Integrated Engineering Workflow focused on the Structural Engineering in the Industrial Environment

Johan Palm, HATCH Africa (Pty.) Ltd., South Africa (jpalm@hatch.co.za)

Summary

The engineering and construction industry has been slow to exploit the full potential of information technology. The industry is highly fragmented, price sensitive, risk-adverse, and profit margins are small. Each project is unique with a small amount of technological innovation opportunities to capitalise on from one project to the next.

Technological innovations that have been taking place are just simulating the old traditional paper workflow. Engineering information in digital form is being conveyed using traditional paper representations, which have to be interpreted by humans before the information can be used in other applications, thereby creating ‘islands of information’. It can be seen that poorly implemented IT strategies are duplicating paperwork, rather than reducing or eliminating it (Crowley et al., 2000).

This paper will introduce the *Integrated Engineering Workflow* (*IEW*) concept to re-organise a structural discipline working on multi-disciplinary projects so as to maximise the advantages offered by new information technology.

1 Introduction

1.1 Background

Most engineering consultants stop technological innovation with three-dimensional computer aided design (3D CAD) and utilise it as an effective way to create drawings as a construction deliverable. To utilise 3D CAD fully and effectively as an integrated engineering solution, the consulting engineering practice needs to re-engineer its traditional workflow.

The latest information technology available, challenges the consulting engineer to rethink the traditional workflow. In structural engineering a 3D analysis and design model is created and then from the engineering model, the tender drawings are generated. After placing an order with a fabricator, the fabricator creates 3D detailing models and from this, produces detail and construction drawings. In this traditional 3D workflow, the 3D structural model is created three times and drawings are produced twice. With effective use of information technology, the model and drawings, need only to be created once and in some cases drawings are replaced by reports to provide information ‘fit for purpose’.

Intelligent three dimensional (3Di) models raise the level of sophistication of the engineering information, which can extend the use of 3D CAD beyond the traditional use of creating 2D drawings (Palm, 1999). 3Di modelling changes the way that engineering work is done and changes the work product. The model and database contain information that is ‘nearer to fabrication and construction’ and this reduces or eliminates the need for intermediate and repetitive deliverables, review processes and clash checking. This in turn reduces the time schedule, cost and opportunities for user error i.e. it reduces re-work resulting from engineering documentation errors and omissions. The key differentiator of 3Di delivery compared with traditional methods is the ability to implement multi-disciplinary concurrent engineering with integrated data integrity.

1.2 Problem definition

The pursuit of greater productivity has encouraged many consulting engineers to evaluate and re-engineer conventional processes. The search for new methods and enabling tools has become a priority for engineering managers. The migration from a 2D CAD system to a 3Di design solution provides a natural progression for engineering departments demanding increases in efficiency and quality to differentiate them from the competition.

Technological innovation creates a difference between implementing 3D CAD, which corresponds to traditional paper workflow, and 3Di modelling as an *IEW* solution on structural projects. Implementing 3Di as an *IEW* requires *Business redefinition*.

2 Case study on engineering workflow.

2.1 Introduction

Two case studies on two EPCM (Engineering, Procurement, Construction and Management) companies undertaking billion dollar projects using different engineering workflows, will be analysed. The case studies will focus on the structural engineering discipline within multi-discipline industrial EPCM companies.

Case Study 1 utilises the traditional paper based workflow whereas Case Study 2 uses the IEW.

2.2 Case study 1 (Company A: Traditional paper workflow)

2.2.1 Introduction

Company A started with 3D design in 1999, utilising the best 3D modelling software available at the time. Their prime focus was to increase productivity by utilising 3D modelling software. It was important for the company to use their proven and tested traditional engineering deliverable workflow and they felt no need to change the type or information content of deliverables. Engineering productivity enhancements by utilising the latest 3D technology was their primary goal.

2.2.2 Workflow

Figure 2-1 indicates a simplified information flow diagram based on the most important deliverable activities: tender and issue for construction (IFC) drawings.

