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Object-oriented model for life cycle management of electrical instrumentation control projects

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ABSTRACT

Electrical instrumentation and control (EIC) systems can account for as much as 60% of maintainable items as well as being critical to safe and efficient operations. Thus, it is imperative that as-built documentation is error-free and reflects precisely what has been installed. Yet EIC as-built drawings that are produced often contain errors and omissions. If EIC systems are ineffectively and inefficiently designed and documented, then asset owners' plant, equipment and facilities may fail to operate, which can result in considerable economic loss and jeopardize system safety. In order to improve the quality, efficiency and effectiveness of documentation production, it has been suggested that engineers should switch from using computer-aided design (CAD) to an object-oriented model, which takes the form of a systems information model. Such a model provides the ability for electrical engineers to effectively integrate their work with a building information model. This paper builds upon the authors' previous research, which examined the need for a SIM by presenting and describing how an object-oriented model for EIC can be used through a project's life cycle. Examples are used to demonstrate the functionality and robustness of the SIM. The adoption of a SIM will not only lead to productivity throughout a project's life but also reduce the costs associated with managing and maintaining information.

1. Introduction

A building information model typically comprises of an array of software applications, which are integrated to form a single point of truth (i.e., structuring the model and associated schemata so that every data element is stored exactly once) [1]. Increasing emphasis has been placed on the development and integration of software packages for architectural, structural, heating ventilation, air conditioning (HVAC) and hydraulics. Such elements have scale, geometry and therefore can be visualized within the BIM. However, electrical instrumentation and control systems have no scale and geometry and cannot be adequately visualized in a three-dimensional (3D) view, although cable trays and components can be modeled. As a result, there is a reliance on the use of computer-aided design (CAD) to detail the connections and relationships between components. While BIM is beginning to be widely adopted by engineers within the construction industry, within the energy and resources sector CAD remains the primary tool to draft and design EIC systems [2,3]. Noteworthy, there has been limited research undertaken with regard to BIM software and its use within the field of electrical engineering [4,5]. Research has revealed that the adoption of building information modeling (BIM) related software by electrical engineering contractors has been increasing as a result of the need to address productivity and the increasing complexity of electrical systems [4].

Energy and resource projects are typically delivered using engineering procurement construction (EPC) or management (EPCM) arrangements. In Western Australia, for example, most projects are being procured using an EPCM arrangement. Under the auspices of EPCM deliver method, the contractor needs to coordinate all design, procurement and construction work and ensure the project is delivered on time. The EPCM contract is typically based on a ‘cost plus’ (or ‘cost reimbursable’) arrangement and the client (or operator) pays subcontractors directly for materials, equipment and on-site works. The EPCM contractor is paid their actual direct costs for performing engineering and supervisor services, plus an agreed margin. The contract documentation produced by the EPCM contractor often contains errors and omissions [1], and as a result all relevant drawings that have been produced in CAD need to be rectified due to the 1:*n* relationship that exists between real-world objects and their counterparts on drawings when drafted in CAD (i.e., they can be referenced on a number of drawings) [2]. The rectification process can be a very labor intensive and time consuming process, yet the EPCM contractor is paid their actual costs so there is no immediate incentive to adopt a more robust and efficient way to draft and document EIC systems.

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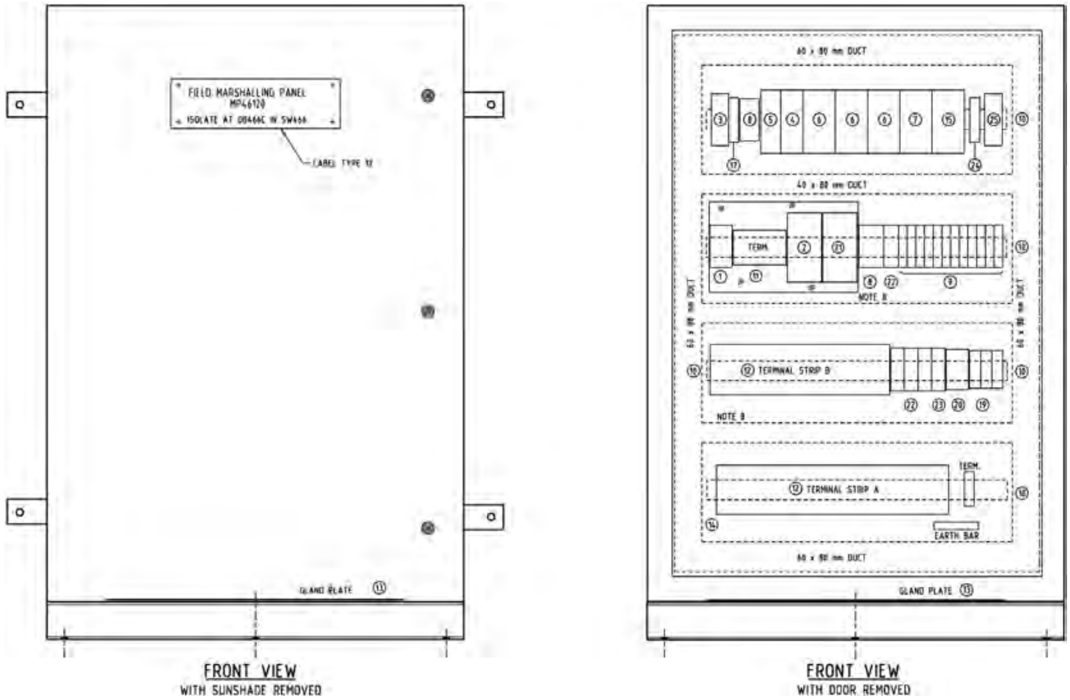


Fig. 1. Layout diagram.

In the resources industry for example, EIC systems represent 29% of the world's capital expenditure on plant [5]. In plant operations, EIC typically accounts for 60% of maintainable items as well as being critical to safe and efficient operations [5]. Recognizing the importance of having accurate, reliable and complete design documentation to enable efficient and effective maintenance, companies such as the Fortescue Metal Group, the world's fourth largest Iron Ore producer, have begun to recognize the need to switch away from CAD for drafting EIC systems and use a systems information model (SIM). A SIM was implemented on their multi-billion dollar Solomon Iron Ore Project in the Western Australian Pilbara[1] and as a result reduced rework and commissioning delays. In the authors' previous research in resources and energy sectors [1], it was revealed that as-built documentation for EIC systems often contains errors and omissions. If EIC systems are ineffectively and inefficiently designed and documented, then asset owners' plant, equipment and facilities may fail to operate, which can result in considerable economic loss and jeopardize safety. Thus, it is imperative that as-built documentation is error-free and reflects precisely what has been installed [2]. This paper extends the empirical research presented in Love et al. [1] and further examines the need and nature of a SIM, specifically in the context of EIC systems in resource projects.

1.1. Electrical instrumentation and control systems

The design of EIC systems presents a mathematically indeterminate problem. There is no single optimum design but 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 were 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 reasonability of the design, this issue has been resolved. Other advantages offered by CAD in electrical engineering are as follows:

- 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).

