University of Alberta

Estimation and Planning Methodology for Industrial Construction Scaffolding

By

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of

Master of Science
in
Construction Engineering and Management

Department of Civil and Environmental Engineering

Fall 2013
Edmonton, Alberta

For my father,

without you I wouldn’t be the person I am now..

ABSTRACT

Scaffolds are temporary structures that are built to support workers and materials and facilitate direct work on construction sites. A considerable amount of man power resources are consumed by industrial construction scaffolding, which makes effective planning and estimation of the same very critical to the project. The present research attempts to analyze affecting factors for different stages of estimation and concepts in advance planning of industrial scaffolding, and presents useful observations and recommendations. A simulation tool for predicting scaffold erection man-hour values for individual equipment on site in an industrial project was developed in Simphony 4.0 and is based on mapping the geometry of equipment and other factors to man-hours of scaffold work. The stages and methodsof estimation, their uses and an efficient scaffold flow process for industrial construction lays a solid foundation of new concepts and analysis in industrial scaffolding research work.

ACKNOWLEDGEMENT

I take this opportunity to express my sincere gratitude to everybody who helped me directly or indirectly over the course of my Masters in University of Alberta. First and foremost I would like to sincerely thank my supervisors Dr. S. Abourizk and Dr. Y. Mohamed for their unparalleled guidance and support professionally and personally. I went through some difficult times and without their support, I wouldn’t have been able to successfully complete my Masters. I would also like show my gratitude towards Mr. U. Hermann and Dr. H. Taghaddos for taking time of their busy schedules in helping me with the research work.

I would like to thank Mr. Stephen Hague, Mrs. Maria Al-Hussein and Ms. Amy Carter for all the guidance and knowledge in the course of my research work. I would especially thank Mr. Stephen Hague for his programming expertise which was greatly needed for someone like me who does not have a programming background.

I would like to express my gratefulness to my colleagues and friends for providing me with immense support and help, in any problems I had, over my stay in Edmonton. Without you guys, it would have been difficult to adjust and prosper in a country and culture which was totally new to me.

Last but certainly not the least I thank God for giving me the courage to live through all the good and bad days. I have faith in you.

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Chapter 1 — Introduction

1.1 Background

Scaffolds are temporary elevated platforms built to facilitate the work of laborers and use of materials, mostly at higher-than-ground-level elevations. Scaffolds are an integral part of construction operations especially high-rise construction, in any field of construction. While scaffolding is often considered to be of lesser importance within the overall project requirements, it does account for a considerable amount of labor-hours. Understanding scaffolding construction requirements necessitates extensive knowledge of all affecting factors. These factors depend on the level of estimate to be prepared and the data available at hand for performing the estimating process. However, not all factors share the same level of importance in the estimating process.

1.2 Industrial Construction

Construction processes vary as per the scope of work and various other governing factors. Industrial construction in general is quite different from residential or infrastructure projects based on its needs, requirements and deliverables. Firstly, construction processes for a power plant or a petroleum refinery etc.are not concentrated at a single location, as is the case with constructing a stadium or high rise building. Moreover work areas do not share the general elevation level for the whole project which implies that workers have to work at different height levels with respect to ground level and need to adjust to specific working conditions. Industrial plants are also normally constructed far off from main cities; hence laborers have to work in comparatively harsh conditions, which could decrease productivity. Also, material handling becomes more relevant to keep the project progress smooth and avoid any delays due to late arrival of raw materials or transport related problems. The construction activities for a general industrial project include trades like civil, electrical, and mechanical, pipefitters, insulators etc.

1.3 Temporary Structures in Construction

> “Temporary structures are those structures that are erected and used to aid in the construction of a permanent project. They are used to facilitate the construction of buildings, bridges, tunnels, and other above and below-ground facilities by providing access, support, and protection for the facility under construction, as well as to assure the safety of the workers and the public.” [1]

They are in most cases dismantled after they have been used, but circumstances might occur where they are embedded into permanent structure[1]. The reasons could be factors like costto take them out, or need for them in some future work. In addition to new construction projects, temporary structures are also a major component in maintenance, repair and inspection works[1]. Some of the different types of temporary works are –

1) Coffer dams
2) Tunnel supports
3) Scaffolding
4) Bridge deck supports, etc.

1.4 Scaffolding

Scaffolds are temporary structures built to facilitate the work of laborers, mostly at higher-than-ground-level elevations. Some of the common definitions used for Scaffolding are as follows:

- "The word 'Scaffolding' refers to any raised platform or ramp used for ingress and egress for pedestrian movement and/or the passage of building materials."[2]
- "Scaffold or scaffolding-any temporary elevated platform and its supporting structure used for supporting workers, or workers, equipment, and materials."[3]

Scaffolding in one form or another has been used since "humans moved from single storey huts at ground level to taller structures"[2]. While in most cases they are erected temporarily, and then taken down once the work is finished, sometimes they are incorporated as a part of the permanent structure. They become part of the permanent structure if the same point of work is to be used regularly during the course of the project or for maintenance works afterwards. Different materials have been used over the years based on availability and general design requirements for the construction of scaffolds. Scaffolding in any construction project can be broadly divided into three different kinds[4] –

- Supported scaffolds
- Suspended scaffolds
- Miscellaneous scaffolding systems

The different types of scaffolds are explained in detail in Chapter 2 – Literature Review.

1.5 Industrial Construction Scaffolding

Industrial construction scaffolding operates mostly on an as-needed basis and is difficult to plan well in advance. The type of scaffolding used in an industrial project would not only depend on the availability of materials and type of job, but also on the agency constructing the scaffolding. A particular work can be performed by different agencies in different manner and might lead to different cost estimates. Some industrial contractors have their own scaffolding division which provides the necessary labor force for all scaffold related jobs; however, in most cases the materials are on a rental basis. For others, scaffold jobs are sub-contracted to a company expert in this field. The material may or may not be supplied to them depending on the scope of the contract. Based on various discussions with industry experts it was determined that most scaffolding jobs in industrial projects require supported scaffolds, or in some specific scenarios, miscellaneous scaffolds like scissor lifts are used. Tube and clamp, all around, dance floors etc. are some of the typical scaffolding systems used in industrial projects.

Another important feature of industrial construction scaffolding is the amount of modifications a particular scaffold undergoes before it is taken down. A particular kind of scaffold is constructed to suit the needs of one or more trades at a particular instant of the project. There might be other trades that need the same scaffold, but may be at an elevation higher or a few meters away in a horizontal direction. To take care of such scenarios, the present scaffold is evaluated and suitable adjustments are made to support the changing needs. This makes the planning of scaffolding even more challenging as it has to foresee and take into account any further modifications that could be needed in the same working location. Construction and dismantling of scaffolds are labor intensive jobs, and as labor is the major cost component in any construction project, minimizing the scope is beneficial in most situations. Dismantling and then constructing the same scaffold again would increase the cost ofthe project significantly as well as affect the project duration. An advanced scaffoldplan is important before the start of a particular job to anticipate such conditions in advance.

1.6 Scaffold Estimation

The level of detail of scaffolding requirements at the start of a project or during the estimation phase is at most times not totally clear, and hence, a systematic planning and estimation technique seems difficult. However, a higher level of estimation process is generated by most companies by meticulously analyzing existing data from past projects. This research would formulate the process for estimation of scaffolding both at higher level and on a detailed level. The factors influencing the estimate would vary in both scenarios.

Based on various discussions with some industrial contractors, it was found that most companies include scaffolding as a part of indirect expense and it is calculated as a factor of direct work in that particular project. Using data from already completed projects, companies have maintained some factors which are used for calculating scaffold requirements for new projects. There are considerable amount of limitations associated with such estimating procedures. First, they are not detailed enough for other considerations like material estimation. Secondly there might be changes during the course of the project which would make the estimate redundant. Also, the percentages developed based on historical data do not consider all affecting factors to scaffold estimation. Contributing factors to scaffold estimate include weather effects, material storage locations, labor availability, the amount of congestion and type of work in a particular area, etc. While scaffold type seems in a logical sense to determine the man-hour requirements, in reality, as per a leading scaffolding expert, it does not. The material available on site is constrained to specific varieties and the types of scaffolds used in industrial construction sites are quite limited in number. In most cases a framed or tube and clamp scaffolding is sufficient to satisfy the needs of the job at hand. The factors that affect scaffolding and the dependence of scaffold requirements on the geometry of the structure will be dealt with in detail in Chapter 4.

1.7 Research Objectives

The present research attempts to formulate a methodology for effectively planning and estimating industrial construction scaffolding. This would be achieved by understanding and analyzing industrial construction scaffolding requirements based on logical constraints and arriving at an estimating and planning algorithm for estimation of labor man-hours of work in scaffolding construction. The following objectives are in line with the thesis developed:

1. Understanding the scaffolding process and its requirements in relation to industrial construction scenarios.
2. Defining the parameters that affect the prediction of scaffold construction requirements.
3. Developing relationships between affecting parameters and scaffold erection man-hours of work.

4. Recommendations of improving relationships developed as a course of this research and an effective planning process for managing scaffold construction requirements on industrial sites.
5. Implementation and organization of the developed relationship in the form of a basic estimating tool and suggesting ways to improve and enhance it.

1.8 Research Methodology

The methodology used for this research involves analytical techniques in conjunction with detailed discussions with experienced personnel in the field of industrial scaffolding construction and planning. The five points discussed above are addressed in the following way during the course of this research work –

1. Various discussions were held with prominent and experienced people in two different companies to understand the present industry methods in scaffold construction and planning.
2. The discussions led to the development of a theoretical set of parameters that affect scaffolding estimation. The parameters were logically analyzed based concepts generated based on existing literature and field personnel in construction.
3. All available scaffold data were collected, and using data mining techniques, relationships were developed between affecting parameters and scaffold erection man-hours of work.
4. Scaffold planning process was analyzed for two different companies and a suggested process model was developed for improving existing techniques.

5. A simplified estimation tool was developed in Simphony 4.0 simulation interface to be used by industry personnel.

1.9Thesis Organization

Chapter 2 deals with the literature review associated with this scaffolding research. Types of scaffolds, planning and existing methods of scaffold estimation and other related topics and researched and existing works have been critically reviewed.

Chapter 3 deals with concepts and analysis regarding scaffold estimation and planningscaffold process flow models developed for two companies and new concepts in scaffold estimation.

