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Toward productivity improvement in electrical engineering documentation

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Abstract

Purpose – The purpose of this paper is to determine the unproductive time and additional cost to re-engineer a safety control system for a Floating Production Storage Offloading vessel that was originally engineered and documented in computer-aided design (CAD).
Design/methodology/approach – The "As-Built" drawings contained numerous errors and omissions, which resulted in a "requests for information" being raised and productivity rates reduced – these costs and productivity losses are quantified. The use of CAD to originally engineer and document the safety control system was found to be inefficient as a 1:*n* relationship existed. Systems Information Models (SIMs) presents an alternative method to produce engineering documentation for the safety control system; where a 1:1 relationship is created between the model and the real objects. By constructing a 1:1 model, information redundancy can be eliminated, which reduces the propensity for errors and omissions to be made by engineers.
Findings – The use of a SIM to re-engineer and document the new safety control system resulted in significant productivity benefits being achieved. Consequently, it is proffered that a paradigm shift from a 1:*n* to 1:1 perspective is required for engineering electrical and instrumentation systems so as to ameliorate the quality of documentation produced and productivity.
Originality/value – The paper concludes by suggesting that future research is required to examine how processes and procedures can be re-designed to accommodate the use of a SIM.

Keywords CAD, Errors, FPSO, Omissions, RFI, SIM
Paper type Case study

Introduction

Graphical and written representations developed by engineers are typically represented in two dimensions (2D) and constructed using computer-aided design (CAD). When a change is required, a 2D drawing and each corresponding view require a manual update thus a 1:*n* relationship exists. The modification of drawings can be a very time-consuming and costly process. Furthermore, as drawings are invariably manually coordinated between views in 2D, there is a propensity for documentation errors to arise particularly in the design of complex electrical and instrumentation (E&I) systems, which may comprise of hundreds of drawings that are not to scale and have to be represented schematically. In this instance, information is often repeated on several drawings to connect each schematic together. Consequently, the time to prepare the schematics can be a lengthy and tedious process, especially as the design gradually emerges and individual

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documents are completed. Any inconsistencies that manifest between the documents require re-editing and cross-checking before they are issued for construction.

Omissions and errors in contract documents have been identified as major sources of rework and thus contribute to significant productivity losses being experienced. For example, Love *et al.*'s (2013, 2014a) analysis of 107 "As-Built" drawings of an electrical system for a stacker conveyor identified 449 errors and omissions, which required an estimated 859 extra man-hours to rectify and an additional cost of AU$128,850. Empirical studies have indicated that between 50 and 60 percent of change orders that occur in projects are attributable to poor-quality design documentation (Hibberd, 1980; Kirby *et al.*, 1988; Love *et al.*, 2006). Moreover, the costs of rectifying errors that arise from the design and documentation process can potentially increase a project's cost by 5 percent (Gardiner, 1994).

Against this contextual backdrop, the research presented in this paper uses a case study to determine the unproductive time and additional cost to re-engineer a safety control system for a Floating Production Storage Offloading (FPSO) vessel that was originally engineered and documented using CAD. As a consequence of using a conventional CAD approach the "As-Built" drawings contained a plethora of errors and omissions, which resulted in a significant number of "requests for information" (RFIs) being raised and losses in productivity being experienced. In addressing this issue, a System Information Model (SIM) is used to re-engineer the new system and the resultant productivity benefits that arose are presented.

E&I engineering in CAD

The design of E&I systems present a mathematically indeterminate problem as there is no single optimum design – rather there are several different ways to solve a given problem. With the advent of CAD, electrical and system engineers have been able to efficiently and effectively experiment with various alternative design solutions. Moreover, circuits can be validated more readily and the accuracy of the design improved. For example, the design of a bi-stable circuit can be readily checked in CAD (i.e. values of load resistance attributed to the various components). Faulty permanent magnet design used to be a significant problem for electrical engineers as it resulted in partial demagnetization. However, as a result of CAD's ability to verify the design's reasonability, this issue has been resolved. Other advantages offered by CAD in electrical engineering are:

- providing an understandable representation of the numerical results (e.g. through graphs and other graphic devices);
- reducing the tediousness of solving common and complex equations;
- ability to use simple numerical methods to solve complex problems that would be time consuming to undertake; and
- testing the design (such as the maximum value of load resistance the design can support).

Typical types of drawings created within CAD for E&I systems are: block; schematic; termination; and layout. In addition cable schedules and "Cause and Effect" (C&E) diagrams will be provided within the documentation produced, though this is dependent upon the nature of the system that is being designed and documented.

Despite the benefits that CAD has provided to the field of electrical and systems (E&I) engineering, engineers are prone to making errors and omissions, especially as objects are often replicated on several different types of drawing as noted in Figure 1. Concepts and requirements from several sources are translated on to documents and drawings in varying patterns. As noted above, the same information is placed on several documents to form relationships between them (Figure 1). Different information about the same component will regularly be placed in various places and so equipment and cable tags are often repeated. As a documentation package evolves it is difficult to ascertain which particular documents contain the same information or show related information. Checking the accuracy of the information contained within the documentation therefore forms a critical component of the engineering process. Yet, the extant literature consistently demonstrates that effective checking is rarely undertaken due to time and financial constraints imposed on engineering firms (e.g. Love *et al.*, 2006, 2009; Lopez and Love, 2012). When meticulous checking is undertaken, errors and omissions are invariably found and consequently, several iterations of the documentation may be required. Unfortunately, due to the time constraints imposed upon the engineers, incomplete or inaccurate documentation is often distributed to contractors.