2.2.3 Workflow: 3D Setup

For each project, the 3D system is setup so that multiple users can use the same project files on the network e.g. reference files, library items and client\project CAD standards. Before the 3D CAD system is opened, the users specify a project code, which points the CAD system to the correct 3D setup for that specific project.

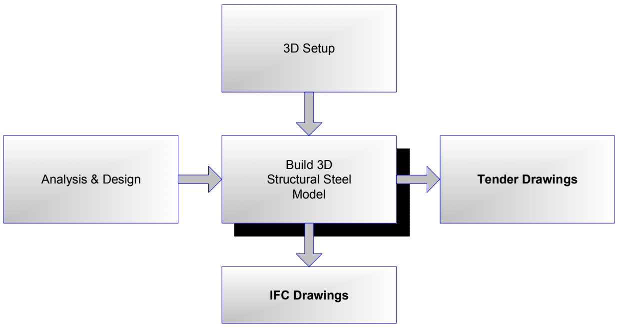


Figure 2-1: 3D workflow with primary deliverables indicated in bold.

2.2.4 Workflow: 3D Model

Modelling 3D structural steel members takes place in a multi-disciplinary environment. The conceptual steel layout is built while *referencing* other discipline 3D models (e.g. vendor equipment and piping). Referencing features ensure that different workstations are using the same database files and that the modelling information is current. (Heisler, 1994). Referencing is achieved by setting up the 3D modelling environment to plant coordinates and using CAD techniques to locate all CAD files via a common datum point.

2.2.5 Workflow: Frame Analysis

A new *Frame Analysis* model is created from sketches, produced from the 3D model (layout design model). After completing analysis and design of the structure, the 3D model is updated manually with analysed and designed section sizes produced from the Frame Analysis model.

2.2.6 Workflow: Tender Drawings

Tender Drawings are generated from the 3D model by utilising volume clips. Volume clips consist of a 3D display cube in the 3D model, which enables you to filter out geometry outside the volume of interest. Hidden line removal algorithms are executed on a number of previously saved volume clips to create drawing views. Certain predefined rules can be set in the hidden line algorithms, e.g. single or double line representation of sections and automatic annotation of the section names. The drawing views are then placed on a drawing border where dimensions are placed manually. If the 3D model changes, the hidden line algorithms are regenerated on the saved volume clips and the related drawing views are updated on the drawings. The drawings are annotated with manual CAD techniques to visually indicate moment connections and any contractual notes, which can affect the tenders.

2.2.7 Workflow: Drawings Issued for Construction

IFC Drawings are the same drawings used as for tender drawings. Non-standard connection-, grating, handrailing details and special notes are placed additionally into the IFC drawings. The quality of the IFC drawings applies to international drawing standards.

2.2.8 Goals, Achievements and Comments

(Heisler, 1994) stated that using 3D modelling correctly will reduce engineering hours by 25% in a multi-disciplinary engineering environment against that of drawings produced on the traditional drawing board. This is in comparison to 2D CAD, which provides only a 6% reduction over the traditional drawing board methods.

Company A claimed that they can create a set of structural engineering drawings in less than half the time they would have on 2D CAD by using 3D CAD. The limitation now is the management of engineering resources and engineering changes. The ratio of structural engineers to engineering draftsmen has also changed with 3D.

2.3 Case study 2 (Company B: IEW)

2.3.1 Introduction

Company B started with 3D design in 1985 and from the start had a vision to use information technology to optimise their engineering workflow. Their vision was to share and integrate the engineering information with the client, vendors, manufactures, and contractors on site.

According to (Lawrence, 2004) the 3Di modelling philosophy applied by *Company B* is to design and build the plant in the computer. They use 3Di design reviews to:

- Obtain ‘buy-in’ of the design in progress by the various disciplines, by the client and other contractual parties.
- Optimise multi-disciplinary layouts.

- Identify and resolve critical interface issues

They use the 3Di functionality to report steel quantities accurately and early for ordering 'long lead' items, to automate fit for purpose deliverables, and to report structural member interferences. This enables them to improve the quality and efficiency of the tendering processes and to resolve many procurement, construction, operation and maintenance issues early in the design process for a 'no surprises' result.