Chapter 4includes methodsof data collection in relation to development of scaffold estimation models and details about the available data set.

Chapter 5 explains all analysis performed on the available dataset, dependence of scaffold requirements on input parameters, suggested techniques in data collection and a simulation tool for estimating purposes.

Chapter 6 explains the conclusions of scaffold research and recommendations for future work in this field of expertise.

Chapter 2 — Literature Review

2.1 Scaffolding

Temporary structures are an integral part of industrial construction projects and scaffolding consumes a considerable amount of project man power and resources. As defined in Chapter 1, “Scaffold or scaffolding-any temporary elevated platform and its supporting structure used for supporting workers, or workers, equipment, and materials”[3]. As this is a means of reaching points of construction which need temporary access, they have been part of construction activities for avery long time, in forms that have varied and developed over the years. As the needs of the industry grew and more challenging activities had to be performed, the materials, types and methodsof scaffold construction also evolved. By the middleages, more complex systems of scaffolding started to develop and around the mid-1920’s, the concept of using steel pipes fastened together with couplers was introduced.[2] In the late 1930s and 1940s, the concept of welding pipes and tubes into prefabricated frames became popular[2].

2.1.1 Scaffolding Types

Scaffolding required in construction activities, be it residential or industrial, is divided into three major categories[4]:

- Supported scaffolds
- Suspended scaffolds
- Miscellaneous scaffolds

Industrial construction is mostly limited to the use of supported scaffolds, however situations may arise which require the use of other scaffolding methods. The following section describes the typical scaffold configurations that constitute the three categories as mentioned above.

2.1.1.1 Supported Scaffolds

> "Supported scaffolds consist of one or more platforms supported by outrigger beams, brackets, poles, legs, uprights, posts, frames, or similar rigid support."[4]

The most common types of supported scaffolds are the following:

Tube and coupler: Tube and coupler scaffoldsare the most common scaffolds used on an industrial construction site, owing to their directional versatility. They also have anideal configuration when multiple points of entry and/or platforms are required. Figure 2-1 shows a typical tube and clamp configuration at a modular yard and Figure 2-2 shows a detailed connection joint.

Figure 2-1 Tube and clamp scaffolding in PCL Modular Yard, Nisku, Edmonton

Figure 2-2 Tube and clamp connections, PCL Modular Yard, Nisku, Edmonton

There are three basic elements in a tube and coupler scaffolding[2]:

- Posts
- Bearers
- Runners

Standard couplers or clamps are used to connect these elements together to form a complete scaffold. Figure 2-3 shows the typical elements in such configurations.[2]

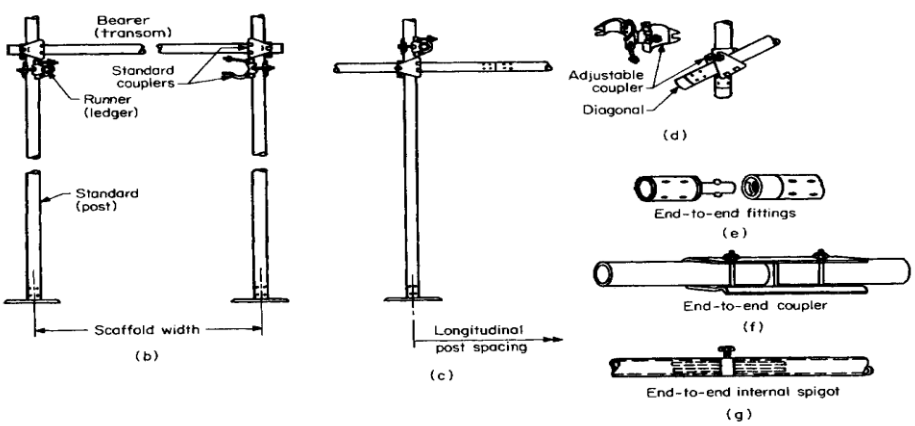


Figure 2-3 Elements in tube and clamp scaffolding

Frame or fabricated scaffolding:

> "Fabricated frame scaffolds are the most common type of scaffold because they are versatile, economical, and easy to use."[4]

However, such scaffolds suit mostly residential or other kinds of symmetrical construction where a single configuration would be repeatedly used. Framed scaffolds are also used in industrial projects depending on the type of situation as they are far easier to construct and take down than a normal tube and clamp scaffold which in turn saves considerable resources.Figure 2-4 shows a typical framed configuration and Figure 2-5 shows different types of frames used.[2]

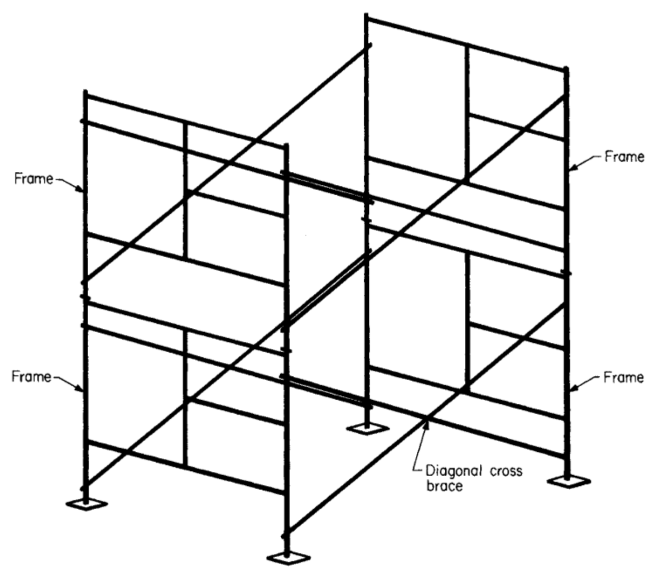


Figure 2-4 Typical framed configuration

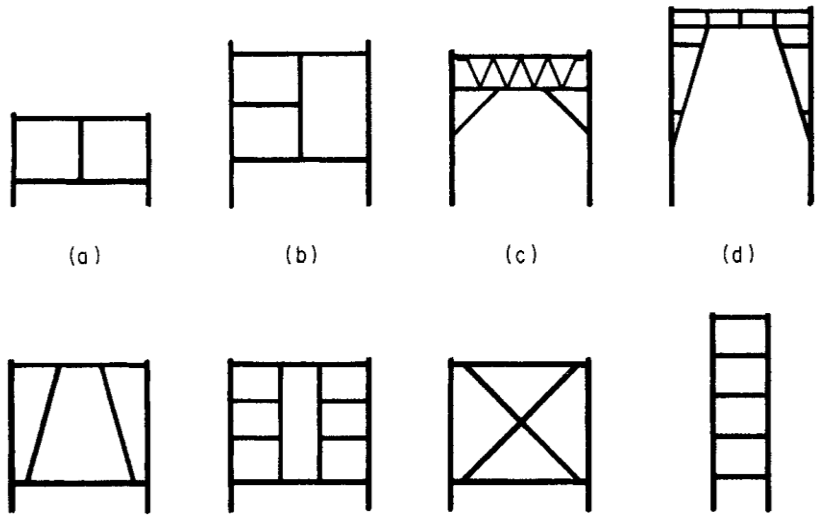


Figure 2-5 Different types of frames

Mobile scaffolds:

> "Mobile scaffolds are a type of supported scaffold set on wheels or casters. They are designed to be easily moved and are commonly used for things like painting and plastering, where workers must frequently change position."[4]

Figure 2-6shows a mobile scaffold. [4]

Figure 2-6 Mobile scaffold

Systems scaffold: Systems scaffold or all around scaffolds can be applied to a wide variety of rectangular, dome or circular configurations. [5]. They are not as adjustable as a tube and clamp; however, they are comparatively quicker to set up and take down. Figure 2-7 shows a typical system scaffold.[5]

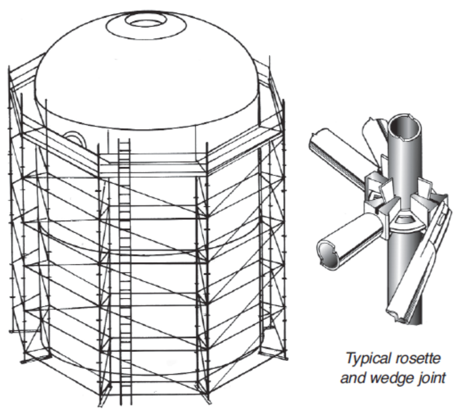


Figure 2-7 System scaffold

Dance floors: These types of scaffolds are very common in industrial construction projects and commonly used in scenarios when the ceiling of the structure has to be accessed by different trades. This allows the trades to stand on the platform and work around the modules. These types of platforms are normally supported by steel beams for support and strength.

Figure 2-8 Dance floor scaffold in PCL Modular Yard

2.1.1.2 Suspended Scaffolds

> "Suspended scaffolds are platforms suspended by ropes, or other non-rigid means, from an overhead structure."[4]

Some of the most common suspended scaffolds are described below.

The most common suspended scaffolds are the following:

Two point adjustable scaffold: The most common type of suspended scaffolding is the two point adjustable scaffold.

> "Planked platforms are supported at both end by ropes and suspended from an overhead anchorage."[2]

They are mostly used in jobs like shipbuilding, painting, window cleaning etc. They are not commonly used industrial construction projects as most structures are erected from ground elevation and the conditions are asymmetrical in most cases. Figure 2-9 shows a typical two point adjustable scaffold configuration.[2]

Figure 2-9 Two point adjustable scaffold

2.1.1.3 Miscellaneous Scaffolds

Pre-fabricated access systems like scissor lifts or hydraulic lifts are used in situations which require workers to work at small elevations for a small time and with fewer tools. They are mobile in nature and are used depending on the work at hand. They are not very common in industrial construction sites as most construction activities require access points for large amounts of time and are at higher elevations.Figure 2-10 shows an example of a scissor lift in construction [29].