Incorrect labeling, missing labels and omissions represent typical examples of errors that can be found in E&I drawings (Love *et al.*, 2013). Moreover, connections between various devices represented as shapes and lines may distribute among several drawings. Errors and omissions that are identified by engineers on-site invariably result in RFIs being raised. An RFI seeks to identify and resolve issues on-site to avoid potential contract disputes and claims at a later date (Tadt *et al.*, 2012). Raising an RFI can be costly and may adversely impact upon the contractor's productivity. Love *et al.* (2013) revealed that the use of SIM to engineer and document an E&I system could provide a staggering 94 percent improvement in productivity.

Research approach

To examine how a SIM can provide significant cost and productivity improvements a triangulated research method was adopted. Triangulation formed the basis of the data collection process, which took place at the offices of the participating E&I organization. Triangulation involves the use of multiple research methods and/or measures of a

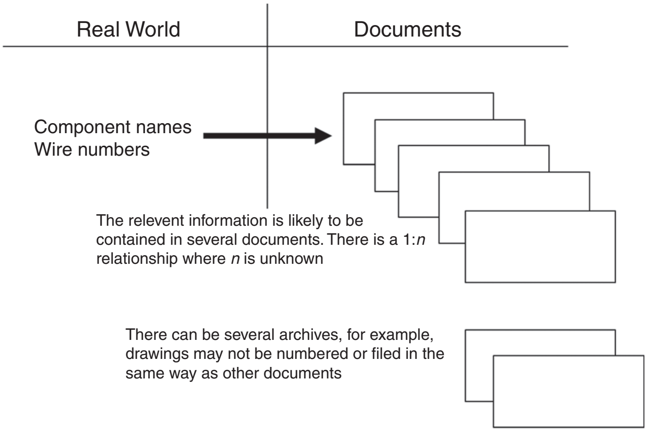

Figure 1. Replication of information: 1:*n* relationship

Source: Love *et al*. (2014b)

phenomenon, in order to overcome problems of bias and validity (Denzin, 1988; Black, 1993). 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. This approach was adopted to provide additional context to the problem and provide validity to the research process.

Unstructured interviews were used as a primary and secondary data sources. 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. Interviews that were undertaken with the managing director, business development manager and engineers 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 used as the medium to record the interviews.

Documentary sources are commonly referred to as unobtrusive measures (Robson, 1993). 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 and access to documentation from other projects, such as lessons learned documents (where the latter provided a contextual backdrop for the study). The analysis of documentary sources is commonly referred to as content analysis, which is non-reactive in nature (Holsti, 1969). In essence it is "a research technique for making replicable and valid inferences from data to their context" (Krippendorf, 1980). In its simplest format, content analysis is the extraction and categorization of information from documents. Inferences can only be drawn from the data extracted if the relationships with what the data means can be maintained between their institutional, societal or cultural contexts. To preserve anonymity and confidentiality, the actual names of participating companies and individuals have been disguised.

Case background

The FPSO is on an oilfield off the Western Australian coast. The safety control system had caused shutdowns frequently, many of which were specious and resulted in oil production losses. To achieve a system with integrity and enhance the production rate, Energy A (owner of the FPSO) decided to upgrade the FPSO's safety control system. However, due to a contractual dispute with the shipyard that converted a tanker to an FPSO, many "As-Built" drawings were unavailable. Consequently, this adversely influenced their ability to perform the required system upgrade. Difficulties associated with CAD produced documentation and subsequent losses in productivity due to RFIs raised are examined hereinafter.

FPSO vessel. FPSO vessels are among an array of floating systems used to process and store hydrocarbons extracted from subsea fields (Figure 2). They can replace fixed production platforms and pipeline systems, which extract oil and gas from shallower fields or those that are not technically or commercially viable for smaller, deep water applications (Love and Edwards, 2013). FPSOs are also capable of receiving oil produced from nearby platforms (or subsea) and process, and store it in readiness for tanker offloading or pipeline transportation (Lombardo, 2003). New build FPSOs or tanker conversion variants which use an existing hull, can be towed and permanently fixed to an offshore reservoir to form a "hub," which is connected to seabed wells via flexible risers (Love and Edwards, 2013; Love *et al.*, 2014c).

A turret mooring system used enables an FPSO to "weathervane" through 360 degrees. This type of mooring effectively ensures that the vessel's bow is kept pointing into the prevailing wind and currents, thereby minimizing the impact of severe inclement conditions. Often, thruster systems used aid station-keeping and control the vessel's heading. Anchor wires, flexible risers and control umbilical's from the seabed all reach the surface through the turret. External turret moorings, mounted at either the FPSOs bow or stern, provide an adequate mooring system for moderate climatic environments. FPSOs are typically preferred in frontier offshore regions, as they do not require a pipeline infrastructure to export oil, which makes installation easier and capital expenditure, and operational expenditure lower (Love *et al.*, 2013). In turn, these efficiency measures translate into quicker revenue generation and renewed hydrocarbon field investment and development.