2.3.2 Workflow

A simplified workflow used on the project indicating main deliverable activities is shown in Figure 2-4.

2.3.3 Workflow: 3Di Setup

3Di Setup is seen as an important part of the project before it commences. In addition to the setup process of company A (see section 2.2.3), company B includes the setting up of project specific procedures for 3Di tools, these act as training and implementation guides to promote consistency in a local or work shared project execution environment. All aspects of set-up: CAD standards, modelling method, review and approval procedures, system integration \ data flow, information flow, attribute status control, checking, reporting and detailing interfaces are covered. A clear definition of deliverables – internal \ external, format \ content and handover is documented.

2.3.4 Workflow: 3Di Model

Modelling 3Di structural steel components (See Figure 2-2) also takes place in a multi-disciplinary environment by using reference files as explained in section 2.2.4. The 3D structural models are created in a *multidiscipline* 3D CAD environment and when the information in the model reaches the milestone 'Issue for Detailing', the model is transferred to a *specialised* 3D detailing tool used by the contracted detailing team (See section 2.3.10). Once the detailing model is reviewed, it is transferred back to the multidiscipline 3D CAD model for final clash detection (See section 2.3.11). The deliverables from the detailing model are issued for construction.

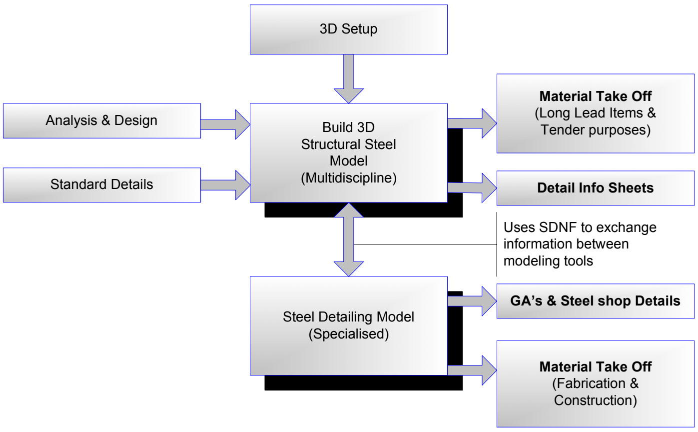


Figure 2-2: 3Di workflow with primary deliverables indicated in bold.

2.3.5 Workflow: Standard Details

Standard Details: To improve efficiencies in steel fabrication, the company has developed standardised connections details. The standard details have been created taking the following into consideration:

- Maximising the tonnage of steelwork in any structure that can be manufactured using automated fabrication techniques, i.e. no weldments – just cut, punched, coped, drilled etc.,

and if weldments are required they are arranged as much as possible to selected individual beams.
- Simplifying connection details and rationalising connection components to reduce the number of different parts and to increase repetition.

2.3.6 Workflow: Frame analysis

Frame Analysis is prepared with the information received from the 3Di model, in the form of 'detail info sheets'. (See section 2.3.7) After analysis and design of the structure is completed, the 3Di model is updated manually with designed section sizes.

Frame Analysis is prepared independently of the 3Di CAD layout design. According to (Rushton, 2002) this allows the engineer to analyse the structure and understand the critical load paths throughout the frame. After completion of the analysis and design process, the engineers review the 3D model to verify member sizes, connection details and non-standard details before the model is issued to the Steel Detailer for detailing.

2.3.7 Workflow: Detail info sheets

Detail Info Sheets are the preferred structural steel design deliverables. They are similar to traditional structural steel arrangement drawings, but are generated from a 3Di model with automated steel member dimensions (node-to-node) and minimal user annotation. The purposes of the Detail Information Sheets are:

- Together with the bill of material, provide enough information to the fabricator for accurate tendering.
- Additional information to the electronic 3D model for issue to the structural detailer.
- It also provides a method of checking the 3Di design model and for building a Frame Analysis model.