The design of an EIC system is typically produced in CAD and presented in a 2D format (Figs. 1 to 4). The drawings produced can be classified as follows [2]: layout, block, schematic and termination. A layout diagram describes the general arrangement of the equipment that forms the basis of an electrical control system (Fig. 1). A block diagram

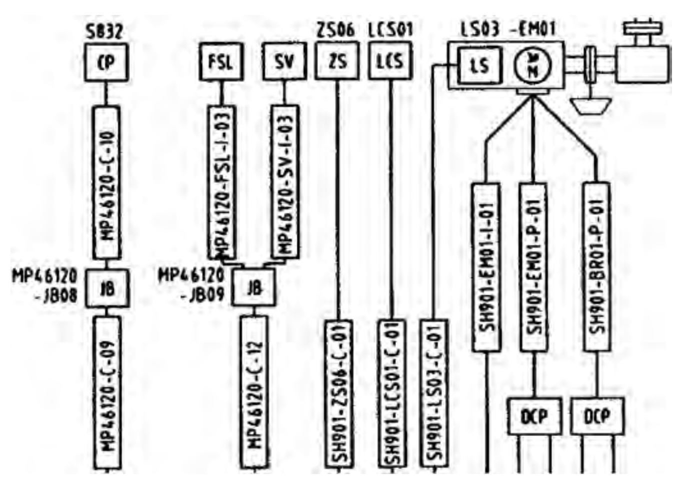


Fig. 2. Block diagram.

1 http://www.dad.net.au/v10.0/Files/DAD%20Testimonial%20PFM.pdf.

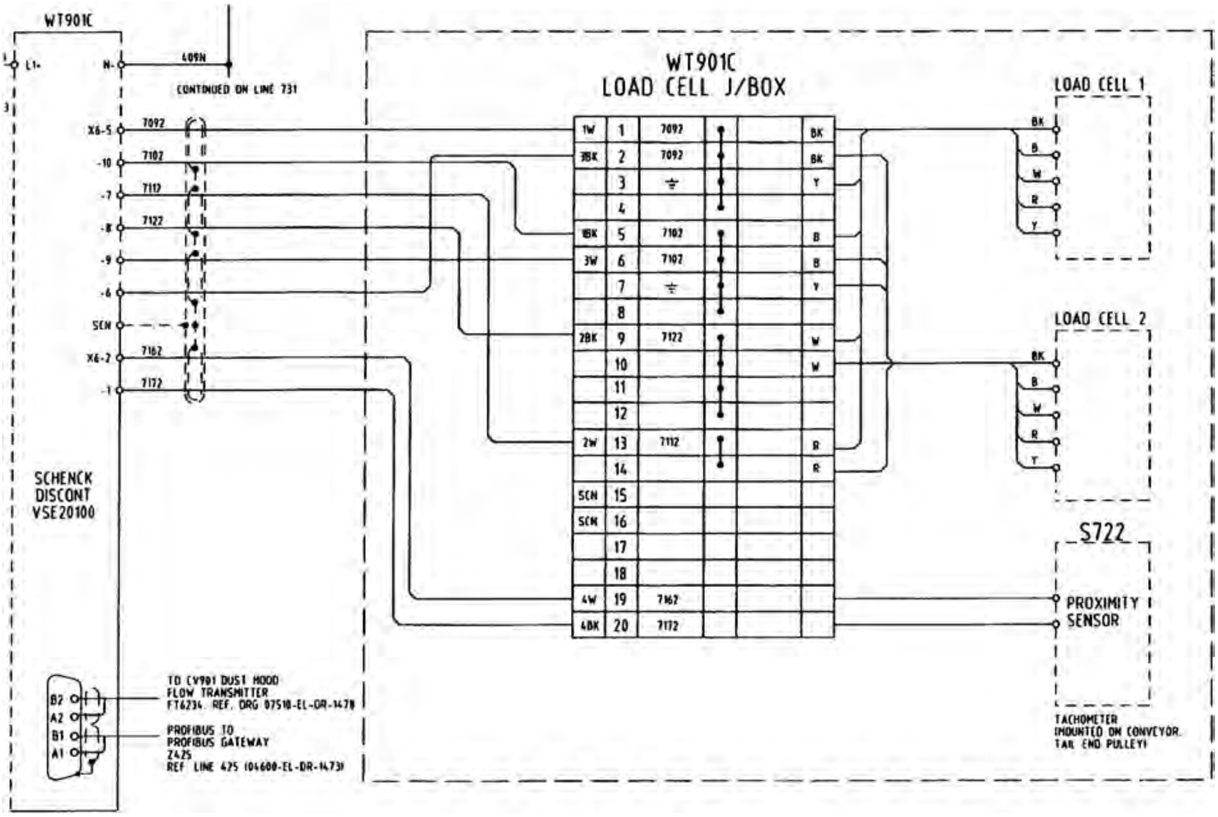


Fig. 3. Schematic diagram.

is composed of blocks and lines denoting the relationship between them (Fig. 2). It describes the system structure from a higher order level and aims to illustrate its general function rather than focusing on its specific details. A schematic drawing describes the design and function of the equipment using simplified symbols and shapes (Fig. 3). A termination drawing is used to illustrate the terminal connections for equipment (Fig. 4). In addition to these drawings, cable schedules are used to document the interconnected wiring between various devices. A typical example of cable schedule for a stacker conveyor is shown in

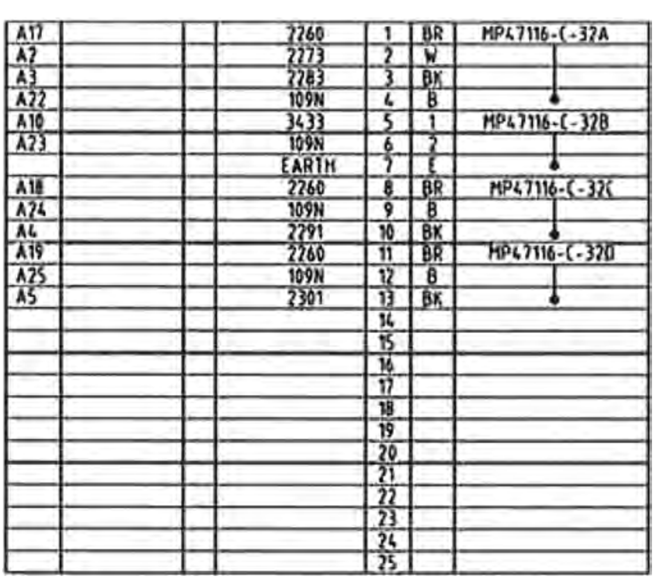


Fig. 4. Termination diagram.

Table 1. As cable schedules document the connection relationships between devices, site engineers, who are responsible for connecting wiring between devices, tend to rely on them to complete the job rather than tracing the connections between drawings to acquire the information.

To create a set of drawings, intensive communication needs to take place between design engineers and the draftsmen. However, the quality of engineering documentation (e.g., drawings, cable schedule) produced by engineers and draftsmen for a project may be influenced by the schedule and fees to be paid [6–8]. For example, when an organization is subjected to schedule and/or fee pressure tasks such as design checks, reviews and verifications of the drawings are often omitted, which result in errors not being identified [9]. Thus, the errors enter a period of incubation and manifest on-site requiring possible rework, if identified.