Figure 2-10 A scissor lift

2.1.2 Construction Sequence of a Simple Scaffold System

All scaffolds are constructed in different ways but common points of impact like having a sound base, alignment of elements etc. remain the same. The following figure shows the erection process of a simple system scaffold.[5]

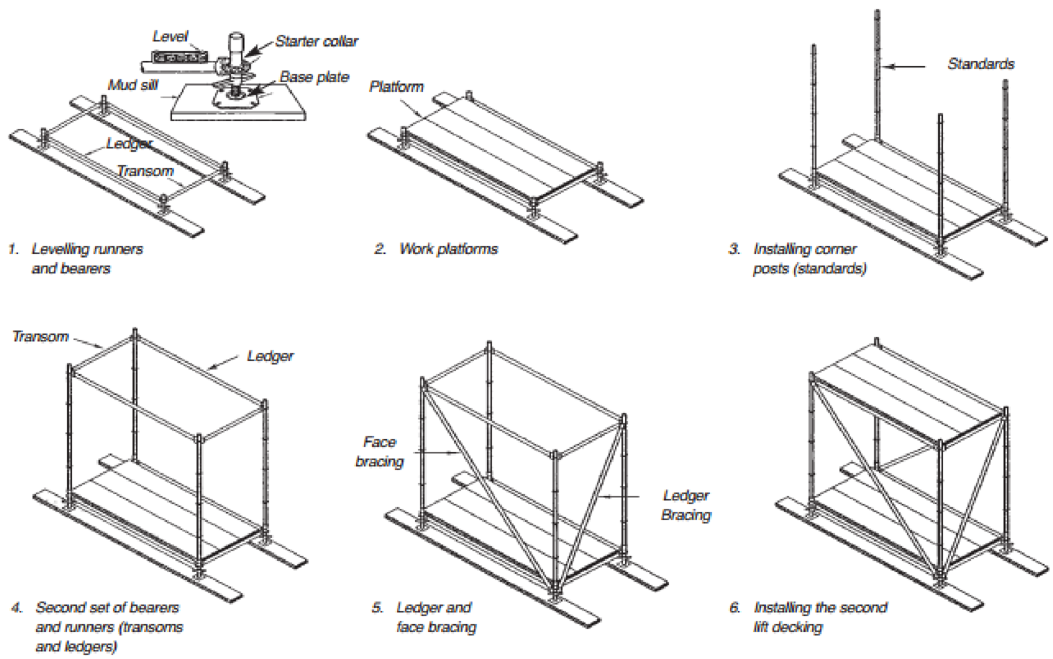


Figure 2-11 Erection process of a simple system scaffold

2.2 Industrial Construction

> "Industrial construction includes a wide range of construction projects essential to our utilities and to basic industries, such as petroleum refineries, petrochemical plants, nuclear power plants, and off shore oil and gas production facilities."[6]

Industrial construction differs considerably from residential construction owing to its asymmetrical construction scenarios. On-site construction processes would include installation of modules, vessels, equipment, piping etc. which all require a different set of trades and resources for completion. Consequently, most scaffolds to be built are also situation dependent in industrial construction sites.

Wang [6] talks about the assembly of modules in a modular yard before they are transported to the site for final installation. In most cases the modules are not erected by the same Engineers who designed them, and that leads to certain level of uncertainty in the requirement of scaffoldson site for the connection and other purposes of the said module. Figure 2-12 shows part of a PCL Industrial site and the scaffolding components.

Figure 2-12 Scaffold in industrial site

2.2.1 Need for Planning and Estimation of Industrial Scaffolding

The first topic to discoverat this particular point is the need of planning and maintaining information about scaffolding. Geoff Ryan [7] explains the importance of an effective management system for scaffolding in the following points:

- Avoiding delays of crews due to absence of scaffolding materials or even man-power.
- Scaffold utilization projections and availability of scaffold data to justify in management meetings the cost of scaffolds.
- Information to project management teams and owners who constantly want to be in loop of effective management of resources.

To date, scaffolding has not been a major research focus in the field of construction engineering and management, perhaps because a revolutionary change in this field is highly unlikely. Variations in scaffold construction methodologies are often limited to small alterations in construction methods or the type of materials used. Existing literature mostly deals in the structural aspects of scaffold construction: mostly specific scenarios, but some research does explore construction and planning aspects. Planning of scaffolding is to be considered equally important and necessary as planning permanent construction works for anyproject, particularly to understand the resource requirements and to avoid work space conflicts, which can lead to decreased productivity[8]. Space management is an integral part of building construction and involves three major steps—site layout planning, path planning and space scheduling[8]. The same holds true when an industrial construction site is being planned. The amount of materials, location of materials, and man-power resources on site are to be planned accordingly in advanced for both direct and indirect works like scaffolds to avoid any space conflicts and lead to efficient and productive site.

Scaffolding materials and manpower consume a considerable portion of the total resources used in an industrial construction site. Some research discusses site layout planning with scaffolding materials and facilities as an integral part of such an analysis[9]. This is only possible if a detailed estimation mechanism exists for calculating the scaffolding requirements at a more detailed level. Feuffel and Hanley[10]explain the Work Face Planning model developed by Construction Owners Association of Alberta (COAA), and the need to assign responsibility for coordination and planning of scaffolding and other temporary works. All major works on a site are actually directlydependent on the effective planning and erection/dismantling of scaffolds associated with themas the access points are required for workers to perform the jobs. Hence, any delays in scaffolding directly affect the performance of the projects and so every work package model or planning mechanism developed for industrial construction should contain scaffoldingas an integral component [10]. Some papers discuss the planning mechanism for temporary structures, primarily scaffolds, for building construction using Building Information Modeling (BIM) [11]. Building construction however is comparatively less situation dependent and more symmetrical than industrial construction, but useful information can be gathered from the paper and can be made relevant to the present research. The symmetrical configuration and repetitive process in most residential and building construction scenarios makes it comparatively easier to plan and estimate scaffolding as the project scope is known beforehand. The objective is to address the safety perspective of planning of temporary structures in building construction but the idea of a CAD model and visualization of temporary structures like scaffolds is extremely useful for industrial as well[11]. Figure 2-13 explains the usage of BIM in risk assessment.[11]

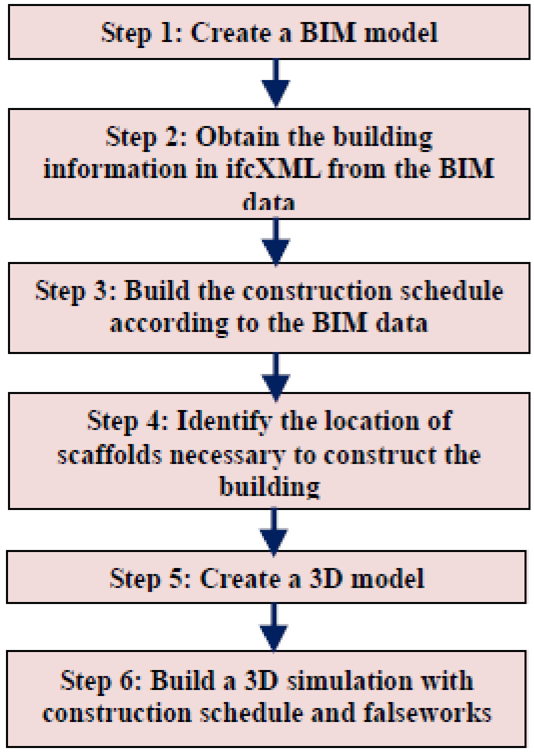


Figure 2-13 Risk assessment process using BIM

Step 4 of the risk model shown in Figure 2-13is the critical part and as explained before cannot at present follow a perfect algorithm in the case of industrial construction. The idea for a 3D simulation, however, is also very appealing for any further industrial scaffold research. While this thesis does not cover 3D visualizations, it does deal with automatic extraction of related data from Navisworks models of the construction project. This willbe explained in detail in Chapter 4.

Figure 2-14 represents a conceptual outlook on the selection of temporary structures in residential construction. [12]

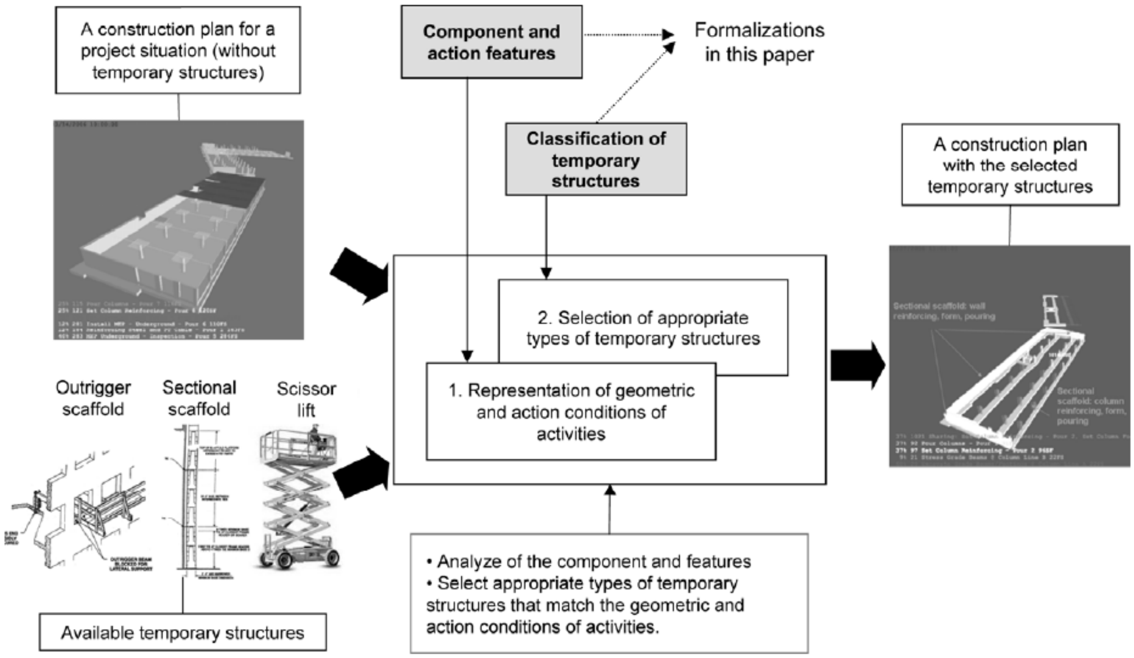


Figure 2-14The role of formal representation of features and classification of temporary structures for selecting temporary structures

Use of a particular kind of scaffolding system varies not only from project to project, but also depends on the availability of labor and materials, which varies in different places. Kim and Fischer[12] present a heuristic approach to predict the type of scaffolding system for a particular kind of construction work. As discussed above, temporary structures like scaffolding can lead to space conflicts, and the same can happen for time conflicts as well.