The information shown on the sheets include:

- Automated member size annotation and dimensions (node-to-node).
- Grating extent and span direction, removable panels or any special requirements.
- Grating penetrations for piping.
- Grating cut-outs for equipment.
- Handrail extent and ladder positions.
- Non-standard structural connections and reference to non-standard connection sheet.
- Drilling for equipment supports and reference to vendor drawings or details.

It is important to note that Detail Info Sheets are not traditional drawings. It is basically a sketch, which is produced in a semi-automated fashion. Information automatically generated on the sheets e.g. member annotations and node-to-node dimensions, are not to any international drawing standards and are left "untidy" (e.g. left as is produced through the automated annotation process) provided the automated information is legible. The focus is to minimise the user input on drawings and present only relevant information.

2.3.8 Workflow: Bulk material take off

Bulk Material Take Off (MTO) is produced from the 3Di designer's model automatically. This is done before detailing takes place, and facilitates early and accurate bulk ordering of material without the need to generate drawings purely for MTO purposes. According to (Lawrence, 2002) this approach has reduced the project time schedule, reduced material wastage and eliminated material supply delays on long lead items. The MTO's together with the Detail Info Sheets are used as engineering deliverables for checking, tender documents and detailing.

2.3.9 Workflow: Design Reviews

Design Reviews are done through interactive real time walk-through simulation that has access to the model data. Interrogation is conducted with comments recorded on views, which are captured as image files for attachment to the review meeting minutes. The minutes are then signed off and are kept as a design review audit trail. The reviews are conducted at scheduled stages in the design cycle and are a key step in achieving pre-defined engineering milestones.

2.3.10 Workflow: Structural Detailing

The Structural Detailing package is contracted directly to the engineer (in lieu of the Fabricator) as an extension of the engineering team. The engineering deliverables being issued to the detailers are the design model, Structural Detail Neutral File (SDNF), checked and approved Detail Info Sheets and Non-Standard Detail Sheets.

The detailers convert the SDNF file into their own detailing modelling system to add all connection details, grating and handrail details, i.e. the design model is imported and added to, not rebuilt. Before the detail model is issued for fabrication, the engineering team will review it. As part of the review and checking process, the connected model is back integrated into the multi-disciplinary model environment, where final clash detection is done for clashes between connection details and services and equipment. (See section 2.3.11).

The detailer produces IFC deliverables to the fabricator. These include:
- Electronic data files for beam-line and other numeric control (CNC) fabrication machines.
- Automated 2D assembly details for each fabrication item.
- Profile drawings (e.g: as DXF CAD files) of each fitment for plate nesting.
- Material ordering list.
- Bolt list.
- Reports for procurement and erection.
- 3-D generated general arrangements (GA) as erection drawings or marking plans.
- Electronic transmittals.

Company B also engaged potential fabricators \ constructors before the commencement of each project in value adding discussion workshops to:
- Rationalise steel members and connections to suit efficient fabrication.
- Use detailing methods with emphasis on automated CNC beam, cropping and profiling systems.
- Determine the most efficient delivery to match fabrication and erection techniques.

2.3.11 Workflow: Clash Detection

Clash detection is accomplished through automated software tools. It will report on hard and soft clashes. A hard clash is a physical interference e.g. a bracing gusset plate clash with a pipe. Soft clashes are non-physical clashes e.g. a bracing member runs through an access walkway clearance perimeter, which has been modelled as a spatial envelope. Visual checks are required to ensure that access and safety considerations have been designed into the plant layout.

2.3.12 Goals, Achievements and Comments

In addition to the workflow of company A, company B applied the following IEW activities:
- Contracting the Structural Detailing as an extension of the engineering effort.
- Considering standard details early in the design process.
- Reducing total manual engineering drawing effort by utilising Detail Info Sheets.
- Multi-discipline real time walkthrough design reviews with data interrogation.
- Automated multi-discipline clash detection.