The upgrade and requirements. For the case study FPSO, the upgrade of the safety control system consisted of four parts: engineering design; on-site engineering; hardware; and system installation. The engineering design consisted of three specific phases: information interpretation from the existing design; new system design; and Programmable Logic Controller (PLC) programming. The engineering design cost was AU$3.5 million, while the on-site engineering cost was AU$2 million and dealt with the management of cable connections. On-site engineers reconciled the cables and connections with various devices to ensure the required signals were delivered to the correct points. The hardware procurement consisted of a variety of equipment such as TT PLC units, control cabinets, marshalling panels and cables at a cost of AU $2.3 million. The system installation, which cost AU$0.5 million, was undertaken by Energy A's dedicated project team. Thus, the overall project cost was AU$8.3 million. Figure 3 illustrates that the cost associated with information interpretation accounted for 9.08 percent of the total project cost and 21.54 percent of the engineering design phase cost.

The FPSO was to be refurbished at a dockyard and hence, the length of stay could have a significant financial impact in terms of lost production. For example with an average production rate of 35,800 barrels of oil per day (bopd), then a total loss of production for five months would exceed 5.37 million barrels of oil. Considering the price of the crude oil, which was US$96/barrel (June 2013), the total capital loss would have been US$515.52 million.

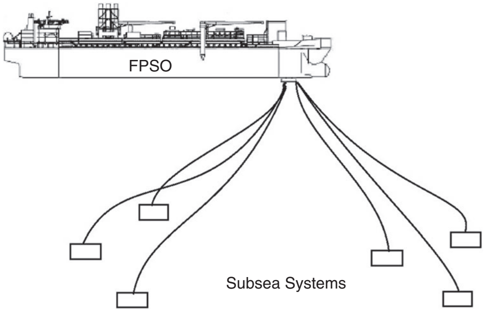

Figure 2.
FPSO and subsea system

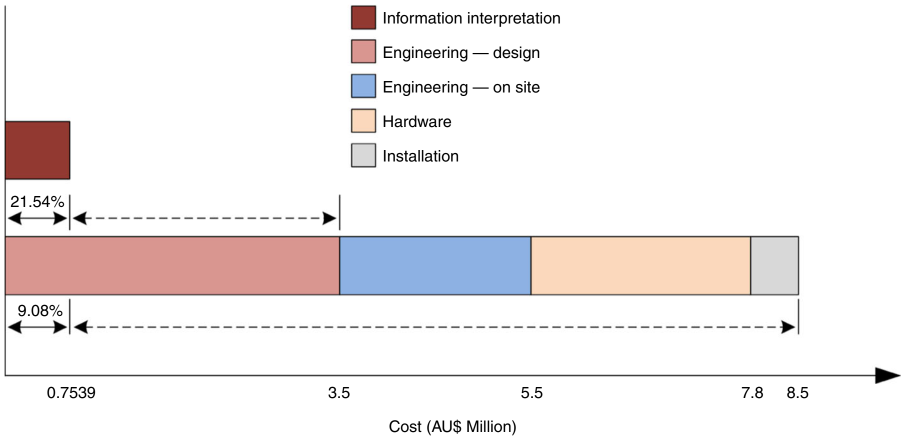

Figure 3. Cost of as a proportion total contract value

Equipment layout. Ten modules, three local equipment rooms (LERs) and a central control room (CCR) are installed on the FPSO studied in this paper. The safety system residing in the LER and the CCR required an up-grade to their equipment. As a distributed control system, field devices can communicate with the control devices, for example, a solenoid valve can distribute signals of its current status and receive the control commands that are generated by the control devices. The entire system is monitored and supervised directly by those who have immediate access to the terminals in the CCR. If a critical event occurs, the operators can immediately shut down the system from the critical alarm panel (CAP), which is located in the CCR.

In Figure 4, the BBB safety control system and CAP (denoted by red boxes) was replaced by a TT safety control system and a CAP (denoted in blue boxes). TT is a state-of-the-art fault tolerant controller that is based on Triple-Modular Redundant architecture. It uses two-out-of-three voting to provide high integrity, error-free, uninterrupted process operation with no single point of failure. TT is typically used for the following systems: burner management; fire and gas (FGS); safety instrumentation (SIS); turbo-machinery control and nuclear safety (NSS). The new safety control system consists of FGS and SIS and a set of new marshalling panels. To efficiently manage system wiring and ensure maintenance processes could be conducted, the field signals supplied from the junction boxes were passed through nine newly designed marshalling panels instead of directly connecting to the PLCs. A total of 21 control cabinets were replaced while the total number of inputs and outputs (I/O) for the system were 1,860.

Re-engineering of the safety control system. System integrators were provided with a set of integrated control and safety system (ICSS) drawings and C&E drawings (refer to Figure 5), and PLC codes (I/O list) for the old system as well as to be re-engineered safety control system design. Unfortunately, due to disputes between the shipyard and the FPSO's previous owner, the master cable schedule of the ICSS was not available to the E&I firm. The ICSS drawings depict the safety control system's wiring that consists of 258 individual drawings that are sub-classified into layout, block, schematic and termination diagrams. The C&E drawings are used to describe the safety control system's functions (i.e. descriptions of actions taken should a cause event occur). For example, if a gas leakage occurs at the elevator trunk