> "Hence, there are often tradeoffs between providing the perfect temporary structure for each activity and the number of different types of temporary structures needed, the total amount of temporary structures needed, and the duration a temporary structure is up in an area."[12]

From the analysis of different construction projects,Kim and Fischer[12] conclude that to select the appropriate temporary structures for a given job condition, the geometrical parameters of the construction work at hand play acritical role. That statement formed the basis of direction of this research work as well. Various interviews have been conducted with experienced personnel in Company A and Company B[1], who have been dealing with planning and construction of scaffolding in industrial construction for a long time,and they all agree that the geometry of the structure is the driving force towards the need of scaffolding for that module or equipment. The geometric and action conditions of the job are explicitly represented and computer simulation is used to identify and select the type of scaffolding that best suits the needs [12]. Type of scaffolding is not a major concern in an industrial construction site as the type of materials is more or less always consistent.Some research explains an innovative system used for scaffolding operations for high rise construction and its cost comparison with a traditional scaffold system[13]. As explained before, such analysis does not benefit industrial construction as different structures have different configurations and have to be dealt with accordingly. Hence, a particular innovative system might not work out over the phase of the project.Combinations of important configurations like tube and clamp, system, dance floors etc. are used to satisfy the requirements of a particular job. However, geometry of the structure to be installed relates directly to amount of scaffolding resources required for that particular equipment. Figure 2-14 demonstrates the modeling mechanism used by authors in [12] to predict the type of scaffold to be used for a building construction project.

> "Design and schedule changes in a construction project often require re-planning temporary structures to fit the changed geometric and action conditions."[12]

[1]The actual names have been removed for confidentiality reasons and notations are consistent throughout the thesis.

This sparks the need of a CAD dependent simulation model that would take in minimum inputs and predict the new scaffolding requirements.

The estimation and planning process of scaffolding in industrial construction is affected by many variables. Industrial construction has an ever-changing nature, and scenarios change on a day-to-day basis; hence, accurate prediction of scaffold needs before the start of a project is difficult. Based on discussions with various people in the industry over the course of my research, it can be concluded that involving the Construction Engineer and Scaffold Superintendent in the estimation and planning process at the bidding stage optimizes the process. Fedock[14] emphasizes the importance of involving Construction Engineers in the design process of temporary structures. The early involvement of Construction Engineers in the design process would benefit the constructability scenarios of the equipment minimizing the requirement of temporary works during theactual installation processes. One of the main ideas that comes up regularly in this regard is the use of permanently attached scaffold platforms to the modules, vessels etc. which would be attached to the module etc. during assembly itself. The four step approach for project execution incorporates construction technology into specific project execution and for the development of historical data for future projects [14]:

1. As early as possible in the project, influence the material supply with regard to the size and configuration of shipping assemblies, the number of shipping assemblies and the sequence of transport.
2. Planning of the construction process to identify the methods, techniques, man power resources etc.

3. Upon the end of the project, auditing the methods, equipment etc. used in the projects and the consequences.
4. Develop a list of construction standards and processes based on the evaluation from the third step.

The Construction Engineer plays an important role in the implementation of this approach and early involvement would ensurethat construction drawings and calculations related to not only direct work, but temporary structures like scaffolds are present before the start of the work to ensure a safe and productive work scenario[14]. Hence, it generates a need for an effective yet simple estimation tool for detailed estimation of industrial construction activities.

2.3 Existing Estimating Procedures

Scaffolding is in most cases considered a part of indirect costs of the projects and in estimating scenarios is categorized under indirect work. Authors [15] indicate Scaffolding to be one of the major indirect costs in construction. Upon discussions with estimators in Company A[2], it was found that scaffolding could consume upto 30% of the total man-hours in a project and since labour is the most costly entity in any construction project, it contributes significantly in the overall cost of the project. Hence, accurately predicting scaffolding requirements is necessary for effective project management, but estimating industrial construction scaffolding is a complicated process owing to complexity and variety of the construction work areas. Also the type and detail of estimate depends on the time of the project the estimate is

[2]Actual Name has been removed for confidentiality reasons and the notations are consistent throughout the thesis.

made to accomplish. Most industries now are more dependent on experience than tools for estimating industrial scaffolding.

> "Experience and knowledge usually reside with the estimator, who in some cases may not have a proper understanding of the work, may not be able to identify the controlling factors influencing productivity, or may not be able to correctly quantify the influence of these factors."[16]

Company A employs a percentage of direct work to estimate the scaffold requirements. These percentages are based on general trends from past data, simple parameters like general elevation of the whole project, a degree of overall complexity etc. However, they are extremely raw in nature and do not deal with equipment at a detailed level. Figure 2-15[17] and Figure 2-16[18]represent sections from handbooks for industrial construction that help in estimating patented scaffolding. Some existing industrial scaffolding techniques are described below.

MANHOURS PER SECTION

Length	One or Two Sections High			More than Two Sections High		
	Erect	Dismantle	Total	Erect	Dismantle	Total
One to two sections long	1.4	1.0	2.4	1.7	1.2	2.9
Three to five sections long	0.9	0.6	1.5	1.0	0.7	1.7
Six or more sections long	0.7	0.4	1.1	0.9	0.5	1.4

Patent tubular steel scaffolding consisting of sections 7-ft. long x 5-ft. wide x 5-ft. high with 2-in. planking top.

Manhours include handling and hauling scaffolding and materials from and to storage, erection, leveling, securing and dismantling of scaffolding and scaffolding materials.

Figure 2-15 Estimate patent scaffolding

TABLE 4-4. Scaffolding, Runways, and Ramps

Work Element Description	Unit	Man-Hours Per Unit
Erect and Dismantle Tubular Scaffold (including Planks and Leveling)	1,000 SF of Wall Surface	40
Construct Runways and Ramps	1,000 SF	64
Place and Remove (runways and ramps)	100 Lin. Ft.	16

SUGGESTED CREW SIZE:
Scaffolding Erection: three to four BUs, increase crew size for multiple tiers.

NOTE: 1. The first tier requires more time due to leveling and alignment procedures.

Figure 2-16 Estimate tubular scaffolding based on wall surface area

While Figure 2-15 and Figure 2-16would be able to predict scaffolding requirements, theyare limited to certain types and projects. Also, they are too generic to be able to meet the complexity of industrial projects. Another estimating manual that comes close to being an ideal for predicting scaffolding in industrial construction scenarios is the Technical Calculation and Estimator's Man-Hour Manual[19]. Figure 2-17 contains all the tables from [19] that help in working out an estimate for scaffolding in industrial projects. The volume of scaffolding can be calculated by the procedure laid out in Chapter IX [19]. Based on the estimating principles the author has predicted man-hours of work, materials required etc. as a factor of volume of scaffolding, which in turn is a factor of the weight of the equipment[19]. While this is an interesting concept, any logical explanation for such correlation with weight of the equipment seems unreliable. Also, the author fails to mention details of the type, location and other details of the projects on which he has based the values which are shown in Figure 2-17[3]. Weight can be one important factor; however, scaffolding is more dependent on the geometrical configuration of the equipment and this would become evident from the results in Chapter 5.

4. EQUIPMENT SCAFFOLDING

4.1 Tubular scaffold (for each piece of equipment separately)

	to 10 m^3	10 : 50 m^3	50 : 100 m^3	100 : 500 m^3	500 : 1000 m^3	above 1000 m^3
Scaffold erection [Mhr/m^3] or [Mhr/m^2]						
Scaffold dismantling [Mhr/m^3] or [Mhr/m^2]						
Total						

Elevation factor at which the scaffold is erected or dismantled:

0 : 5 m	
5 : 10 m	
10 : 15 m	
15 : 20 m	
20 : 25 m	
25 : 30 m	
above 30 m	

kg/Mhr x 2,2046 = lbs/Mhr
kg/m^2 x 0,2048 = lbs/sqft
Mhr/m^2 x 0,0929 = Mhr/sqft
Mhr/m^3 x 0,02831 = Mhr/cuft
m^3 x 35,32 = cuft

4.2 Patent Scaffolding

Sections:

Length :	7 feet; 2,1 m
Width :	5 feet; 1,5 m
Height :	5 feet; 1,5 m

Length	Manhours per section					
	One or Two Sections High			More Than Two Sections High		
	Erection	Dismantling	Total	Erection	Dismantling	Total
One to Two Sections Long						
Three to Five Sections Long						
Six and More Sections Long						

Figure 2-17 Man-hour calculation for scaffold erection and dismantling

[3] Values are removed as the document is not free to be used.

Software programs like BrandNet, Scafflogicetc. are proprietary systems either developed inherently by a core scaffolding company or available in market to be purchased. These systems, however, are very complicated in nature and need more expertise to understand and operate. Also, they might involve modeling the structure itself on the software which would make the task time consuming. These systems, though useful, are mostly beneficial when someone is explaining how the scaffolding works for a construction scenario and soon gets clogged if many systems are analyzed together[7]. Also, the internal working principles and logic behind an output are not available, which would hinder any academic use or further development in the field of research.

2.4 Scaffold Data Maintenance

This section is derived from past research [7].As explained earlier, planning scaffolding is very important. One integral part of such planning procedures is keeping track of scaffolding requirements to adjust to new scenarios which might arise in future and to check the firm execution of the planned schedule. The following flow chart describes the workface planning model for scaffold tracking:

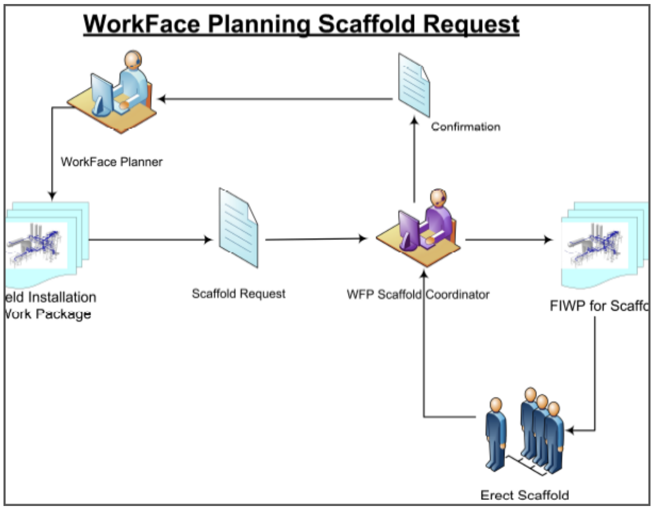


Figure 2-18 Work face planning scaffold request

A scaffold database is not a new concept, but maintaining consistency in data recorded on site is a difficult task especially for indirect works like scaffolding. The best methodin thesescenarios is to link the scaffold works to their FIWP's (Field Installation Work Package). FIWPs exist for all direct work, and as scaffolds are erected to facilitate direct work, they can be linked to respective FIWPs. The ideal scaffold database for workface planning according to the author is depicted in Figure 2-19.