(Rushton, 2002) expressed the view that by bringing the detailers into the design team, with an IEW, the company is not only able to save design time and improve on engineering accuracy, but has also been able to achieve better engineering solutions by taking fabrication deliverables in to account early in the design process. Benefits to their projects are:
- Engineering teamwork as one design\detailing team.

- Steel detailing starts much earlier and constrictions in document delivery are removed.
- The traditional duplication of engineering effort between engineering drawings and steel detailing is eliminated.
- Electronic data integration greatly reduces errors and clashes.
- The traditional paper trail review process is eliminated.
- Automated reports assist procurement.
- Productivity is improved in the design office, detailing office, fabrication workshop and on site.

3 Comparative Analysis

3.1 Duplication of information

Traditional engineering workflows manage engineering information and activities effectively with the engineering processes and tools available. Between the different engineering activities, information was dissimilar i.e. the three primary participants involved in the workflow (Designer, Engineer and Detailer) used different types of information for the same steel structure. The Designer created the skeleton line drawings (single line representation of the structural steel) and referred to separately drawn connection design details. The Engineer analysed and designed sections of the structure using analysis techniques e.g. moment distribution and the Detailer repeated the information by creating fabrication drawings of the steel.

With the introduction of engineering information tools, company A has continued to keep its engineering information as separate activities. Each engineering entity in the engineering workflow has centred productivity enhancements in its own separate domain. The Designer creates a 3D steel model, the Engineer creates a 3D steel model for analysis and the Detailer re-creates a 3D steel model to produce fabrication drawings. Unlike the traditional paper workflow, using 3D, the engineering information now has the 3D steel model as a similitude.

It is these similarities in the engineering information, which company B utilised to transform a fragmented workflow into an integrated workflow to reduce engineering duplication and overall project time schedule. Company B has abridged three design activities by using the 3D model more effectively and by engaging the detailing effort as part of the engineering activities. The reduced activities through the automated process are:

- 2D drawings do not need to be produced to normal drawing standards because they will only be used for exchanging information and for auditing purposes internally. This has led to the production of Detail Info Sheets in a semi-automated manner to convey the engineering information, which in turn economises the workflow.
- MTO’s are generated from the 3D model itself and not from the 2D drawings.
- Company B has removed a contractual interface by producing structural details as part as the engineering effort. This enabled them to translate the designer’s 3D model into the 3D system used by the detailers, thus saving project cost by eliminating the reproduction of a 3D model. Once the detailer’s 3D model is completed, it is translated back into the multi-disciplinary environment for final automated clash detection.

3.2 Schedule comparison

Figure 3-1 demonstrates two engineering \ construction schedules based on a traditional and integrated workflow. The schedules are based on a 2500-ton structural steel structure constructed on a brownfield (existing plant) site. The structure is part of a process plant with multi-discipline interfaces.

The figure 3-1 indicates the total engineering \ construction schedule for the traditional and integrated workflow, which are 50 and 38 weeks respectively and a schedule difference of 12 weeks, i.e. the schedule of the integrated workflow is 25% less than the traditional workflow.

The schedule differences consist of two components, reduced- and parallel activities, and both are promoted by the integrated workflow. With the IEW, the reduced activities are:

- Detail Info Sheets, which have replaced 2D Drawings. A schedule saving of 3 weeks.
- MTO's are generated from the 3D model automatically. With the paper workflow, MTO's were created manually from the 2D drawings. A schedule saving of 1 week.
- 3D Detailer model is populated from the 3D designer model data, as an automated 'node connected' model. Time saving of 1 week.

A substantial difference in the schedule is obtained because of parallel activities without contractual bottlenecks. Company B has engaged the detailer activity as part of the engineering effort. This allowed for parallel activities. The detailing was done through the 7-week tender period. At the time the order was placed on a fabricator, they received the shop detail drawings and CNC data as a final deliverable and not just steel layout drawings. A schedule saving of 7 weeks.