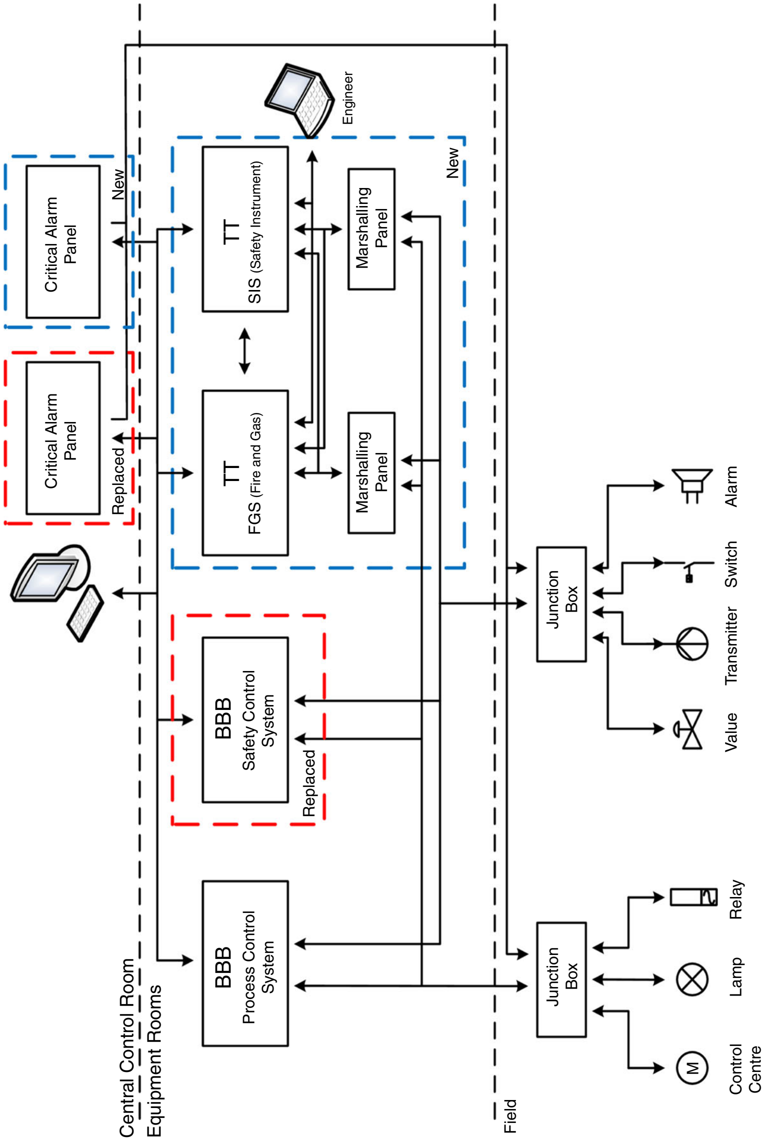

Figure 4.
Illustration of system upgrade

Fire and Gas Cause and Effect Diagram				Note					16	8	15	9, 15
				Effect description	General PAGA alarm	Facility E shutdown	General Facility shutdown	Start Fire water pump	Single gas detection	Confirmed fire under M60	Deluge release zone C	Open M60 deluge valve
				Tag No.	PAGA	ESD1	ESD2	FWP	SGO	Activate Fire	Deluge Zone C	B4 XY 3,004
Cause description	Notes	Tag	Fire Sub zone		1	2	3	4	5	6	7	8
Point gas detection 10% LEL single	2, 14	A, K, L, M	M60	A	XI				XI			
Point gas detection 20% LEL single	2, 6, 14	A, K, L, M	M60	B			XI	XI				
Point gas detection 30% LEL confirmed	1, 2, 14	GAS HH 2ooN	M60	C								
Flame detection single	2, 6	B		D	X		X					
Flame detection confirmed	1, 2, 11, B	FLAME 2ooN		E								
Flame M60 under main deck	12	61 KIR 3,623	M60	F	XI	XI		X	X			
Flame M60 under main deck	12	61 KIR 3,624	M60	G								
PAHH M60 confirmed deluge released	2, 3	84 PT 3,024	M60	H	X		X		XI		X	
Point gas detection 20% LEL confirmed	2, 14, 18	GAS HH M60	M60	I			XI	X				
M60 comp A fire confirmed	1, 2, 11, C	FLAME M60	M60	J			X		X	X	X	X
HP comp A water mist released	2, 4	84 PIT 4,005	M60	K	X				X	X	X	X

Figure 5. Cause and effects drawing

of the accommodation area, it is detected, confirmed and a human-machine interface alarm (and corresponding CAP lamp) will be triggered; the facility's emergency shutdown is then initiated. Such an operation is achieved under the actuation of the PLC controllers that is based on the logical computations of the software preinstalled. Connections at the PLC input/output ports are recorded as an I/O list. Interpreting the information contained within the design of the old system presented a major challenge to the E&I firm as it commenced re-engineering the safety control system. Engineers were required to check all ICSS drawings, C&E drawings and compare against the I/O list. This task sought to ensure that all the system logics were correct and all the required system functions were fulfilled. When a problem was identified, an RFI was raised by the system engineer who then sought an answer from Energy A's engineer. The next stage of the re-engineering process was to design a new safety control system based on the TT PLC modules, which is compatible with the old BBB process control system. Then the PLC program was written to achieve the required functions of the safety control system.

