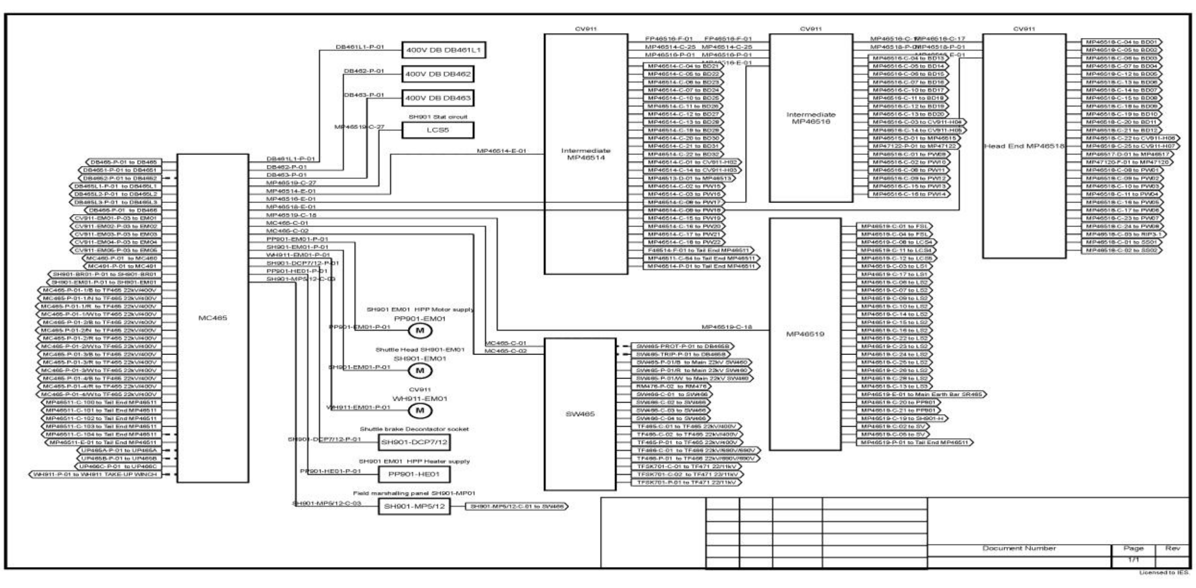
For the Stacker Conveyor, the ‘As Built’ cable schedule was only required to produce the documentation in using DAD. Figures 7a and 7b were produced in CAD and illustrate the single line diagrams of the motor control center MC465. A detailed examination of these two drawings revealed that a considerable amount of information had been omitted. The drawings were produced in DAD and were combined to form Figure 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 Figures 7a and 7b.