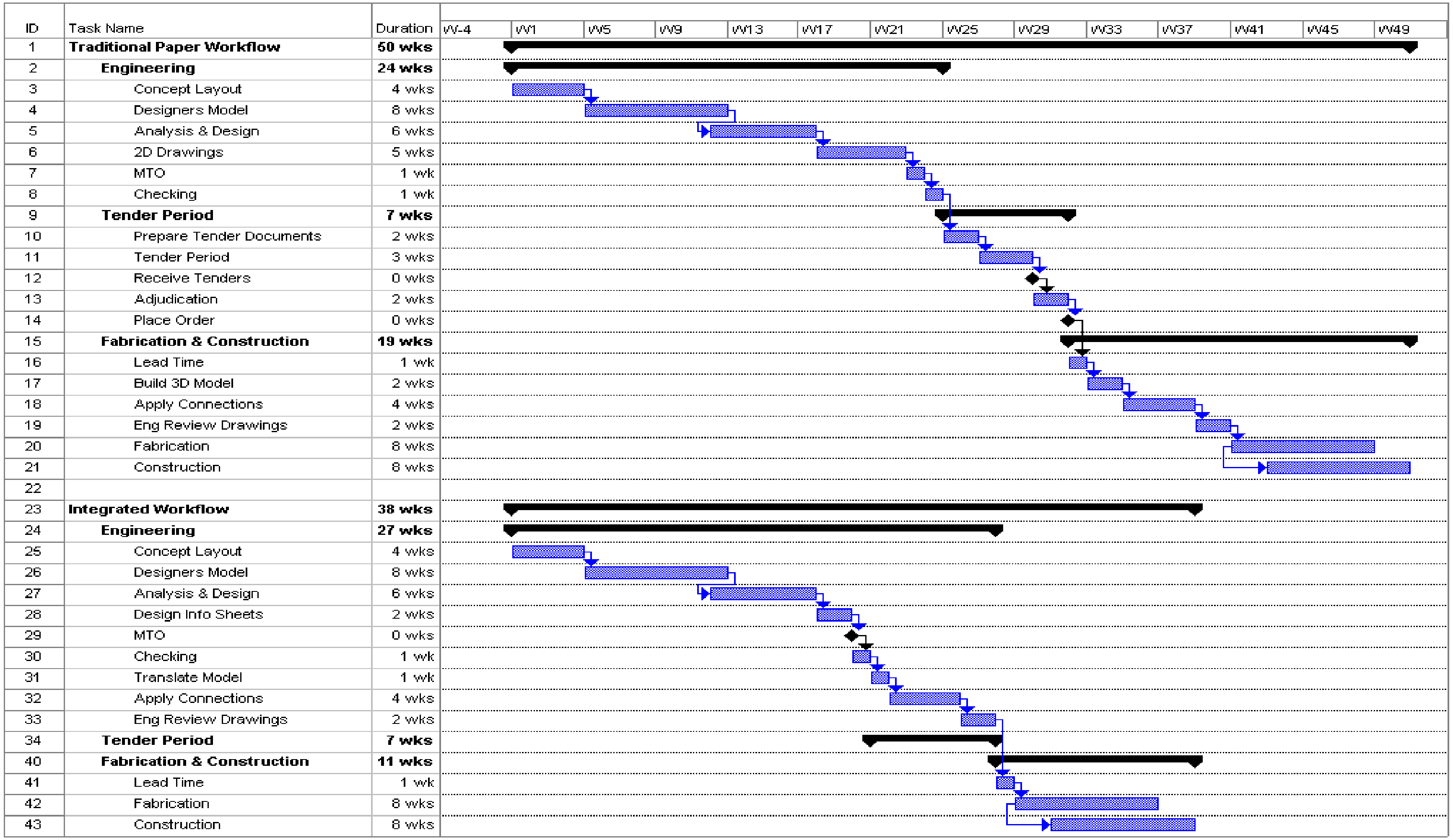
3.3 Design and construction deviations

3.3.1 Contextual definition of „Deviation“

"*The term deviation, rather than failure or defect (which are commonly used in the manufacturing industries), indicates that a product or result that does not fully confirm to all specification requirements does not necessarily constitute an outright failure.*" (Davis et al. 1989) Deviation includes changes to the requirement that result in rework, as well as products or results that do not conform to all specification requirements, but do not require rework.