There are a plethora of PLC manufacturers who are unique and offer a bespoke service, for example, ABB, Siemens, Rockwell, Mitsubishi and Triconex. The most commonly used PLC coding language is ladder logic but due to varying features and specifications, it is extremely difficult to transfer a PLC program from one manufacturer's device to another. Consequently, system engineers had to review existing C&E drawings and software codes to understand how the old system functioned – then, the program was recoded into the new TT PLCs. Interpreting the information within the old system was deemed to be the most difficult aspect of this project with an engineer from the system integrators stating "most of our man-hours have been consumed to interpret the information trying to find out what is correct, what is wrong and what the client really want." It was proffered that the design's documentation (that was produced with CAD) was confusing and often misleading for the system engineers. On CAD drawings, any single device can appear on several other different drawings simultaneously. Thus, a 1:*n* relationship between the real world and the documents is established and the risk of introducing errors and omissions is increased as eluded to earlier.

Analysis of RFI data

The documentation provided to the system integrator by the client to re-engineer the safety control system consisted of 258 ICSS drawings, 64 C&E drawings and two I/O lists (i.e. the BBB, CAP Masters). A detailed analysis of these documents revealed that 3,181 field devices formed part of the process and safety control system design for the FPSO. The number of specific devices involved in the design of the safety control system was 2,881, which accounted for approximately 91 percent of all the field devices. A total of 1,590 RFIs were raised relating to issues for 956 devices (33.18 percent) for the safety control system and 79 system functions. Typically, the system engineer would raise an RFI and propose a possible solution based upon their knowledge; an engineer from Energy A would review the proposal and then either approve or reject the proposal. In total, 12 distinct types of RFI were identified from a detailed analysis of the 1,590 RFIs raised (refer to Table I):

1. no action required: the design is correct and no action is required;
2. unsolved: the problem remains unresolved after the RFI due to either nonresponse or inadequate response;
3. insufficient information: the design is correct but further information is needed to clarify present information;
4. conflicting information: information between different documents conflicts with each other;
5. labeling mistake: the component/notation is mistakenly labeled;
6. redundant information: the component/information provided is redundant and of little use;
7. inconsistent labeling: the labels/notations are inconsistent among different documents such as C&E and I/O;

Problem type	Valve	Detector	Transmitter	Lamp	Switch	Functions	Queries (*n*)	%
No action required	28	45	69	3	100	8	253	15.91
Unsolved	16	0	32	0	36	0	84	5.28
Insufficient information	70	7	78	6	203	26	390	24.53
Conflicting information	45	12	40	4	56	4	161	10.13
Labeling mistake	11	7	12	10	43	1	84	5.28
Redundant information	14	2	6	2	25	3	52	3.27
Inconsistent labeling	172	5	27	4	77	42	327	20.57
Incorrect connection	0	0	1	0	1	0	2	0.13
Omission from C&E	26	0	15	37	31	1	110	6.92
Omission from I/O	15	0	29	0	26	0	70	4.4
Missing label	0	0	0	0	7	0	7	0.44
Wrong design	3	9	12	2	24	0	50	3.14
$\sum$	400	87	321	68	629	85	1,590	

Table I. Classifying RFIs from the "As -Built" drawings

(8) incorrect connection: incorrect connections among C&E and I/O;

(9) omission from C&E: component or notation cannot be found in C&E;

(10) omission from I/O: component or notation cannot be found in I/O;

(11) missing label: label is missing from C&E or I/O; and

(12) wrong design: the design is incorrect.

The 956 devices associated with the RFIs can be classified into five distinct types: valve; detector; transmitter; lamp; and switch. Table I reproduces the distribution of problems identified within the five devices and system functions.

Classifying RFIs

"Insufficient information" was the most prevalent among the 12 types of RFIs accounting for 24.53 percent and can be attributed to poor system documentation, which resulted in difficulties in understanding the drawings (e.g. unclear or misleading descriptions and insufficient instructions). A total of 203 RFIs were raised related to insufficient information for switches, which represents 52.09 percent for this category. This was due to some switches that were configured as "for display only" to show if an individual damper had tripped or did not perform other functions. However, this was not specified in the C&E drawings and created unnecessary confusion when interpreting the information presented.

"Inconsistent labeling" was another prevalent problem identified among the drawings. Most of the inconsistent labeling problems identified indicate that the device labels appeared on the C&E drawings. However, a close examination of the I/O list revealed that a mismatch existed with device labels, which rendered it difficult for the software programmers to understand the drawings and write the PLC codes. For example, 172 valves were identified as inconsistent labeling; a situation that arose because several draftsmen had worked off the same set of drawings and had not followed the same documenting procedures. Each of the draftsmen may work on different drawings simultaneously and create labels for a same device using different symbols or descriptions. This inconsistency reduced the traceability of a device among the drawings.

A total of 253 (15.91 percent) RFIs were identified as having "no action required." Discussions with engineers revealed that this issue could have arisen as the individual used their experience, knowledge and understanding to fill in the missing information gaps contained on the drawings. For example, a gas detector 61-KGP-3641A was identified as "2 or more detectors in alarm status" in the C&E drawings; the system engineer assumed that the detector applied a two out of two Diagnostics (2oo2D) architecture. However, Energy A's response to the RFI was to reject the assumption by confirming that a two out of N (2ooN) architecture was applicable in this instance and that the C&E drawing should remain unchanged.