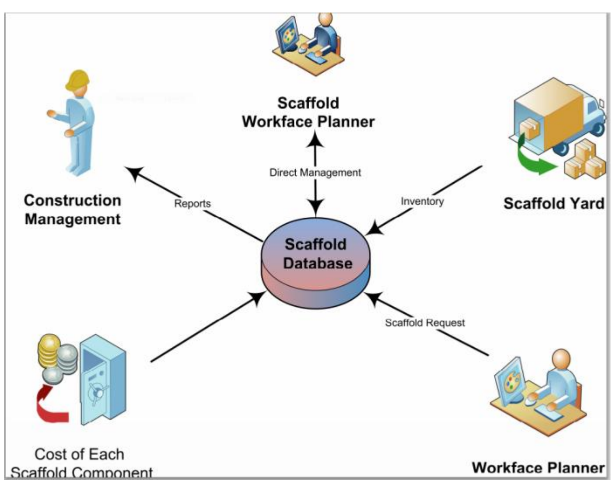


Figure 2-19 Ideal scaffold database

An efficient scaffold management system is an industryneed, and the present research is a stepping stone towards the objective at hand. The author explains the need of integration of 3D models with scaffold management for estimation, planning and visualization. While this research does not cover the scope of visualization, it does implement linkage between Navisworks 3D model and a simulation platform, which in turn present the output needs of a particular project.

2.5 Codes and Standards

Various codes and guidelines exist that govern the erection, dismantling and working scenarios of scaffolds in construction projects. These codes do not specify the type of construction like residential or industrial etc. for which the scaffold is being used; rather, they deal with loading scenarios and stability of construction. The following table shows a list of some of the international and regional codes that drive the scaffold design and construction process:

Table 2-1 Codes and standards

CSA (Canadian Standards Association)	• S269.1 – 1975 – False work for construction Purposes • CAN/CSA – S269.2 – M87 – Access Scaffolding for Construction Purposes
OSHA (Occupational Safety and Health Association)	• http://www.osha.gov/SLTC/scaffolding/index.html
IHSA(Infrastructure Health and Safety Association)	• http://www.ihsa.ca/resources/health_safety_manual/pdfs/equipment/Scaffolds.pdf
SSFI (Scaffolding, Shoring and Forming Institute) Inc.	• http://www.ssfi.org/resources/scaffolding/safe_practices_guide/Scaffold%20Code%20of%20Safe%20Practice%20Web%208-01.pdf
AS (Australian Standards)	• AS 1576 – Scaffolding
OH&S (Occupational Health and Safety	• http://www.humanservices.alberta.ca/documents/WHS-LEG_ohsc_p23.pdf

Code),Alberta, 2009	• http://www.humanservices.alberta.ca/documents/WHS-LEG_ohsc_p01.pdf

In addition to these codes, various guidelines are also compiled by companies that satisfy the guidelines from the codes as well as take into consideration the company's working principles and methodologies.

2.6 Parametric Estimation

As described above in estimating procedures, prediction of scaffolding requirements is based on a set of functional relationships with affecting factors. Based on discussions held with the Project Manager, Construction Manager, Chief Estimator and Civil Superintendent in Company A, some of most relevant factors or parameters and their importance in industrial construction are:

Table 2-2 Factors affecting scaffold estimation

FACTOR	IMPORTANCE LEVEL (Low, Medium and High)
Weather	Medium
Elevation of Construction of Scaffold	High
Manpower Availability	High
Trade Hours of Work expected on Scaffold	High
Trades to work on the constructed Scaffold	Medium
Type and Complexity of Construction Work Area	Medium
Availability of Materials	High
Type of Scaffold	Low
Experience of Labor	Medium

Geometry of Equipment to be erected	High
Weight of Equipment	Medium
Location of Scaffold Material Storage Area	High

For the purpose of this research work, the parameters chosen to develop the linear regression model of scaffold estimation are not totally data driven, but based on logical conclusions as well. Also, factors like distance to the storage yard are not taken into consideration, the materials are assumed to be on site when needed and the labor maintains a minimum level of experience necessary.The factors or parameters used, their uncertainties and the relationships are described in Chapter 4.

2.7 Simphony 4.0

Simulation is an effective technique in planning and estimating construction processes, and hence, the use of a Special Purpose Simulation Platform was used. Simphony 4.0 is an indigenously developed Simulation Platform developed within the Construction Research Group in University of Alberta, Canada.

> "Simphony is a Microsoft Windows based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of construction SPS (Special Purpose Simulation) tools."[20]

Since its development, Simphony has grown and improved to accommodate new features of modeling and simulation. Various Special Purpose Simulation templates have been developed over the years on this platform modeling important construction processes like tunneling, earthmoving operations, reclamation projects, etc. This research is intended to add a scaffolding template to the list which could be easily used by companies for estimating scaffolding for industrial projects. Figure 2-20 shows the development process of a Special Purpose Simulation template[21]. The details of the simulation model are found in Chapter 5.

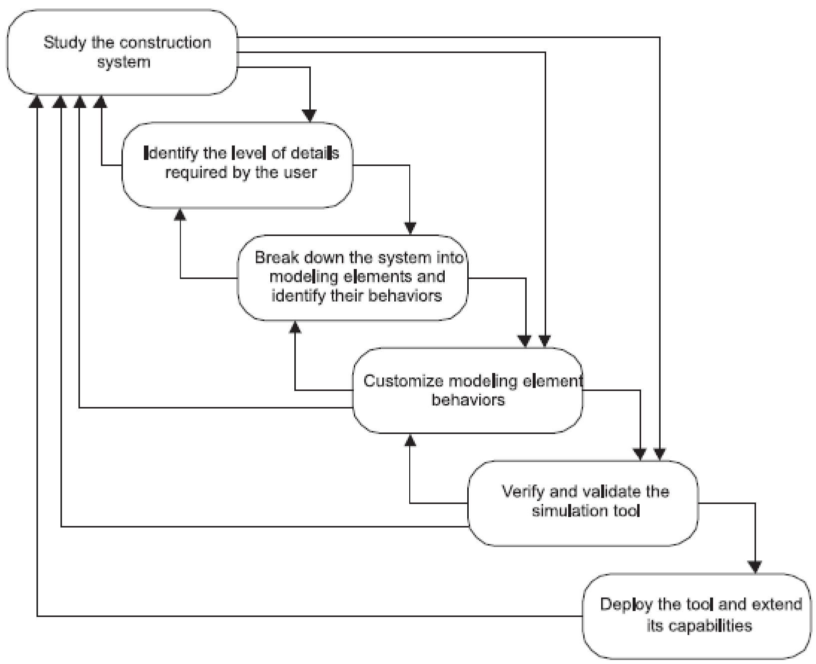


Figure 2-20 Special purpose simulation tool development model

2.8 API

API stands for application programming interface.

> "An API can provide a hook for colleagues, partners, or third-party developers to access data and services to build applications such as iPhone® apps quickly."[22]

Autodesk products offer users the unique chance code API's that act as an Add-In to the software like AutoCAD® or Navisworks® which are intended to perform a specific function that in totality is missing from the existing version of the software. These codes can be written in .NET coding frameworks like C# or Visual Basic and be added to the software as an external Add-In.

This research utilizes this opportunity to code an API in Navisworks 2011 to perform certain requisites of the research methodology and provide desired outputs. The details of the API, and its functionality, are explained in detail in Chapter 4.

2.9 Mathematical Modeling Techniques—Linear Regression

> "Regression analysis is the method to discover the relationship between one or more response variables (also called dependent variables, explained variables, predicted variables, or regressands, usually denoted by y) and the predictors (also called independent variables, explanatory variables, control variables, or regressors, usually denoted by x1; x2;…; xp). Linear regression requires that model is linear in regression parameters."[23]

There are three types of regression models [23] –

1) Simple linear regression – This models the linear relationship between two variables. There is one dependent variable and one independent variable.

$$y = \alpha 0 + \alpha 1(x) + \varepsilon$$

2) Multiple linear regression – This is used in cases where there is one dependent variable and many independent variables.

"The multiple linear regression assumes that the response variable is a linear function of the model parameters and there are more than one independent variables in the model." [23]

$$y = \alpha0 + \alpha1(x1) + \alpha2(x2) \ldots\ldots \alpha p(xp) + \varepsilon$$

3) Non-linear regression – This is based on the assumption that the relationship between the dependent and independent variables is nonlinear in nature. An example is shown in the equation below.

$$y = \frac{\alpha}{1 + e^{\beta x}} + \varepsilon$$

The use of the regression technique, its attributes and related parameters are described in detail in Chapter 5.

2.10 Gaps in Existing Literature

Existing literature on industrial construction scaffolding is extremely scarce. In fact,scaffolding in general does not seem to be a well-researched area. A number of reasons could attribute for the above conclusions,the first being it is categorized under indirect works and most indirect works have always been kept part as a factor or percentage of direct work involved in a project. Since the major portion of the cost relates to direct work, most researchers tend to investigate topics and processes in direct work. The second reason for sparse literature in this field is the diverse and complicated nature of industrial construction scaffolding. Industrial scaffolds are dynamic both horizontally as well as vertically which makes planning and estimation difficult. Analysis of such scenarios would involve in-depth analysis and a considerable amount of time spent with the chance of success quite less compared to some other fields of study. Most existingliterature concerns the structural aspect of scaffold construction in specific scenarios. These would be specific to a particular requirement and in most cases residential construction where the structure moves only in a vertical direction.