Figs. 1 to 4 illustrate the complexity of EIC drawings on which an array of devices and wires can be represented in differing formats. It is noteworthy that a single piece of equipment may appear several times on a number of drawings. If a change is required, then all drawings that refer to the piece of equipment have to be manually altered when CAD is used as the medium to display information.

Table 2 identifies the extent of redundant information identified in the study conducted by Love et al. [1] for a stacker conveyor system that was used to transport iron ore. A total of 77 drawings were created to document the stacker conveyor's control system, which contained 1545 cables and 1518 components. Love et al. [1] revealed that a considerable amount of information redundancies were buried in the 77 drawings. For example, 2682 cables and components appeared once on 77 documents, 340 cables and components appeared twice and 23 cables and components appeared three times (Table 2). Surprisingly, two components were found to appear seven and nine times on documents. Draftsmen are required to describe the repetitive devices and cables using uniform symbols and labels to avoid misleading. Moreover, a

Table 1
Cable schedule for a stacker conveyor.

Connector name	From	To	Connector type
CV911-EM01-C-01	VS4607	CV911-EM01\RTD Terminal	12 Triad PVC/PVC
CV911-EM01-P-01-1	VS4607	CV911-EM01\CV911-EM01	3C + 3E VSD XLPE/PVC
CV911-EM01-P-01-2	VS4607	CV911-EM01	3C + 3E VSD XLPE/PVC
CV911-EM01-P-01-3	VS4607	CV911-EM01	3C + 3E VSD XLPE/PVC
CV911-EM01-P-01-4	VS4607	CV911-EM01	3C + 3E VSD XLPE/PVC
CV911-EM01-P-02	VS4607	CV911-EM01-HTR	2C + E PVC/PVC
EM01-RTD-B1	CV911-EM01\RTD - B1	CV911-EM01\RTD Terminal	RTD Simple
EM01-RTD-B2	CV911-EM01\RTD - B2	CV911-EM01\RTD Terminal	RTD Simple
EM01-RTD-R1	CV911-EM01\RTD - R1	CV911-EM01\RTD Terminal	RTD Simple
EM01-RTD-R2	CV911-EM01\RTD - R2	CV911-EM01\RTD Terminal	RTD Simple
EM01-RTD-W1	CV911-EM01\RTD - W1	CV911-EM01\RTD Terminal	RTD Simple
EM01-RTD-W2	CV911-EM01\RTD - W2	CV911-EM01\RTD Terminal	RTD Simple
MP46511-C-24	CV911-EM01\EM01-LCS	MP46511	8C + E PVC/PVC
MP46511-C-26-C	Gearbox\RTD Bearing	MP46511	1PR + SCN

considerable amount of errors and omissions have been found among the drawings. It has been found that 244 cables (15.79% of all the cables) and 182 components (11.99% of all the components) were identified with errors and omissions, which were distributed between 56 (72.73%) of the 77 documents. If a mistake is identified on a drawing, then engineers are required to go through other relevant drawings to confirm the existence of the problem and determine the correct answer. All the drawings involved need to be modified/redrawn, reproduced and reissued; this can be a very time consuming and costly process and adversely impact the productivity of a contractor.

As information between drawings is not dynamically interconnected and there is a propensity for a draftsman or engineer to make an error [1], particularly when reference numbers are used to trace connections between equipment and drawings. For example, Fig. 5 illustrates a block diagram of an iron ore conveyor system on which a total of 29 reference drawing numbers are identified. Two of them were mistakenly labeled which are marked with clouds. It has been identified that the referred devices cannot be located in the corresponding reference drawings. As connections between drawings rely heavily on reference drawing numbers, mistakes in referencing can lead to a reduction in information traceability.

1.2. System information model

System information modeling is a generic term used to describe the process of modeling complex systems using appropriate software, which is akin to the development of a building information model. A SIM is a digital representation of the connected system, such as electrical control, power and communication systems. When SIM is applied to design a connected system, all physical equipment and the associated connections to be constructed can be modeled in a database. Each object is modeled once. Thus, a 1:1 relationship is achieved between the SIM and the real world. As a consequence, information redundancy contained within the documents is eliminated [1,2]. A SIM can be created using software such as dynamic asset documentation (DAD) and applied throughout a project's life cycle. Fig. 6 denotes the workflow for design, construction and maintenance using a SIM.

Table 2
Information redundancy contained in the drawings.

	Number of times appearing on drawings								
	1	2	3	4	5	6	7	8	9
Number of cables	1348	196	1	0	0	0	0	0	0
Number of components	1334	144	22	12	4	0	1	0	1
Total	2682	340	23	12	4	0	1	0	1

Source: Love et al. [1].

1.2.1. Design and engineering

Engineering design and documentation can be undertaken simultaneously when using a SIM. Each physical piece of equipment to be constructed in the real world is modeled in the SIM as design progresses and is assigned a unique tag name. Each piece of equipment is created with 'type' and 'location' attributes. The 'type' attribute is used to define equipment functionalities. The 'location' attribute is used to describe the physical position of equipment within a plant. With such a classification, engineers are able to browse the SIM model and locate the information that they require. Cables and signal flows between each piece of equipment are modeled as 'connectors'. Shape, width and color can be chosen for each individual connector to cater different scenarios. To facilitate the design, attributes, such as a device module, cable size and specifications can be assigned to each individual object.

Software such as DAD can be used on a PC (personal computer) or mobile devices. The PC version is compatible with the Windows operating system. Its mobile version can be installed on industrial tablets to enable its use in the field. Through DAD, a SIM model can be accessed either locally or remotely. More specifically, the model database can be stored on a local workstation or a remote server, which can be accessed online. When CAD is used in this situation, the design can only be accessed and operated by a single user at any point in time. In the case of DAD, for example, it enables multi users to cooperate concurrently on a same database. Both local and remote users can undertake reviews and modifications to a SIM simultaneously.

Within DAD, a complete history log is provided to monitor and record the activities that have been performed within the model (Fig. 7). Any modification to a particular object, including the person who performed this activity, is automatically recorded in the system for future checking and verification. As a result, this function can be used to trace the revision history and assist engineers in the comparison of previous and current design versions. For example, it can be seen in Fig. 7 that a user created a component 'FP46511' on 26/09/2012. Then they defined its 'location' and 'type' attributes. Two cables 'RFC46511-F-01' and 'RFC46511-F-02' are connected. However, in a drawing based design, revisions have to be maintained manually. All the revised versions of a drawing and its original copy need to be categorized and archived in order to enable the design to be traceable.