Project deviations can be broken up as follows:

- **Design deviations** are related to design of the project. It can be classified in the following categories. Design changes, errors or omissions.
- **Construction deviations** are related to the construction phase of the project and consist of those activities and tasks that take place at the project site.
- **Fabrication deviations** are related to shop fabrication. Changes, errors, and omissions that occur during field fabrication are included in the construction deviation.
- **Transportation deviations** are related to the transport of equipment, materials, or supplies.
- **Operability Deviations**: Process changes to a facility to improve operability.



ID	Task Name	Duration
1	**Traditional Paper Workflow**	**50 wks**
2	**Engineering**	**24 wks**
3	Concept Layout	4 wks
4	Designers Model	8 wks
5	Analysis & Design	6 wks
6	2D Drawings	5 wks
7	MTO	1 wk
8	Checking	1 wk
9	**Tender Period**	**7 wks**
10	Prepare Tender Documents	2 wks
11	Tender Period	3 wks
12	Receive Tenders	0 wks
13	Adjudication	2 wks
14	Place Order	0 wks
15	**Fabrication & Construction**	**19 wks**
16	Lead Time	1 wk
17	Build 3D Model	2 wks
18	Apply Connections	4 wks
19	Eng Review Drawings	2 wks
20	Fabrication	8 wks
21	Construction	8 wks
22		
23	**Integrated Workflow**	**38 wks**
24	**Engineering**	**27 wks**
25	Concept Layout	4 wks
26	Designers Model	8 wks
27	Analysis & Design	6 wks
28	Design Info Sheets	2 wks
29	MTO	0 wks
30	Checking	1 wk
31	Translate Model	1 wk
32	Apply Connections	4 wks
33	Eng Review Drawings	2 wks
34	**Tender Period**	**7 wks**
40	**Fabrication & Construction**	**11 wks**
41	Lead Time	1 wk
42	Fabrication	8 wks
43	Construction	8 wks

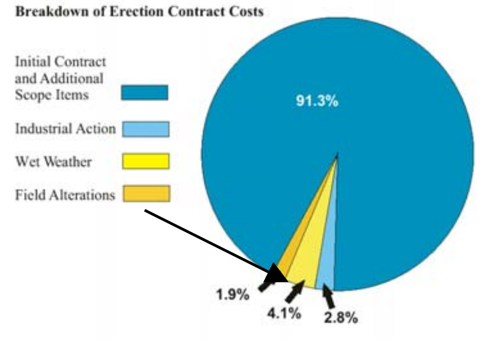
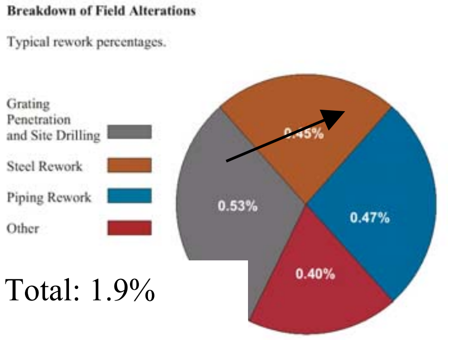
Figure 3-1: Schedule Comparison for the purpose of highlighting activity durations

3.3.2 Deviation comparison

A deviation study (Burati, *et al*., 1992) was done on nine fast track industrial construction projects. Analyses of the data indicate that deviations on the projects accounted for an average of 12.4% of the total project costs. Design deviations average 9.5% of the total project cost and construction deviations 2.5% of the total project cost. These results indicate that rework costs are a significant portion of the project costs.