(a) CAD diagram:omission



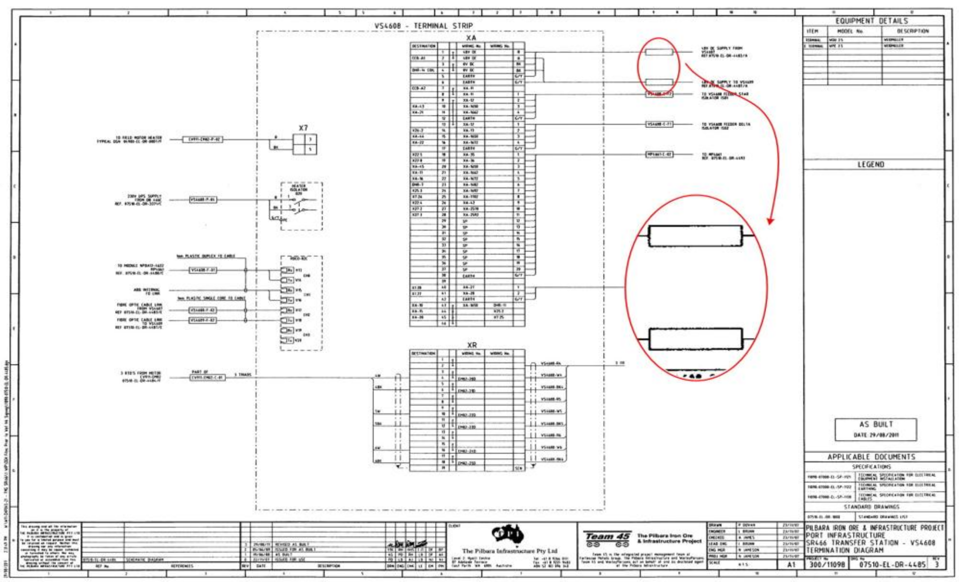
(b) CAD diagram:omission



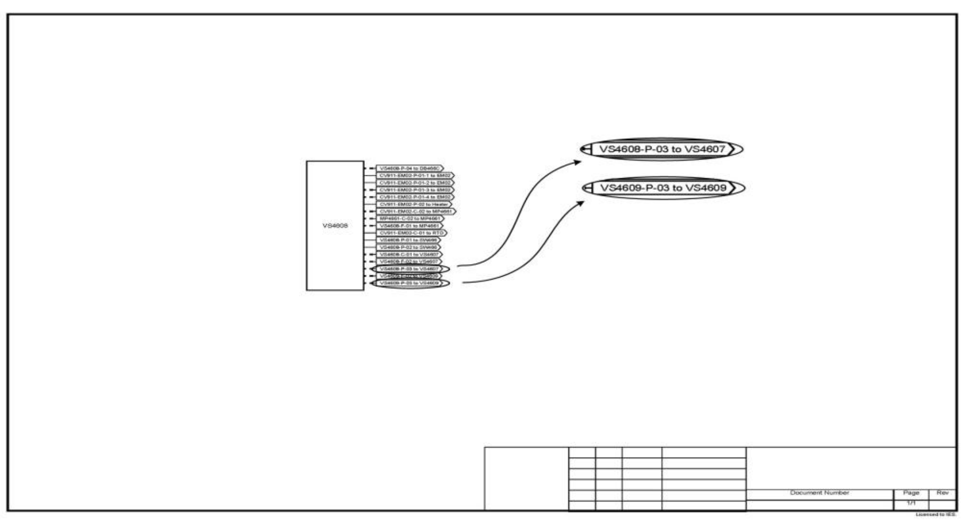
(c) DAD diagram

Figure 7. Drawing omission identified in DAD

In Figure 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 (Figure 8b). The connection relationship, the position and additional information can also be embedded in the model.



(a) Missing Label in CAD drawing



(b) Corresponding Labels in DAD

Figure 8. Missing labels identified in DAD

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.

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.

6.1 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.

The average time to produce a single drawing was two hours. To produce the 107 documents consumed approximately 214 hours. Thus, if a pay rate of $150/hour 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 4.

Table 4. 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/hour	4270	$555,100
DAD	107	2	$150/hour*	214	$32,100

*Note: The market rate for a DAD draftsman as at July 2012.

It can be seen from Table 4 that 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). Figures 9 and 10 graphically represent the productivity improvements of using DAD.

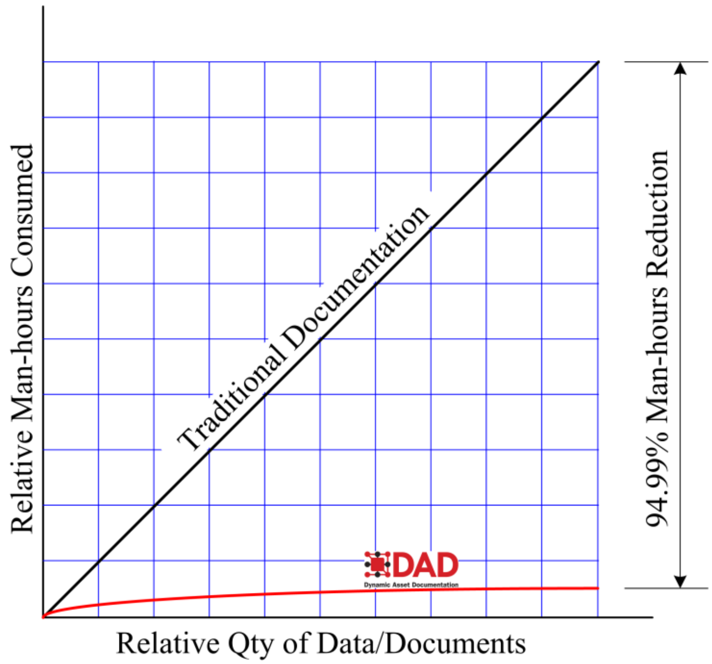


Figure 9. Reduction in man-hours

The determination of the unproductive time due to errors ($127,725) 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 were constant for all the electrical documentation produced then the estimated costs of unproductive time are $2,554,500 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 is therefore would have been in the region of $23.31 million. The use of DAD in this instance would have eliminated information redundancy and provided a budget of $19.20 million. A total of $4.10 million may have been saved using DAD. A comparison of the cost between traditional CAD drawing and DAD is depicted in Figure 11.