As the information modeled is dynamically linked, errors and omissions, which are prevalent among paper drawings, can be reduced significantly. In a previous study the authors quantified the impact of errors and omissions contained within 107 CAD documents (106 drawings and 1 cable schedule) of the electrical control system for an iron ore conveyor [1]. A detailed investigation of the documents revealed a significant amount errors and omissions were prevalent in the as-built drawings (Table 3), which were classified as incorrect labeling, inconsistent labeling, incorrect connection, omissions from drawing, omission from cable schedule, missing label and wrong design. The errors and

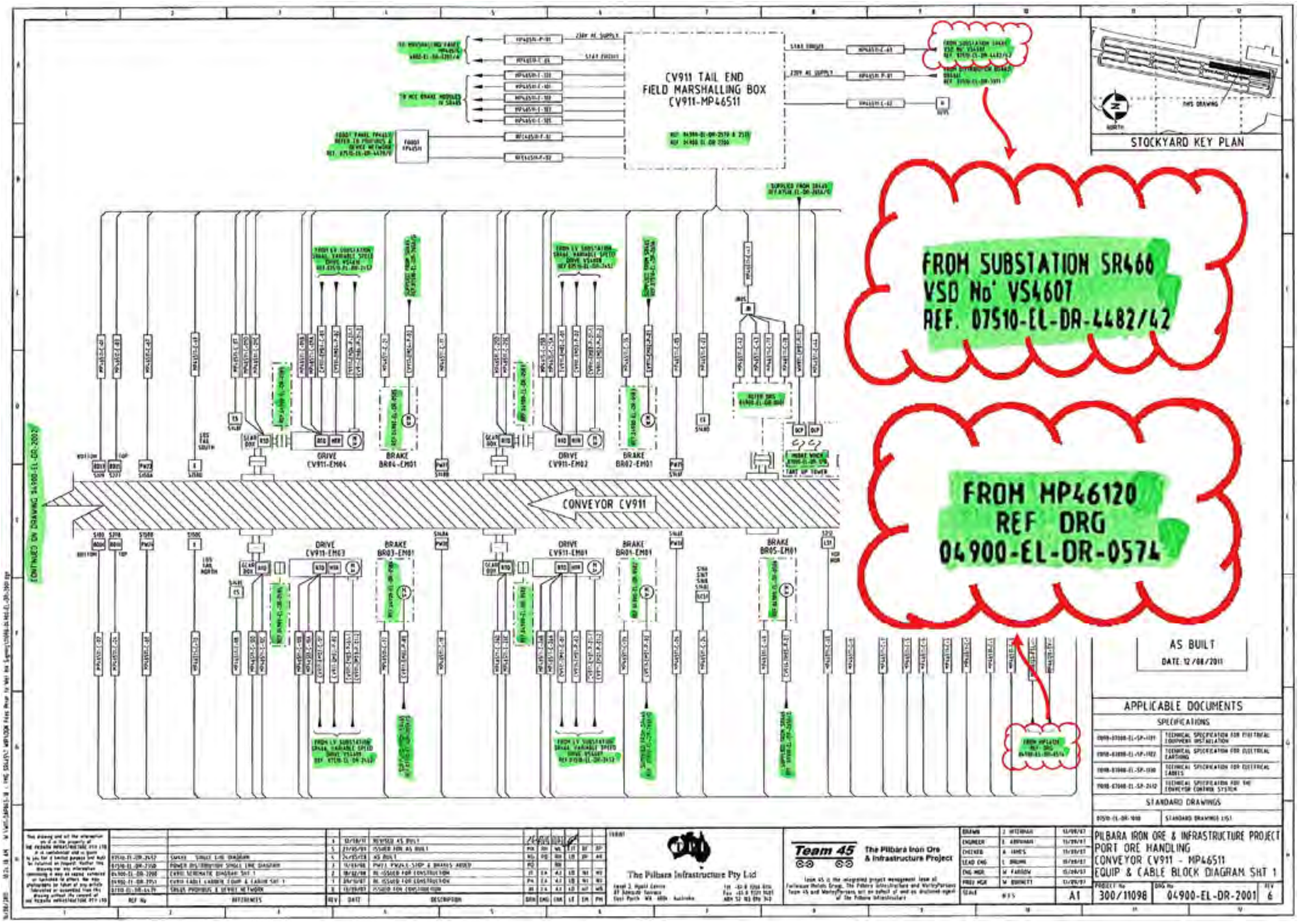


Fig. 5. Reference information among drawing. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

omissions shown in Table 3 hindered engineers' ability to interpreted the design and consequently had an adverse impact on productivity. In addressing this issue, we demonstrated that the use of a SIM, specifically DAD, eliminates the need to use CAD to produce EIC drawings [1,2].

In contrast to the CAD, where the information link between drawings relies solely on reference numbers, in a SIM connections between components are expressed digitally and dynamically. As each connector is uniquely numbered, errors such as incorrect/inconsistent reference numbers identified from drawings are avoided. System design can be interpreted easily by following the connectors among components. Information traceability can be improved significantly.

When design is complete, a read only copy of the model is created, exported and made available as a 'Kernel' to other project team members (Fig. 8). A DAD portal, which is designed based on the Kernel, is the client software that can be used to access the information stored in the SIM Kernel. The users of the portals can import and access all or part of the design information within the Kernel regarding to their respective authorization levels. Private user data can be established and managed via the portal such as editing attributes for the components or attaching additional documents to the model. To guarantee that all the parties involved in the project are working on an identical Kernel, users do not have the authorization to change the design.

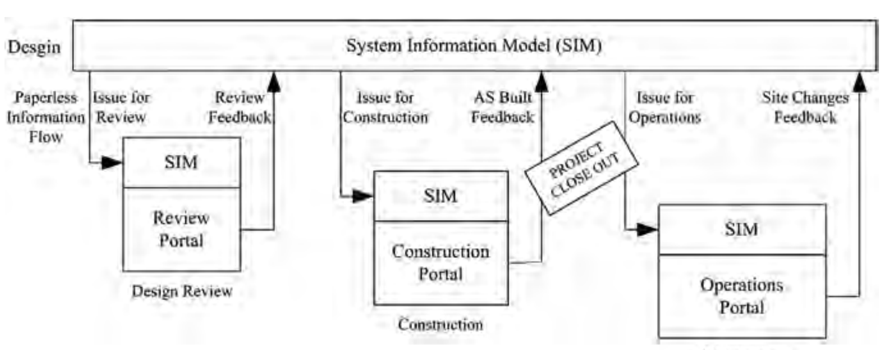
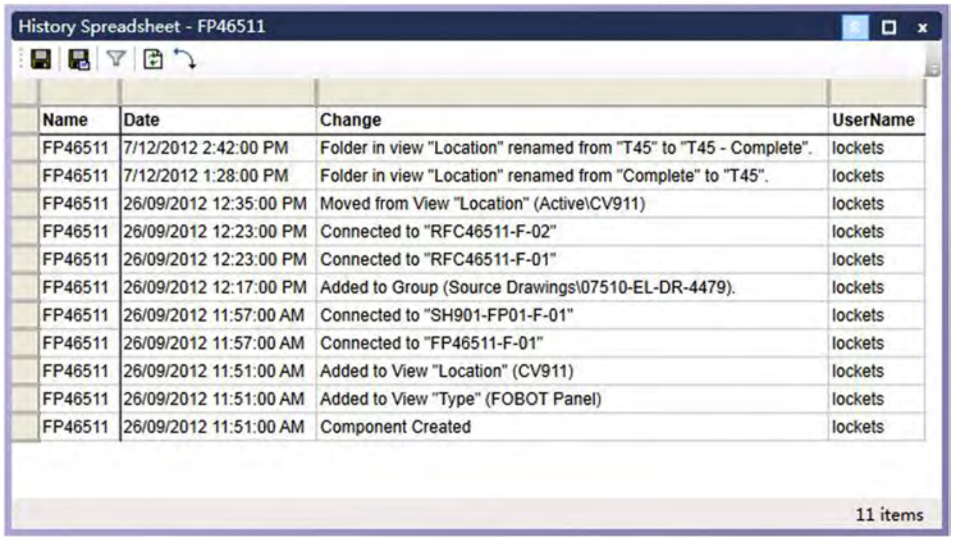


Fig. 6. SIM workflow.