Literature which tackles the problem of effectively planning and estimating industrial scaffolding requirements from the basics doesn't seem to exist,which makes this research one of the foremost attempts. Scaffolds are constructed to facilitate direct work and any improvement in planning them would directly affect the project controls. The need of the industry is an effective planning and estimating tool for scaffold construction in industrial projects which would help in improving productivity and savings in project costs, and this research attempts to begin that process.

Chapter 3 — Scaffold Estimation and Planning

3.1 Need of Scaffold Estimation

Scaffolding in a construction process is required to support the direct work for that process. These are deemed to be of less importance compared to other processes in construction operations. However, based on discussions with Senior Project manager and Estimator in Company A (One of leading contractors in North America), it was found that scaffolding can comprise of up to 30% of the total labor man-hours in an industrial project with 15%-20% being an averaged out number. Labor cost is the most influential in the total project cost and an increase in labor man-hours would increase the total cost of the project. A common problem in scaffolding planning and management is the absence of an easy to use estimating and planning tool that companies can use for a quick and reliable estimate. Also, it is to be noted here that most companies have their own ways of erecting and dismantling scaffolds, hence, such a tool although useful to any company,would have to be customized for a particular company's use based on their historical data and working principles.

A reliable estimate would function as a dependent source for the user based on the purpose it is being used for. Scaffolding for industrial construction is planned in most projects on a day to day or weekly basis, and the Scaffold Superintendent is responsible for the assignment of labor and materials for scaffold erection and dismantling. Now, these Superintendents are basically dependent on their experience for estimating the amount of man-hours or materials to assign for the construction of scaffolds. The system lacks a quick and reliable tool that would be able to help the Superintendent with the process, and thus, would help in better management of labor and material resources. Another point of time where a more accurate estimate of scaffolding is important is during the bidding stage of the project. The bidding stage requires a close to reality estimate of all processes in the construction of the whole project. A deviation at the bidding stage of the project would lead to difficulties in the actual completion of the job. Based on discussions with the Estimator in Company A, it was found that most companies put scaffolding requirements as a percentage of direct work for a particular project. This number is often far from what actually happens after the completion of the project, and hence, they would need a better planning and estimating mechanism for scaffolding predictions.

3.2 Levels of Estimation

As explained earlier,the type of estimate dependson what stage of the project it serves the purpose for. Also, the type and number of affecting input factors would vary for different levels of estimate. Based on such scenarios, a scaffolding estimate can be divided into two levels:

- MICRO ESTIMATION
- MACRO ESTIMATION

These are explained in detail in the following sections.

3.2.1 MACRO Estimate

This is a higher level process of scaffold requirement estimation. A MACRO estimate would be able to predict the amount of man-hours and/or material requirements with a minimal amount of input data. This estimate would be able to serve as a handy tool at the bidding stage or initial planning stage of the project. At this stage of the project a lot of project requirements are variables or uncertain. Most companies estimate scaffolding at this stage as a function of direct work hours that would be put into the execution of the job. These direct work hours are derived from historical data of related works or projects performed by the company. While this does seem to be an effective technique for estimation, there are considerable anomalies in the process. This process fails to address other affecting factors when calculating scaffold needs. These factors can be as simple as weather conditions or labor experience. These factors, when taken into account, would help the estimators in a more detailed and realistic estimate. Table 2-2in Chapter 2 shows all the affecting factors for scaffold estimation. The following factors would serve important at a MACRO level of estimation –

Table 3-1MACROestimation affecting factors

FACTOR	IMPORTANCE LEVEL (Low, Medium and High)
Weather	Medium
Average Elevation of Site	High
Trade Hours of Work expected on Scaffold	High
Trades to work on the constructed Scaffold	Medium
Type and Complexity of Construction Work Area	Medium
Average Distance to Material Yard	High

The process behind forming a MACRO estimation tool would largely depend on performing a series of data mining experiments on existing company data and would need to done at a company level. For some companies there might be one factor which is more important than the others, and hence,Table 3-1can vary for them. There might be other factors like labor experience that can be an important parameter for one company, butnot so much for others. The following algorithm explains an estimation tool development process for MACRO level of estimation:

- Gathering Project Data –The first step in development of such a tool is to collect the maximum amount of historical data from a company. The more the amount of data, the better and accurate relationships can be predicted.
- Organizing Project Data – the next step is the proper organization of gathered data in an understandable and useful manner. This would involve deletion of noise in data, tabulating relevant parameters and maintaining common nomenclature between different project data. Here, it is to be stressed that most companies do maintain the same style of naming their job operations for different projects, but there can be project related naming procedures. It is of utmost importance that data from different projects be consolidated into one set of input parameters to get a more accurate and dependable model.
- Selection of Affecting Parameters – After the data has been organized in a clear and understandable manner, free from errors, relevant input factors have to be selected. The list of input factors is as shown in Table 3-1MACROestimation affecting factors but can have additions or deletions depending on a particular company.
- Performing Data Mining Experiments – The tabulated data is then used for performing various data mining experiments to predict scaffold man-hours or material requirements as a function of these affecting factors. They are called

experiments because different options are exhausted to predict the best and most reliable model for estimating scaffolding. These analyses would involve changes in:

1. The software used for experiments like WEKA, MATLAB etc.
2. Ways to perform data mining analysis like Linear Regression, Neural Networks etc.
3. Identification of input factors that most and least affect the final estimate and their importance to the final estimated value.

- Generation of Estimating Mechanism – The final step is to generate an estimating tool that is easy to understand and use for any person in the company. Microsoft Excel is the software most companies are familiar with and such simple software can be used as a medium to produce the tool. Also, the outputs generated should make sense to the user and be in the units or manner that is most suitable and generally accepted in the company. The estimating tool developed in this research work would include MACRO level of estimation. The relationships, and experiments performed for MACRO estimation are, however, performed by a fellow colleague, Ms. Lingzi Wu and this research only uses the final results obtained by her.

3.2.2 MICRO Estimate

A MICRO level of estimate and the main focus of this thesis is a more detailed level of estimating process to predict scaffold requirements. Now, this thesis would only deal in detail for the estimation of total erection man-hours of work for scaffolding requirements in an industrial construction project. The reason is the unavailability of data concerning material estimation for scaffolding construction; thus, this part has been kept outside the scope of research at this point of time. That being said, a way to collect relevant data for material estimation is shown as a part of Scaffold Data collection form in the thesis.

A MICRO level of estimation would imply all estimation processes that would deal with equipment, modules, vessels etc. at an in depth level of analysis. Estimation of amount of man-hours or materials to be reserved or put in for construction of scaffold required in erection of a module or vessel etc. is generally done by the Scaffold Superintendent on site. She/he performs the estimate based on experience only and general observations made looking at the site and the equipment to be installed. Any error in performing such estimations would yield mismanagement of available resources on site. Also, there can be last minute changes in the structure of the module or vessel, which have to be taken into account when estimating the new scaffold requirements. Hence, this produces the need for a more dependent and easy estimating tool which can be quickly used by Superintendents who may not have sufficient experience in scaffolding too. The same tool can be used to predict total scaffold requirements at the planning stage of the project when relevant structural and geometrical data related to equipment have been finalized. The following factors would determine relationships with scaffolding man-hours of work-

Table 3-2MICROestimation parameters

FACTOR	IMPORTANCE LEVEL (Low, Medium and High)
Type of Structure	High
Elevation of Construction of Scaffold	High
Geometry of Equipment to be erected	High

Weight of Equipment	Medium
Location of Scaffold Material Storage Area	High
Weather	Medium

For the purpose of this research, the effect of weather and location of material storage area is not taken into consideration when performing analysis on the case study. The reason for the same is unavailability of relevant data to incorporate such factors into the estimating model. However, the effects of these factors and how they can be added to determine relationships with scaffold erection man-hoursare explained in detail in the following section.

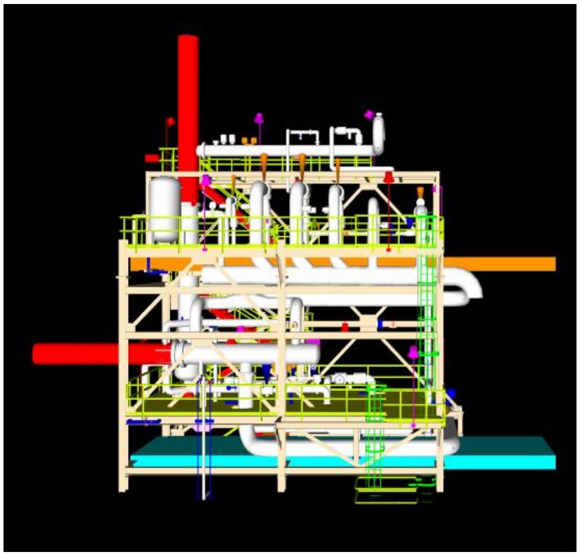
3.2.2.1 MICRO Estimation Factors

The factors for MICRO level of estimation have been decided based on various discussions with the Construction Manager, Scaffold Superintendent (Company A's Modular Yard), Civil Superintendent and Chief Estimator in Company A. Estimation of scaffold requirements is dependent on the geometrical parameters of the module, vessel or equipment to be erected on site. Hence, a particular module should in theory take the same amount of scaffold man-hours for different projects. There is, however, other factors like man-power shortage etc. which can lead to different estimates; however, the effect of such disruptions is outside the scope of this thesis work. The estimating factors are –

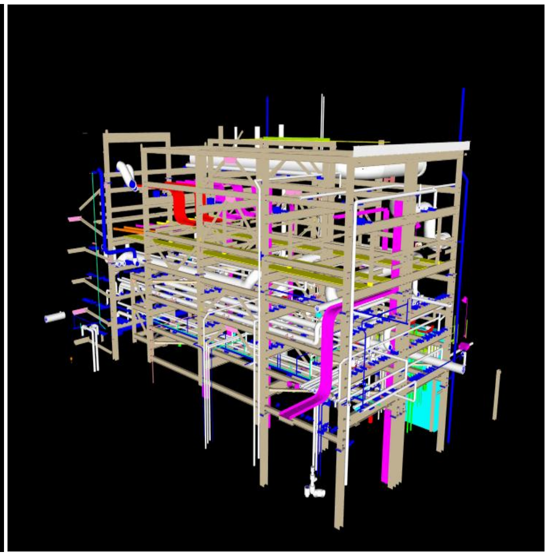
- Type of Structure – All structures to be erected in an industrial construction site can be grouped on higher level within the following –
    1. Processmodules