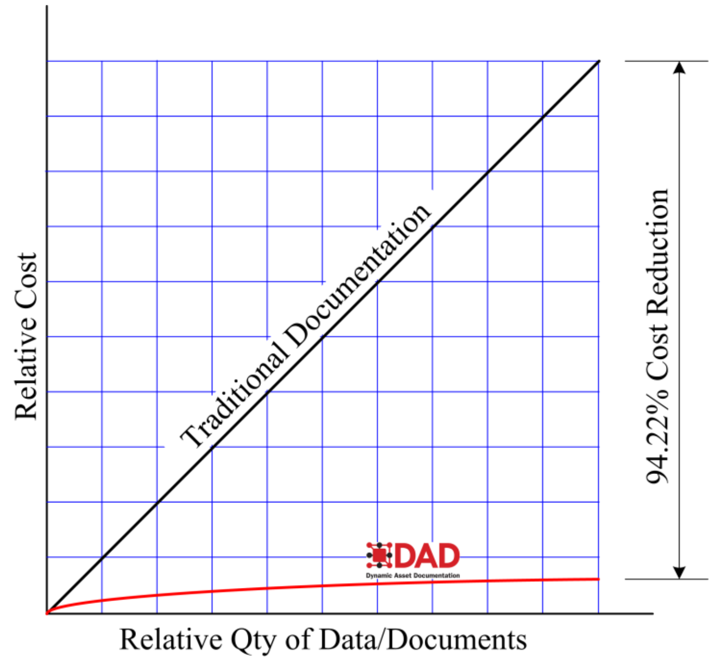


Figure 10. Reduction in documentation cost

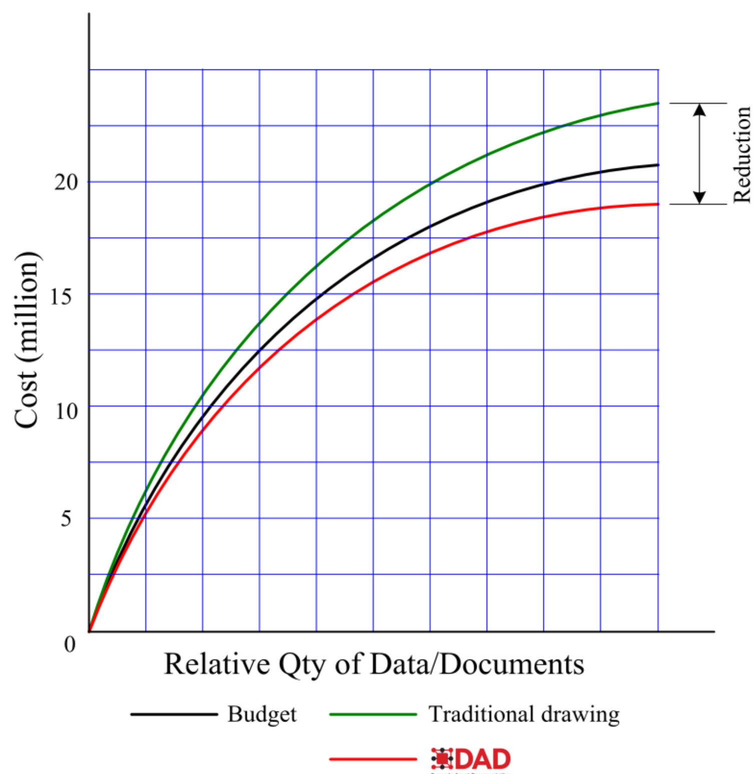


Figure 11. Cost comparison between traditional CAD drawing and DAD

7 Research Limitations

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

8 Conclusion

This has research has demonstrated that electrical documentation is produced inefficiently and contains 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.

Analysis of 106 'As Built' electrical drawings and a cable schedule for a 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 hours 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 851.5 extra man-hours would be required at a cost of $127,725.

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 drawings 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 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 two hours compared to the estimated 39 hours 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.

8.1 Future Research

Integral to PAR is the need to bring about change so that on-going improvements can be made. Before such improvements can be realized at project and industry level further research is required to inform and educate practitioners about innate problems that are being experienced with current documentation practices. Many engineering organizations are reluctant to admit to problems with their existing documentation systems and processes. Such a laissez-faire attitude has contributed to a culture of complacency and what is in fact a chronic malaise embedded within the systems, and processes of projects has become a 'norm'.

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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Appendix A

Table 1A. DAD compared to traditional drawing and documentation production

DAD	Drawings and Documentation
Single archive “Body of information”	Fragmented into individually created files, results in ‘Pile of documents’
Objects are connected together	Connections are lines joining shapes
Objects can be 1:1 with real world	Drawings contain arbitrary amounts of information
Each object is unique in the model	All information on drawings is repeated elsewhere
Model depicts the observable reality	Drawings often convey concepts and circuits so that the information they contain cannot be directly observed
The model is managed as a whole	The drawings and other documents are managed individually so that their interdependencies must be constantly maintained
Connections can be traced on screen	Following connections always involves reading several drawings in conjunction with one another
The model uses object inheritance to propagate shared data.	All information on drawing is entered manually.