History Spreadsheet - FP46511

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

11 items

Fig. 7. History spreadsheet. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

The Kernel containing the design can be issued to a number of parties for review. Parties having access to the design are able to review and provide comments. Thus, information delivery can be achieved digitally and instantly. No paper work is required. Feedback such as comments and approvals can be recorded in the SIM systematically which will be sent back to the design team. By adopting DAD, information flows between designers and reviews can be entirely paperless, making it far more efficient than the designs conveyed by paper drawings. In a paper drawing based project, design review requires the handling of individual drawings. The reviewers must work on fragments of information scattered among the drawings to interpret the design. It is a paper shuffling exercise, slow, expensive and prone to error.

1.2.2. Procurement and construction

When the design is approved for construction, a SIM, a digital realization of the design, can be issued to different parties such as procurement team and construction contractors. With the application of DAD, the design is encapsulated into a SIM. Information management can be achieved digitally and the role of paper drawings is eliminated.

In a CAD-based environment, conducting a take-off and estimating the cost of equipment can be a time consuming process as information can be distributed over a wide range of drawings. As a result of this distribution of information, there is a propensity for a person who is charged with undertaking the take-off to commit an error or omit an item [10], which can have adverse impact on procurement and consequently a project's schedule and cost.

All the components modeled in the SIM are categorized according to their 'type' and 'location' classes. This enables users to browse the database and acquire the information that they need. For example, in determining the technical specification and quantity of circuit breakers for the control system of a conveyor, an engineer could locate them using the 'circuit Breaker' type and filter out those that do not belong to it using a built-in 'filter' function. A 'quick spreadsheet' function can be used to display the results on a spreadsheet. Technical specifications such as model, number of poles, interrupting capacity and tripping current, can also be automatically displayed. The price of each individual circuit breaker is made available to users through the cost attribute assigned to each component. The total quantities for equipment and the cost can be calculated automatically (Fig. 9). A list containing the detailed information of equipment to be procured can be readily generated either in 'pdf' or 'excel' format. The procurement status of individual pieces of equipment is recorded and managed within the model.

A dedicated construction portal is provided for construction. All the information required to perform construction-related tasks is stored in the SIM. Works such as panel assembly, cable connection and programmable logic control (PLC) coding can be undertaken by extracting information directly from the SIM. Traditional paper drawings are no longer needed. Due to the 1:1 mapping between SIM and its real-world counterpart, information stored in the SIM can be extracted more efficiently and as a result the time typically spent looking through masses of drawings is significantly reduced. Problems can be readily identified and revisions can be readily undertaken as a result of the 1:1 mapping that is built into the system. For example, if a site engineer identifies a potential connection error associated to a switchboard (SWB) 562, they could verify the problem by examining its connections within the SIM (Fig. 10). In this instance, there is no need for the site engineer to locate and compare the problem with cross-coupled reference drawings, which is often the case when CAD is used. Once a problem is verified, a dedicated 'request for information (RFI)' folder can be created, which contains the problem to be resolved. The site engineer can mark and describe the problem in the SIM, which is recorded by either a 'pdf' file or a screenshot of the selected area. A 'spreadsheet' can also be

Table 3
Classification of errors.

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

Source: Love et al. [1].

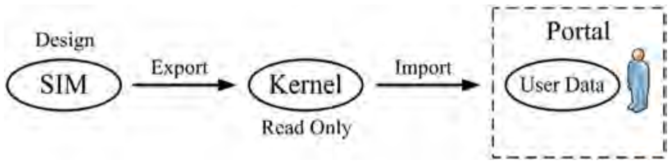


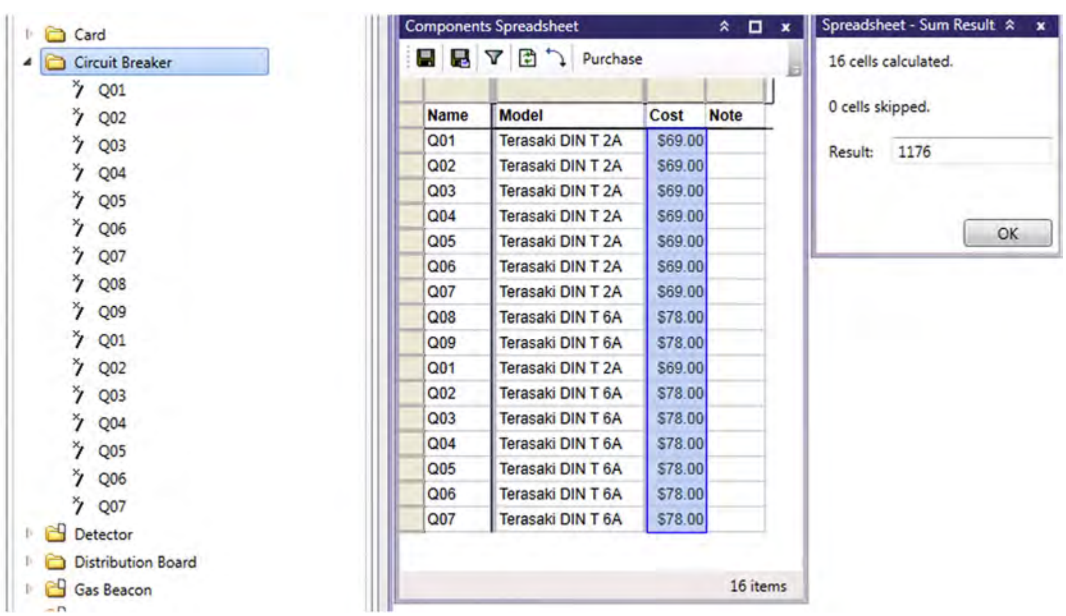
Fig. 8. Portal/SIM relationship. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

automatically generated containing all object information either in 'Excel' or 'pdf' file format. Then the RFI can be sent to the design team by e-mail. The site engineer is unable to continue their work without authorized information and has to wait until the correct information is provided before proceedings with their tasks. On receipt of the RFI folder, the design engineers can review and rectify the problem immediately.

If an error is confirmed, then the design can be readily modified as a design engineer can login into the SIM model, review and then correct the component that contains the error. As each piece of equipment in the real world has only one counterpart in the SIM, there is no need to correct the problem by revising each of those affected drawings. The authors' empirical observations indicate that an estimated ½ hour is needed to locate a problem and raise an RFI when using a SIM environment [1,2]. For an experienced engineer, the average time spent to review an RFI and revise the SIM model would be a little as ¼ of an hour. When a revision is complete, a new Kernel is generated and exported to the users for further application, as denoted in Fig. 11. With the client portal, users can replace the old Kernel with the new one. All their private data saved can be retrieved and reused.