"Conflicting information" between drawings accounted for 161 (10.13 percent) of all RFIs raised and these focussed on determining the conflicts relating to the system's functions rather than "inconsistent labeling" RFI. For example, a heat detector (61-KHF-5831A) was noted in a C&E drawing to have a 2ooN voting function despite being specified elsewhere as being one out of N (1ooN). RFIs denoted as "inconsistent labeling" pertained to disagreements between the referencing of labels for identical equipment. For example, a solenoid valve was labeled as 71-FD-3055A on C&E drawing and 71-FY-3055A on I/O list, respectively. It was confirmed by Energy A that the description on the I/O list is correct and the C&E drawing was modified.

A total of 110 and 70 RFIs were classified as "omission from C&E" and "omission from I/O", respectively. "Unsolved" and "mistake labeling" were found to have resulted in 84 RFIs each being raised (refer to Table I). When an RFI was presented to the design team, the decision to reply to the query or not was depended upon how well the question was phrased and how familiar the design engineer was with project. Poorly prepared RFIs would not be answered in their present form just in case the answer was misunderstood. Any RFI dealt with by a less qualified engineer who may also be unfamiliar with the design, gave rise to answers that did not address the RFI posed.

Errors that were found to be the "wrong design" can adversely influence a system's integrity. For example, a gas detector (61-KGP-8011A) was designed to trip a public address and general alarm (PAGA) system on "confirmed gas detection," which was defined as a situation that 20 percent lower explosive limit (LEL) gas is detected by at least two detectors concurrently. However, the correct design should be a PAGA initiation on 10 percent LEL gas detection by a single detector. Because of this erroneous design, the initiation of PAGA was delayed and jeopardized the safety of the operators and equipment. Most of the RFIs pertaining to "redundant information" were due to design and scope changes. For example, a low-pressure compressor was placed permanently out of service thus, all devices attached to the compressor are configured and were permanently de-energized. Several RFIs categorized as "missing label" were found where devices had been created but surprisingly not labeled. Two connection errors were identified where the devices had been mistakenly connected to the SIS rather than the FGS.

To address an RFI, a series of communication exchanges between the engineer and design team often took place. Table II illustrates that issues associated with 621 devices and 73 functions were addressed by raising a single RFI. However, for 180 devices and six functions two RFIs were required. Similarly, nine devices required five RFIs and two devices required as many as six RFIs to resolve the issue.

The number of C&E drawings produced for the safety control system was 64 and engineers estimated that on average, four hours was needed to scrutinize each drawing. On average, engineers referred to ten drawings to confirm and clarify any problems identified. It took approximately 0.25 hour to locate each drawing and acquire the necessary information; thus 2.5 hours were required for the ten drawings. Another 0.5 hour was used to prepare the RFI and the corresponding document issue. Therefore, it is estimated that three hours was consumed to prepare an RFI. The pay rate for an engineer is $150/man-hour (based on current market conditions at June 2013) and hence the cost of interpreting the information from the drawings can be calculated as follows:

$$C = \left[N_D \times T_D + N_Q(N_{RD} \times T_{RD} + T_{RFI})\right] \times P \quad (1)$$

Table II. Number of RFIs required

Number (n) of RFIs for each device/function	No. of devices	No. of functions	%
1	621	73	67.05
2	180	6	17.90
3	109	0	10.53
4	35	0	3.30
5	9	0	0.87
6	2	0	0.19
$\sum$	1,035		100

where C is the cost on interpreting the information; N_D the number of C&E drawings; T_D the man-hours to check each drawing; N_Q the number of questions; N_{RD} the number of reference drawings; T_{RD} the man-hours to check each reference drawing; T_{RFI} the man-hours to prepare RFI and document issue for each question; and P the pay rate.

As noted above, the number of C&E drawings was 64 and the total number of RFIs raised was 1,590. Assume therefore that: $T_D = 4$; $N_{RD} = 10$; $T_{RD} = 0.25$; $T_{RFI} = 0.5$; and $P = 150$. By substituting the data into Equation (1), it can be calculated that the total indirect cost on interpreting the information contained in the drawings (borne by the contractor) is a staggering AU$753,900. In this case, the cost of raising RFIs as a result of poor documentation was 9.08 percent of the project's overall cost and 21.54 percent of the engineering design. In order to reduce such costs and improve the productivity of the engineering design process, a shift from CAD to a SIM is required.

Systems information model

A SIM is used to describe inter-connected systems – power, control, information technology and communications in a single digital representation. Research has demonstrated that a design that uses a SIM based on software such as Dynamic Asset Documentation (DAD) produces less errors and omissions than CAD (Love *et al.*, 2013, 2014a). This is because the entire engineering design is undertaken within a single digital model *vis-a-vis* creating a plethora of schematic drawings. Thus, all objects (e.g. cables and components) are modeled once when a SIM is used; a 1:1 relationship between the model and the real world is produced. Paper drawings and the "traditional draftsman's" role are redundant and therefore, errors and omissions produced by the draftsmen are eradicated, which reduces the total number of RFIs raised. Many other attributes, such as dimensions, length, location, prices, schedules, product images and files can be attached to the model for each object so as to facilitate the design, procurement, construction and review of activities. When the design and engineering is completed, a read-only copy of the model is created, exported and made available as a "Kernel" to other project team members. The Portal is based upon a read-only copy of the SIM (Figure 6).