The project executed by company B using an IEW recorded a 1.9% of the project cost because of design deviation (See Figure 3-3) compared to the 9.5% average (Burati, *et al*., 1992) on industrial projects. Figure 3-4 gives a breakdown of the 1.9% field alterations where fabrication and detailing re-work was 0.45% (See Figure 3-4) of the total project cost. It is a total project cost saving of 7.6% (9.5%-1.9%) due to the integrated workflow in terms of field alterations. Although figures quoted by company B applies to a single case study, they believe that it is typical for projects using the IEW framework.

The integrated workflow allows company B to eliminate virtually all physical interferences before the plant is build.

<table>
<tr><td>Figure 3-3: Erection Contact Cost</td><td>Figure 3-4: Field Alterations</td></tr>
<tr><td> </td><td> </td></tr>
<tr><td colspan="2">(Rushton, P 2001).</td></tr>
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Typical steel construction figures with 3Di

3.4 Summary

A concise collated analysis indicates that project costs have been saved through integrating the workflow, which encompasses:

- Elimination of fragmented engineering through the use of technology.
- Using technology better.
- Not compromising on quality control reviews but increasing the quality through strict semi-automation procedures.
- Proper software procedures and setup.
- Reducing activity and information duplication, which improves design coordination, reduces errors and increases productivity.
- Increasing the design schedule, but saving overall project schedule through parallel activities. This result supports the understanding that the critical path of the schedule is not determined by engineering, but by the duration to produce and deliver the long lead items.
- Significant project cost savings in construction re-work by eliminating most of the design and construction deviations through automated interference checks on the detail structural work with other disciplines.

4 Conclusions

Through the case study comparison, it is clear that the IEW is one of the most significant opportunities for multi-disciplinary projects to benefit from in terms of engineering efficiency, project schedule savings, reduction in construction deviations and construction quality. The problems that engineering projects which utilise 3D technologies are facing are rarely to do with the technology or tools. The tools work. It is mostly to do with the workflow, which minimises the effectiveness of the process.

Engineering projects and companies are too dissimilar to develop a complete and ultimate workflow procedure. Engineering companies need to invest in integrated workflow studies and implementation procedures. Coordination and understanding of these integrated workflows must be implemented and be completely understood by the project team.

Engineering consultancy companies, which want to move into the area of integrating engineering systems to improve their workflow, need to define a detailed IEW. The definition of these integrated workflows cannot be developed in discipline isolation. A multi-disciplinary holistic approach is recommended.

In the context of this study, an Integrated Workflow can be described as "A practical and proactive method framework to improve multi-disciplinary project planning and delivery with effective engineering workflows structured to integrate and leverage data centric technology."

To successfully implement a well-defined Integrated Workflow, it is important for project management personnel to understand; the *nature of IEW, their role, their responsibilities and the impact of the Data IEW,* in particular:

- Project manager: contractual strategies and his responsibility to get the buy-in from the client into the model approval processes (not drawings).
- Procurement manager: material management and fit for purpose deliverable for tendering.
- Engineering manager: estimating, scheduling, deliverable interfaces of engineering, IEW procedures and integrated engineering progress measurement.
- Construction manager: early impact of contractibility issues via the 3D model reviews.
- Project design coordinator: engineering technology interfaces and information flow, data and information integrity, 3D design review, checking procedures and responsible for the implementation and use of the integrated workflow by the designing team in a proactive manner.

Currently no effective way exists to model effectively a dynamic Integrated Workflow. The need exists to develop process-modelling tools to create, visualise, measure, validate, develop and manage dynamic IEW scenarios, which are multi-discipline interrelated. The process model needs to dynamically forecast the impact (risk analysis) on the project when certain aspects of the Integrated Workflow are changed or certain activities in the workflow are not achieving their status.

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6 Abbreviations

3D	Three Dimensional
3Di	Intelligent Three Dimensional Modelling
CAD	Computer Aided Designing
CNC	Computer Numeric Control
DXF	Drawing Exchange Format
EPCM	Engineering, Procurement, Construction and Management
GA	General Arrangement Drawing
IEW	Integrated Engineering Workflow
IFC	Issue For Construction
MTO	Material Take-Off
SDNF	Structural Detail Neutral File