Using the construction portal, project managers can monitor and control the progress of their project. Utilizing the data that has been updated within the database, the status of each individual object modeled in a SIM can be displayed dynamically. Managers can examine actual cost and schedule against what has been planned. The objects that have been estimated, purchased, delivered, installed, terminated, tested and commissioned are readily available for review. Fig. 12 illustrates a comparison of planned versus the actual schedule of equipment installations on a gas plant construction project. Planned schedule is denoted in grey and actual schedule in red. It can be seen that as a project progresses, the actual work lags. Special events such as technical queries, delays, safety issues, punch list and rework can also be planned and recorded. By providing detailed and updated information, the construction portal enables project managers to review the project progress and make informed decisions.

A difficulty facing many engineers is how to reduce material waste for items such as cable in EIC project because drawings describe connections rather than scales and dimensions. As a result, it is difficult for the engineers to determine the spatial sense of the design. Such problem is compounded in energy and resource projects, for example, iron ore and oil/gas, where the area of a single plant may cover tens of square kilometers. Miscalculation in distance may result in significant cable waste. For example, in the case of the iron ore transportation plant, reported in Love et al. [1], which covers an area of over 20 km^2 and the distances from the ship loader SL701 to the central control room and the substation are approximately 3 km and 4 km, respectively. A considerable amount of cable (e.g., communication and power) was required



Name	Model	Cost	Note
Q01	Terasaki DIN T 2A	$69.00	
Q02	Terasaki DIN T 2A	$69.00	
Q03	Terasaki DIN T 2A	$69.00	
Q04	Terasaki DIN T 2A	$69.00	
Q05	Terasaki DIN T 2A	$69.00	
Q06	Terasaki DIN T 2A	$69.00	
Q07	Terasaki DIN T 2A	$69.00	
Q08	Terasaki DIN T 6A	$78.00	
Q09	Terasaki DIN T 6A	$78.00	
Q01	Terasaki DIN T 2A	$69.00	
Q02	Terasaki DIN T 6A	$78.00	
Q03	Terasaki DIN T 6A	$78.00	
Q04	Terasaki DIN T 6A	$78.00	
Q05	Terasaki DIN T 6A	$78.00	
Q06	Terasaki DIN T 6A	$78.00	
Q07	Terasaki DIN T 6A	$78.00	

Fig. 9. Cost spreadsheet. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

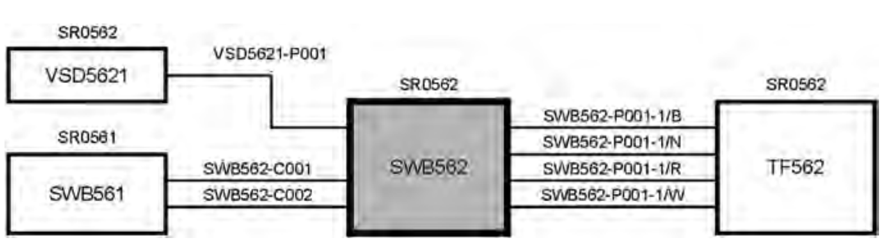


Fig. 10. Example of a connection.

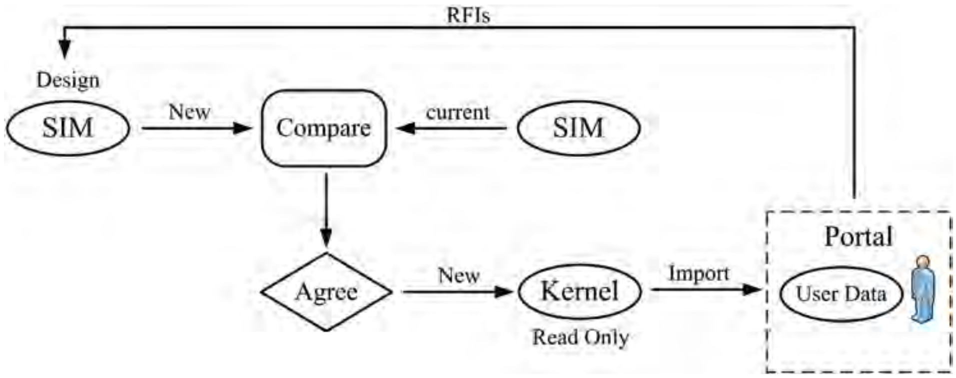


Fig. 11. Kernel revision process. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

between those locations. Such cables are expensive, particularly the power cables. If the cables are 'cut' incorrectly, then considerable waste may be experienced. To deal with such a problem, a spatial portal is embedded into the architecture of the SIM and components can be located at their physical positions using the coordinates predefined in the attributes. Third party software 'Google Map/Earth' is adopted to display the components for establishing a spatial view of the project (Fig. 13). This function can help engineers to measure the routes and distances between components so as to calculate more accurately the length of the cables to be installed.

1.2.3. Asset management

A SIM is specifically useful for asset managers as it enables information to be stored in a single digital model. In a CAD-based environment paper drawings are typically handed over to the asset owner in the form of as-built drawings, which reflect, in theory, the actual construction of every system, component and connection of an EIC project. If an asset manager wants to maintain, repair or upgrade any portion of the plant, then the as-built drawings need to be used. However, recovering information contained on an array of drawings is a tedious task. Any error or omission contained within the drawings will potentially hinder the interpretation of the design. In some instances, as demonstrated in the authors' previous research [1,2], the as-built drawings do not reflect the design that has been finally erected. Therefore, retrieving information is rather difficult and in some instance reengineering may be necessary [2]. Contrastingly, if engineering is undertaken using a SIM it can be stored in a digital format whereby a 1:1 mapping is undertaken. An operation portal is provided to cater for the needs of asset managers. Operations such as test, calibration, inspection, repair, minor change and isolation can be defined and scheduled. In addition, it can act as a