2. Rack modules
3. Equipment
4. Pre-fabricatedstructure like stair towers
5. Vessel

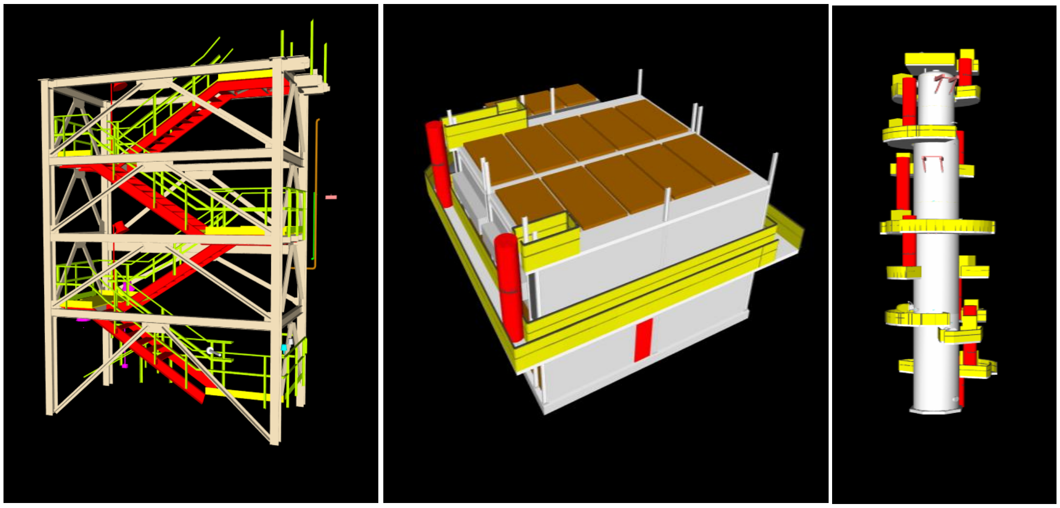
Depending on the type of the project there might be a possibility of adding some types of structure or even breaking one of the above into smaller groups. However, these five accommodate most types of work in industrial sites.Figure 3-1 shows some of the types of structures.



a) Process Module



b) Rack Module



c) Stair structure d) Equipment e) Vessel

Figure 3-1 Type of structures

- Geometry of the Structure –The geometry of the structure comprises of three aspects which define the 3D plane of the structure:
    1. Length of the structure
    2. Width of the structure
    3. Height of the structure

It is to be noted that the three aspects basically define the boundary box around the structure itself to maintain consistency among different forms of structures. For e.g., a Vessel is normally cylindrical structures with parts attached to it, so a bounding box would comprise of the vessel and all its attachments together within the cubical envelope that surrounds it. The units of measurement are also kept consistent throughout to be Metric. One important aspect to notice here is that a module or equipment can be aligned in any way in the site layout and hence, the coordinate axes lines and the three aspects of geometry should be carefully chosen. The length, width is assumed to be the plane of construction while the Z direction determines the height of the structure.

- Elevation of Construction – Elevation of construction represents the height at which the structure is to be erected at the site. This is the total height in metric units from the datum point or reference points of the site to the bottom most point of the structure to be erected or installed. Now, sometimes it is difficult to predict the exact elevation of construction in planning stage or even before the erection process of a structure starts, hence, the elevation of construction could be categorized in intervals if needed. The elevation starts from 0, which is the reference point level and would go up to any meters of height. The intervals can be in range of 5 meters. Hence, the first level of construction would be 0m to 5m, the next 5m to 10m and so on. This enables the user to implement the estimating tool even if some minute details are difficult to obtain.
- Weight of the Equipment – Weight of the equipment may not be one of the obvious parameters that could affect scaffolding, but [19] uses weight as a factor to estimate the volume of scaffold required and consequently the amount of scaffolding required. This, however, has quite a substantial impact on scaffold needs as shown in the Chapter 5.
- Weather Conditions – Weather conditions do affect the erection man-hours of work for scaffolds in construction sites. From the initial project schedule, it can be estimated a time frame in which a particular structure is to be constructed on site and be categorized into winter or summer conditions. According to the

construction manager in Company A, November 15th to March 15th is considered as winter conditions and the rest of the year as summer conditions.

- Distance to Scaffold Yard – This could also be a factor in the total amount taken for the construction of a scaffold. A larger distance would yield lesser productivity of scaffold workers and can lead to work delays. However, in most projects, this is always taken care of and analyzed before the storage yard is decided. For the purpose of this research this aspect is not taken into consideration and is based on the assumption that the materials are available on site when the scaffold construction has to start.

3.2.2.2 MICRO Estimation Model

The parameters that affect scaffolding have been selected based on logical reasons and discussions with highly experienced personnel in Company A and Company B. However, the levels of dependence of these parameters have to be estimated based on evaluating data mining relationships with scaffold erection man-hours of work. These relationships can be based on experience of the Scaffold Superintendents, analyzing structures and their points of importance that determine their scaffolding needs or using historical data. The processes are explained in detail below:

- Scaffold Superintendent Experience– A set of questions can be prepared and handed over to a selection of a set of Scaffold and Civil Superintendents who deal with scaffolding on a day to day basis to quantify their experience. Questions should be designed in a way which would be convertible to numerical or logical set of conclusions. One way of setting up such questionnaire would be to set up options for questions for the Superintendent to select instead of typing sentences which would be harder to quantify and generalize.

- Analyzing Structures – This is a more structural and time consuming analysis technique for determining relationships of affecting factors with scaffold man-hours. The process of conducting such an analysis would involve the researcher to be involved in the construction and planning of the project from the start of the project and be available on site constantly to record data. The level of accuracy generated from such analysis would be excellent; however, the whole process is time consuming and needs dedicated personnel to perform. The researcher would have to study and consistently keep records of –

    1. The triggers that affect scaffolding for a particular type of structure to be erected on site.
    2. The points of impact for scaffold needs on an erected structure.
    3. The common operations of trade work and their working hours that is needed to complete all scaffold needs on a structure.
    4. The effect of surrounding structures and existing scaffolds nearby on construction of new scaffold.
    5. The amount of repetition of scaffold construction in the same location over the course of the project.
    6. The amount of man-hours of work and quantity of materials used for supporting the scaffold needs of the erected structure.

Based on this process, a more detailed and accurate relationship model can be determined for predicting scaffold requirements. Another important constituent of such analysis would be the tracking of scaffold materials used in construction which can be later added as an output for the model. It is also to be noted that such data have to be consistently maintained without gaps and rechecked at regular intervals to maintain accuracy. Also, a suitable nomenclature has to be devised and used to understand the data at any later stage of the project by a user.

- Data Mining Techniques – This is a more company dependent technique and works equally as wellas the other two methods and is comparatively less time consuming when implemented. This is also based on historical data maintained of scaffolding needs of a company on different projects as would be the second method of analyzing structures. But, the relationships in this technique would be dependent on the data already collected by the company and new or other relevant data that might be an essential element in a analysis may be absent from the data available. Also, the authenticity of such existing data must be put under a scanner as there could be gaps during collection processes that people might miss. The case study to implement the principles of this research work is based on this method of analysis. The database available is one of Company A's completed projects called Project 1[4] construction project. The database, its elements and difficulties willbe explained in detail in Chapter 4. The working principle of the estimating tool based on data mining relationships is shown inFigure 3-2.

[4]The name of the project is removed due to confidentiality reasons and is consistent throughout the thesis.

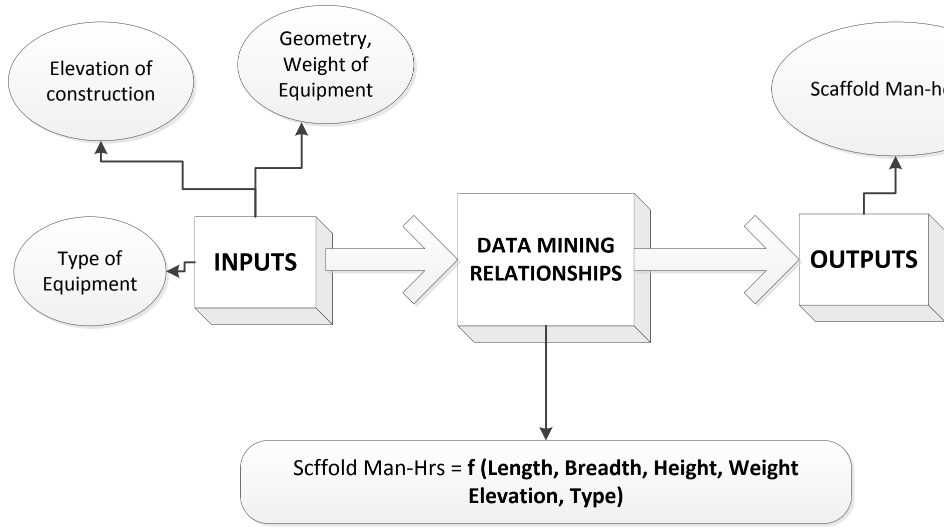


Figure 3-2 Working principle - scaffold estimation tool

These relationships are coded in the form of a simulation template which would be the platform or the tool that would be used by the user to perform such estimating operations. The simulation template is coded in C# programming language in Simphony 4.0 simulation platform, and is explained in detail in Chapter 5.

3.3 Estimated Outputs

The type and nature of outputs is probably the most important aspect of any development. The output has to be clear, understandable and must fulfill the objective of the estimation tool. One of the main objectives of this research is to predict scaffolding man-hours of work at a more detailed level. Also, the nature of construction processes is in most cases not deterministic. The variables like trade hours of work, even geometrical parameters of the structurescan be probabilistic in nature. There are uncertainties associated with these parameters. These uncertainties can be dealt with by using distributions based on Monte Carlo Simulation principles to represent such inputs. Hence, this research enables users to input the values in the simulation tool in the form of probabilistic distributions like uniform, triangular etc. This allows the estimating tool to predict scaffolding man-hours of work in the form of a range estimate which represents the situation realistically. The program provides the output in the form of statistical data based on the number of runs for which the simulation is performed. The program also provides a cumulative distribution curve and histogram of all runs for the selection set generated from the outputs of each run. The program would be able to predict the amount of tubular scaffold required based on numerical relationships provided in [19]. The type, nature and visualization of outputs willbe explained in detail in Chapter 5.