The Portal is a separate application with its own users (e.g. procurement team and construction contractors) and security. Users import and access all or part of the design information within the kernel, depending on their authorization level. In addition, a user can also mark, make notes and attach their own files to the kernel as their private data. Importantly, users cannot change the design within the kernel. If users find conflicts or design errors within the kernel, they can identify them and create a specific RFI folder, which consists of facets needed to ensure they are attended to efficiently. A spreadsheet can be automatically generated containing all object information either in MS-Excel or portal document format (pdf) file format. On receipt of the spreadsheet, the design team can review the design and rectify any problem immediately. A new kernel is then generated and exported to all users for further application as denoted in Figure 7.

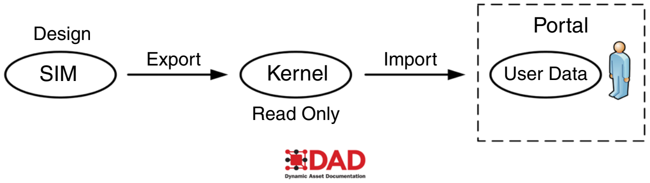

Figure 6.
Portal/SIM relationship

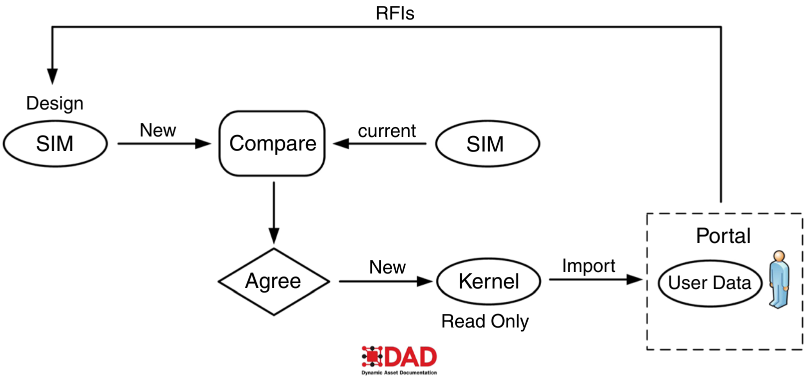

Figure 7.
Kernel revision process

Error rectification is a straightforward process, because engineers do not need to identify all other relevant drawings and revise them manually. Consequently, time and cost can be reduced and productivity increased.

Safety system upgrade

To perform the safety control system upgrade of the FPSO, all information extracted from the ICSS drawings and the I/O lists was inputted into DAD. As the ICSS cable schedule was not available, engineers had to input the information (extracted from the ICSS drawings) into DAD manually which is less efficient than importing the information directly. By doing this, all the physical field devices and PLC I/O points were modeled in DAD. A 1:1 mapping from the drawings and I/O lists to the DAD model was established.

Signal routes among various devices and I/O points were also modeled so as to realize the required system functions. Two types of connectors were used during the modeling process: solid black lines represent the real connections between field devices and control cabinets where PLCs are residing; and dashed pink lines are virtual connectors representing the relationship between the field devices and their corresponding PLC I/O points. For example in Figure 8, a pressure transmitter

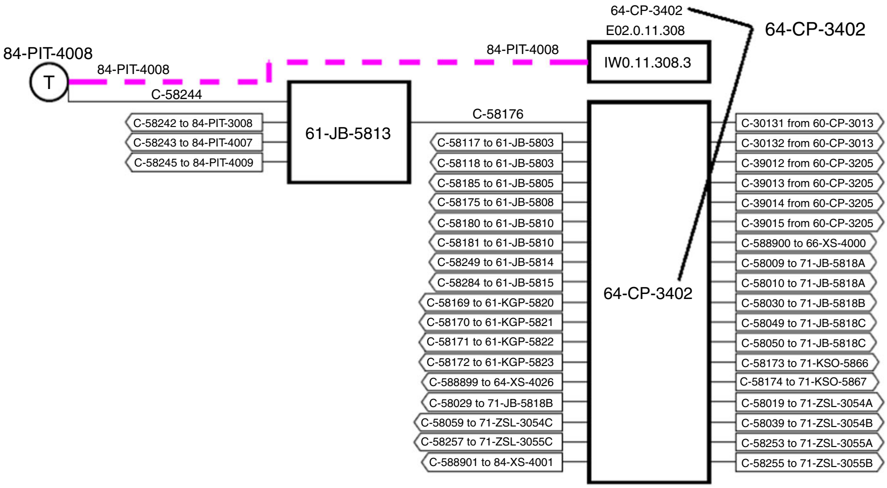

Figure 8.
Relationships between field device and PLC cabinet

(84-PIT-4008) is connected to a control cabinet (64-CP-3402) via solid black connectors (C-58176) and (C-58244) passing through a junction box (61-JB-5813). It is also shown that, along the dashed pink line, the transmitter has a corresponding PLC I/O point allocated in the same control cabinet within location E02.0.11.308. With such a model, the system engineers compared the connections between the field devices, PLC control cabinets and PLC I/O points. For any field device that is connected to a PLC control cabinet, both the solid black line and the dashed pink line should be found between them. If the solid black is missing, there could be an omission problem happened to the ICSS drawings. Similarly, if a dashed pink line is missing, there could be an omission problem happened to the I/O list. Using this method, engineers could also discover latent problems produced by "wrong connections"; for example where black and pink lines starting from an identical field device are connected to different destinations.