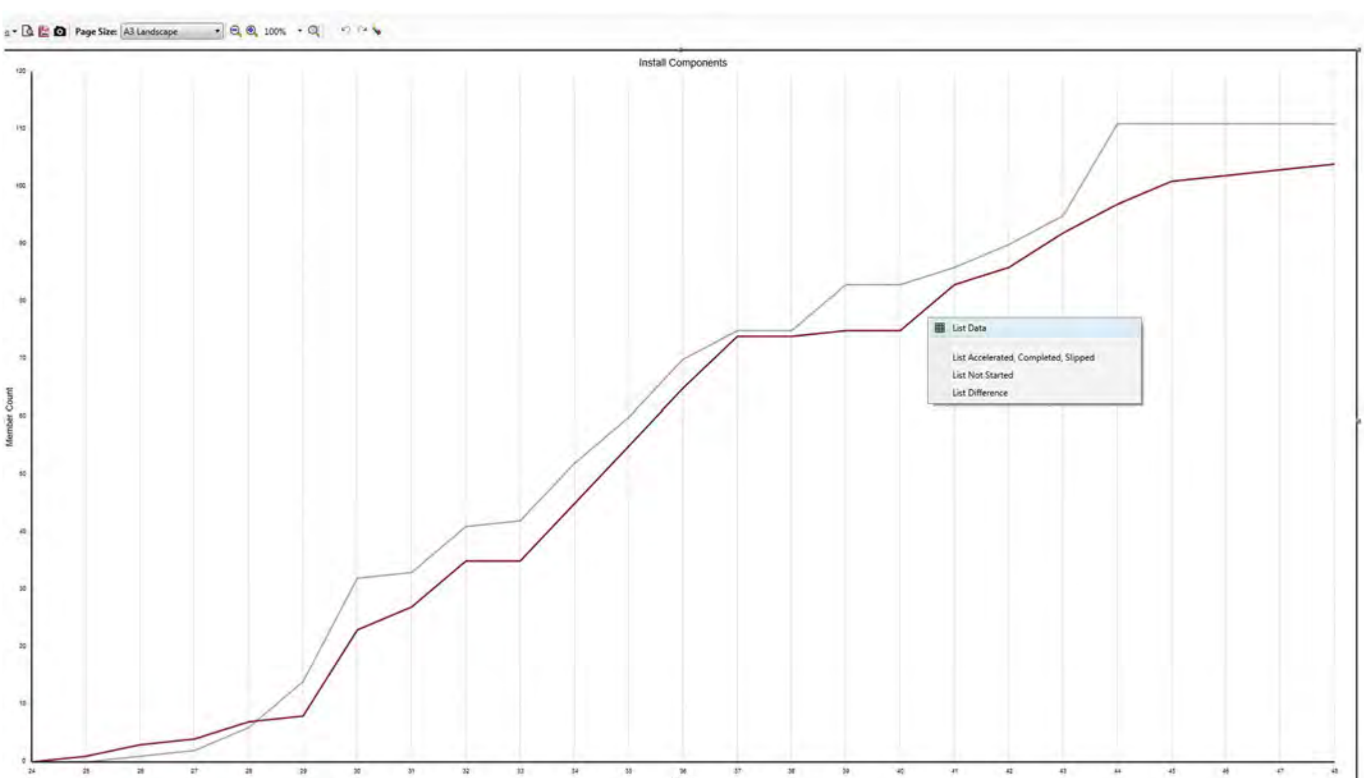


Fig. 12. Comparison between 'planned' and 'actual' schedule. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

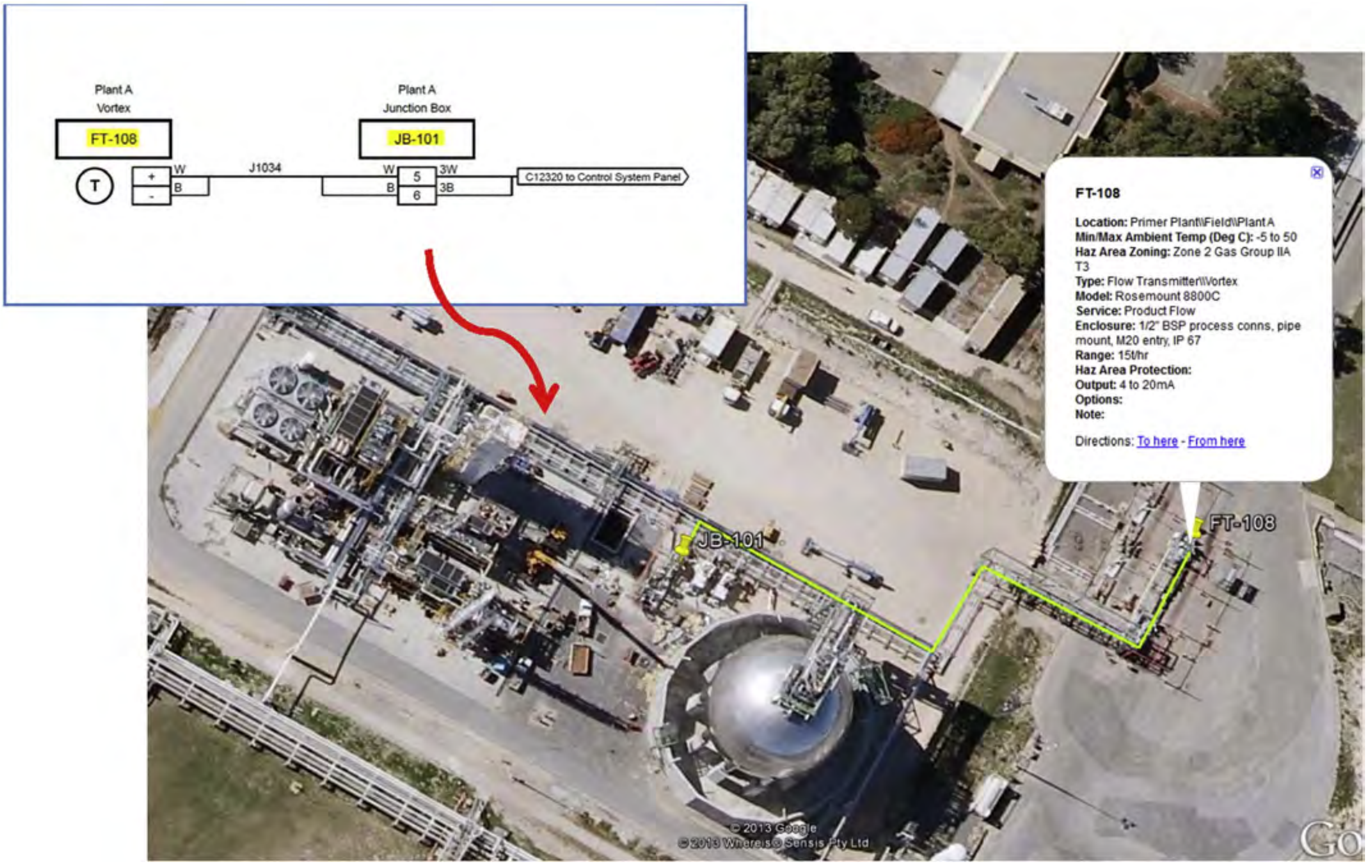


Fig. 13. Locating components with Google Map/Earth. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

training tool, which can be used regularly to assist operators to become familiar with the design.

Being an object-oriented model, the SIM is interoperable and can be integrated with other advanced engineering techniques such as augmented reality. Fig. 14 illustrates the application of DAD and augmented reality through an industrial Tablet. Fig. 15 demonstrates the application of DAD into the construction of a power plant that is presented in a 3D model. The electrical components and cables to be constructed are modeled into a SIM, which is linked to the 3D model of the plant. Interfacing between the SIM and the 3D model enables the communication between objects in the SIM and their counterparts in the 3D model. For example, in Fig. 15, a junction box JB-701 (highlighted in yellow) selected within the 3D model can be easily linked to its counterpart in the SIM. Then the detailed information for those cables connected to it can readily be viewed.

Fig. 14. Industrial tablet. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

1.3. Limitations

The productivity benefits of using a SIM enabled by DAD have been demonstrated in the author's previous research [1]; however, the system possesses a number of limitations, although they are currently being addressed. For example, within DAD, connections between different components are illustrated using non-directional lines, which are not sufficient to describe mono-directional flows. In order to create a more intuitive and robust system, arrows should be shown on the lines where flows are only permitted to travel in a single direction. Interfacing between DAD and other BIM applications via Construction Information Exchange (COBie) and Industry Foundation Class (IFC) exchanges is also being developed.

In addition to the technical limitations that focus on interoperability and the development of IFC, changing the mind-set of electrical engineers and contractors to switch away from using CAD to an OO model will be a major challenge. Demonstrating productivity improvements that can be acquired will be an ongoing issue and therefore continuous education about the benefits of BIM enabled software such as DAD and Revit MEP need to be undertaken. In order for electrical contractors to harness the benefits of operating in a BIM environment within the resources sector, collaborative work structures and practices need to be established within a project. This requires a shift away from the use of EPCM and EPC methods to relationship-based procurement (RBP). However, EPCM and EPC methods have typically formed the cornerstone of clients in the resources sector for decades, and the switch to RBP is perhaps too significant, at least in the short-term.

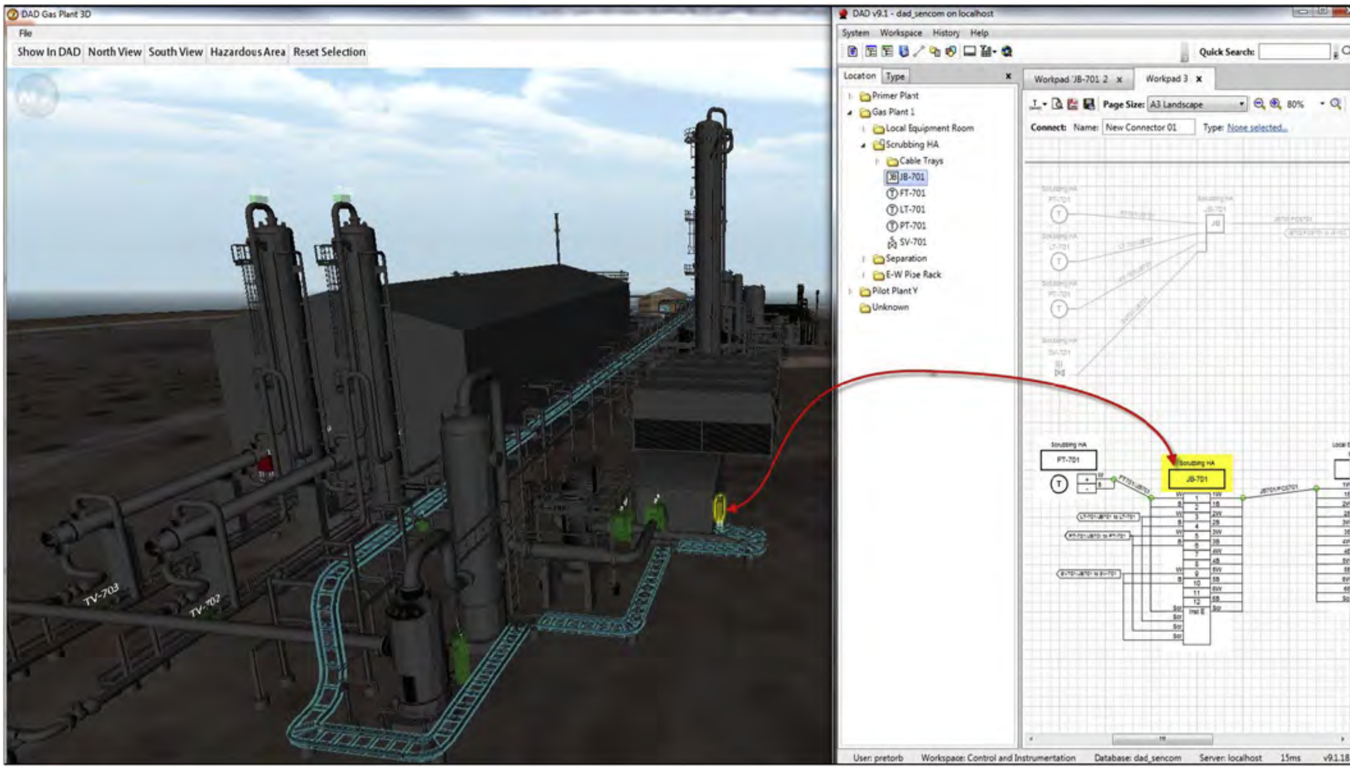


Fig. 15. Application in power plant construction. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

2. Conclusion

There has been very limited empirical research that has demonstrated that object-oriented models can provide significant productivity improvements within the fields of engineering design and construction. The difficulties in measuring productivity are often the cause of uncertainty about expected benefits, particularly in the case of innovation driven change through software applications that enable BIM to take place. As a result, this has tended to be a factor that has led to the low adoption of BIM within the EIC industry and an over-reliance on the use of CAD.

Evidence of the key issues facing EIC projects such as incomplete and erroneous as-built documentation presented in Love et al. [1] has demonstrated that an alternative to CAD-based systems is needed to address this prevailing problem. This paper has extended the research previously presented and described, using examples, about how an OO model such as a SIM can be used to efficiently and effectively manage information throughout an EIC projects life cycle. The use of a 1:1 rather than a 1:n relationship within the model provides the underlying foundation for acquiring productivity gains through an EIC project's life cycle, particularly during the asset's operations and maintenance.

While the potential benefits for asset management enabled by BIM have been widely espoused, there are few examples in existence with measurable realization of benefits. For such systems to be adopted they need, at a minimum, to be able to integrate with existing legacy systems, which emphasize the importance of interoperability with initiatives such as IFC. A SIM is considered to be a key enabler for improving productivity; however, future emphasis needs to be placed on determining how processes can be re-designed within context of ECI systems, to facilitate performance improvement throughout a project's 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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References

[1] P.E.D. Love, J. Zhou, C.-P. Sing, J.T. Kim, Documentation errors in instrumentation and electrical engineering systems: toward productivity improvement using systems information modeling, Autom. Constr. 35 (2013) 448–459.
[2] P.E.D. Love, J. Zhou, C.-P. Sing, J.T. Kim, Assessing the impact of requests for information in electrical and instrumentation engineering contracts, J. Eng. Des. (2013), http://dx.doi.org/10.1080/09544828.2014.935305.
[3] A.S. Hanna, F. Boodai, M. El Asmar, State of practice of building information modelling in mechanical and electrical construction industries, ASCE J. Constr. Eng. Manag. 139 (10) (2013), http://dx.doi.org/10.1601/(ASCE)CO.1943-7862.0000747.
[4] A. Hanna, M. Yeutter, D. Aoun, State of practice building information modelling in the electrical construction industry, ASCE J. Constr. Eng. Manag. (2014), http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000893.
[5] Aveva, Aveva World Magazine, Issue 2, AVEVA Group plc, UK, 2012.
[6] P.A. Tilley, S. Mohamed, A. Wyatt, Indicators of design and documentation efficiency, in: S.N. Tucker (Ed.), Proceedings of the 5th Annual of International Group for Lean Construction, 16th -17th July, Gold Coast, Australia, 1997.
[7] P.A. Tilley, S.L. McFallan, Design and documentation quality survey – designers and contractors perspectives, BCE Doc 00/115, CSIRO Division of Building, Construction and Engineering, Highett, Melbourne, Victoria, Australia, 2000.
[8] J.F. McGeorge, Design productivity: a quality problem, ASCE J. Manag. Eng. 4 (4) (1988) 350–362.
[9] E. Palaneeswaran, P.E.D. Love, J.T. Kim, Role of design audits in reducing errors and rework, ASCE J. Perform. Constr. Facil. 28 (2) (2014) 511–517.
[10] J. Badour, J. Badour, The Dubai Mall—case study, BIM Journal (2014) (Available at www.bimjournal.com. Accessed, 30th January, 2014).