To verify these problems, engineers must check several relevant drawings to acquire accurate and reliable information. Once these problems have been clarified and fixed, engineers initiated the comparison between the C&E drawings and the I/O lists to acquire and verify the information of system functionality. Time-consuming comparisons between the C&E drawings and the I/O list revealed an abundance of ambiguous and misleading information stemming from problems such as "mistake labeling," "omission," "conflicting information," "inconsistent labeling," "wrong design." Yet these issues needed to be clarified and corrected before the design of the new system can be initiated. To address problems encountered, a considerable number of RFIs were raised between the system engineers and Energy A's project team (see Table II). All the corrected information obtained after the RFIs was inputted into the DAD model to form a system with integrity. The new safety control system (based on TT PLC units) was then designed using the corrected information from the old design. The new safety control system was designed to be fully compatible with the old BBB process control system. A model of the new safety control system was built in DAD which is independent from the old model. All old control cabinets were replaced by new control cabinets and a set of marshalling panels were installed to simplify inter-connections between junction boxes and control cabinets. Programs for the TT PLC system were coded and installed in accordance with system functional and technical specifications. The TT PLC system was then assembled into the control cabinets and delivered to the shipyard for installation. However, during the installation phase, new problems emerged and further RFIs were raised.

Information stored in a DAD database is dynamically linked to enable design changes to be updated automatically. Design engineers and/or draftsmen no longer need to check through the cross-coupled documents and fix problems once identified. DAD also eliminates errors such as "inconsistent labeling" and "conflicting information" as each physical device in the real world only has one corresponding device in the database.

DAD affords greater flexibility to users to attach supplementary documents and information to the design model (e.g. pictures, pdf drawings and notes). All the changes made to the model are recorded for future reference to enable a robust process of transparency and accountability. For the project studied in this research, all queries and responses between the E&I contractor and Energy A's project team were recorded in the DAD model as the corresponding changes and upgrades were made. Chronological changes made to the devices or connectors were recorded in their "history spreadsheets" together with details of the persons who performed those actions. This approach is far more flexible, yet paradoxically robust than the traditional CAD alternative where revisions of drawings have to be redrawn, reproduced and reissued with the annotation "Rev1," "Rev2" and so on. Identifying on the changes on "Rev2" is cumbersome unless directly compared against "Rev1" which may no longer be available or lost; in either scenario, the process is time consuming and costly. Therefore, using DAD enables far greater process transparency for engineers who can readily review and trace design changes made.

Projects designed using DAD are more efficient than using those traditional CAD-based methods, which are over reliant upon paper-based documentation (Love *et al.*, 2013). Errors, omissions and redundancies buried in the CAD generated documents significantly reduced the productivity of re-engineering the safety control system. In addressing errors and omissions, RFIs invariably need to be raised, which increases project cost and creates unscheduled delays. The inherent capability of DAD and its benefits over CAD will reduce errors, omissions and information redundancy (within E&I engineering and documentation) dramatically. Thus, the adage of time, cost and quality operate in a congruent manner, which results in significant savings being achieved (refer to Figure 9). Fundamentally, to enable productivity improvements a paradigm shift is required from a CAD-based system that focusses on 1:*n* to a DAD, which takes a 1:1 view of engineering design and documentation.

Conclusion

Errors, omissions and information redundancy are innate features of E&I engineering projects. One could argue that phenomenon is attributable to the engineers (and draftsmen's) vernacular skill, competence and knowledge. While this human factor cannot be ignored, CAD has severe limitations as it operates within a 1:*n* paradigm and provides an environment for errors or omissions to be propagated. Consequently, the example of re-engineering a safety control system using "As-Built" drawings that contained errors and omissions, contributed to a significant number of RFIs being raised. Raising an RFI is a non-value adding and costly activity for both contractor and client. An alternative method is to produce the same engineering documentation using SIM object orientated model where a 1:1 relationship was created between the model and real objects. By constructing a 1:1 model, information redundancy was eliminated and the

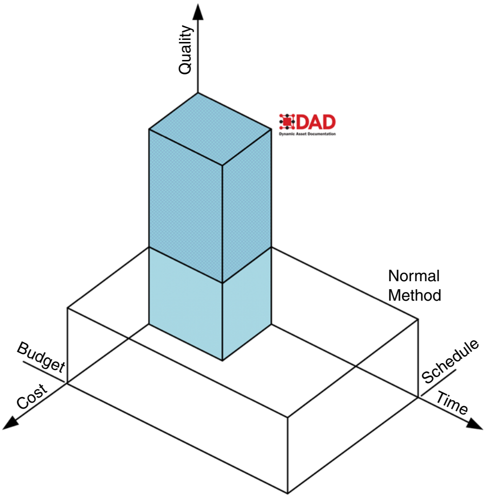

Figure 9.
Attained improvements from a SIM

propensity for errors and omissions to be made by engineers reduced significantly. Using a SIM to re-engineer and document the new safety control system resulted in significant productivity benefits being achieved. Therefore a paradigm shift from a 1:*n* to 1:1 perspective is required for engineering instrumentation and electrical systems so as to ameliorate the quality of documentation produced and productivity. Future research is now required to examine how processes and procedures can be re-designed to accommodate the use of a SIM. A SIM is considered to be a key an enabler for improving productivity, however, emphasis needs to be placed on determining how processes can be re-designed within context of E&I systems, to facilitate performance improvement throughout an offshore engineering projects life-cycle. The changes that are enabled will not only improve productivity and performance but the integrity of asset over its life.

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