3.4 Scaffold Planning

Planning scaffolds for industrial construction processes on site is quite complex owing to the diverse and asymmetric nature of industrial construction. Most companies perform this kind of analysis of their material or labor requirements on a day to day basis or weekly level. The Trade Foremen request scaffolding for their work on a particular structure to the Scaffold Superintendent and based on their requests, the Superintendent assigns labor and material resources to that particular scaffold. As this is performed on a daily or weekly level (depending on the working methodologies of a company), a look ahead into material requirements or extra crews is difficult to ascertain. To understand the flow of scaffolding process from generation of a request to dismantling of constructed scaffold, a process flow model was designed in Microsoft Visio 2007 IDEF0 modeling format. IDEF0 stands for ICAM Definition for Function Modeling, where ICAM stands for Integrated Computer Aided Manufacturing[24]. The model has been generated for two different companies —Company A and Company B. Personnel associated with scaffold planning in respective companies were consulted in formalization of the process models.Figure 3-3 represents the modeling block of an IDEF0 flowchart.[24]

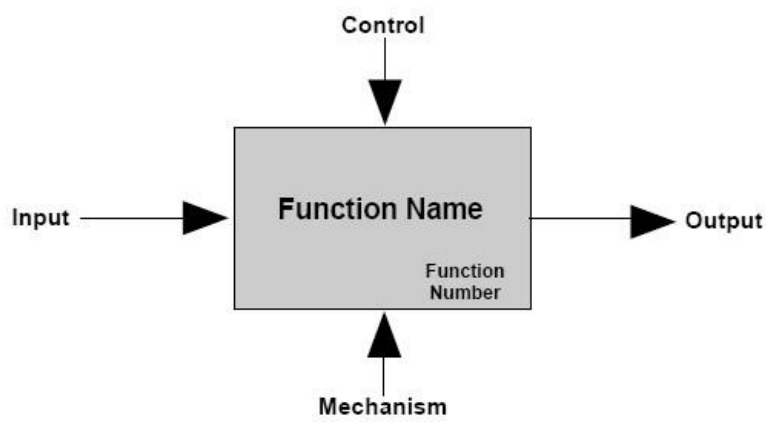
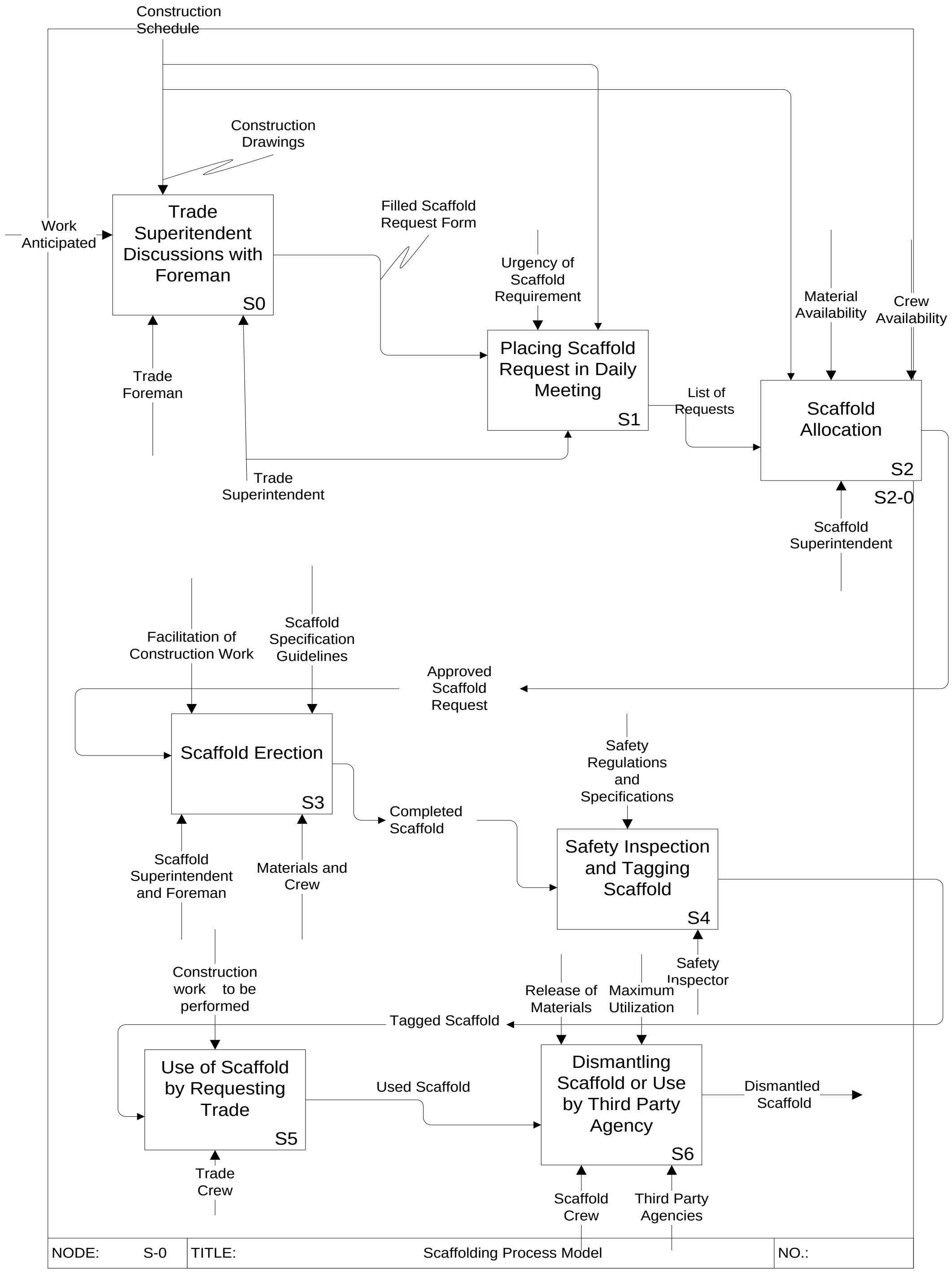
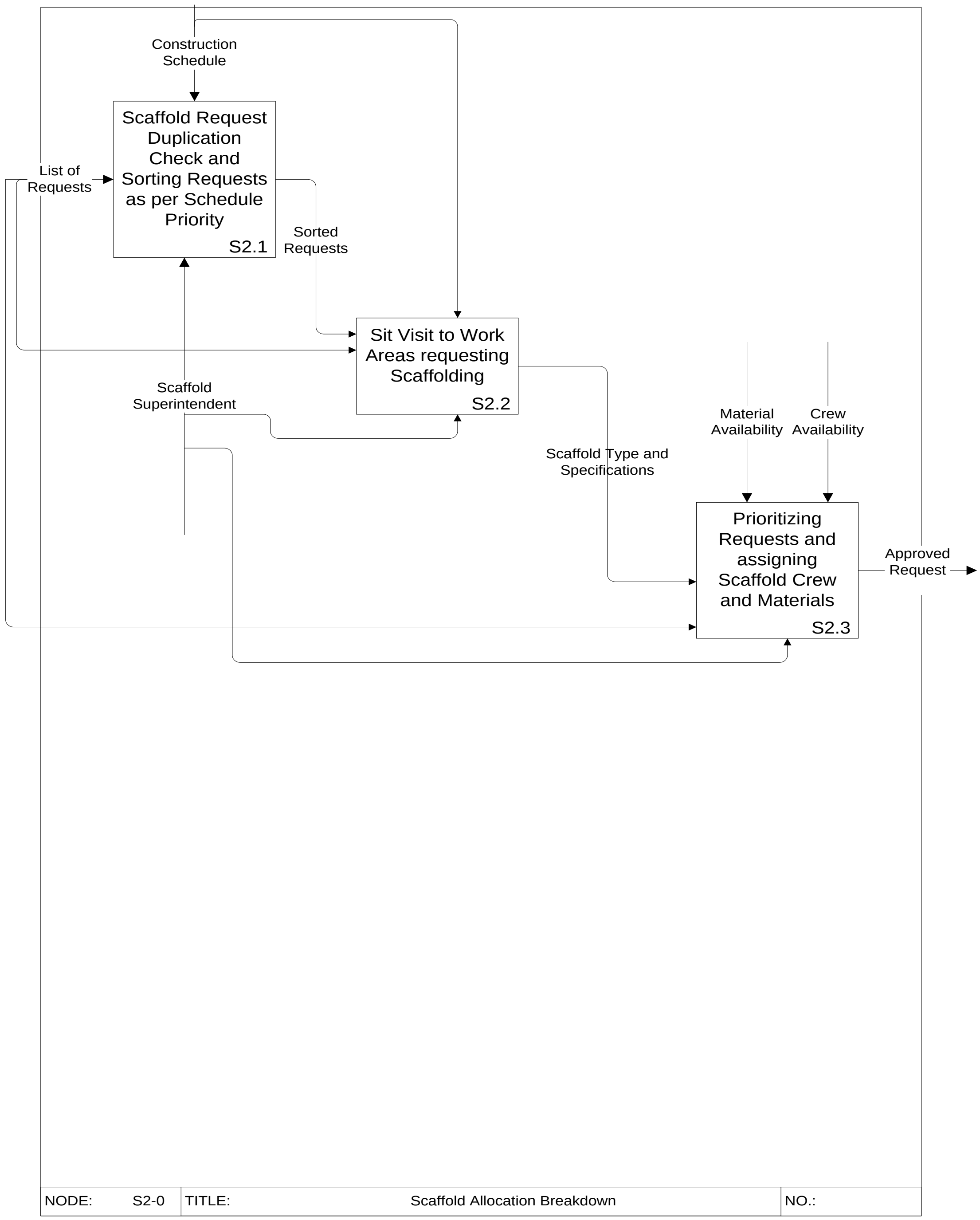


Figure 3-3 IDEF0 modeling box

Figure 3-4 Scaffold process flow model —Shows the IDEF0 scaffold process flow model and the scaffold allocation box sub division and detail for Company A. Figure 3-5represents the corresponding flow diagram for Company B.

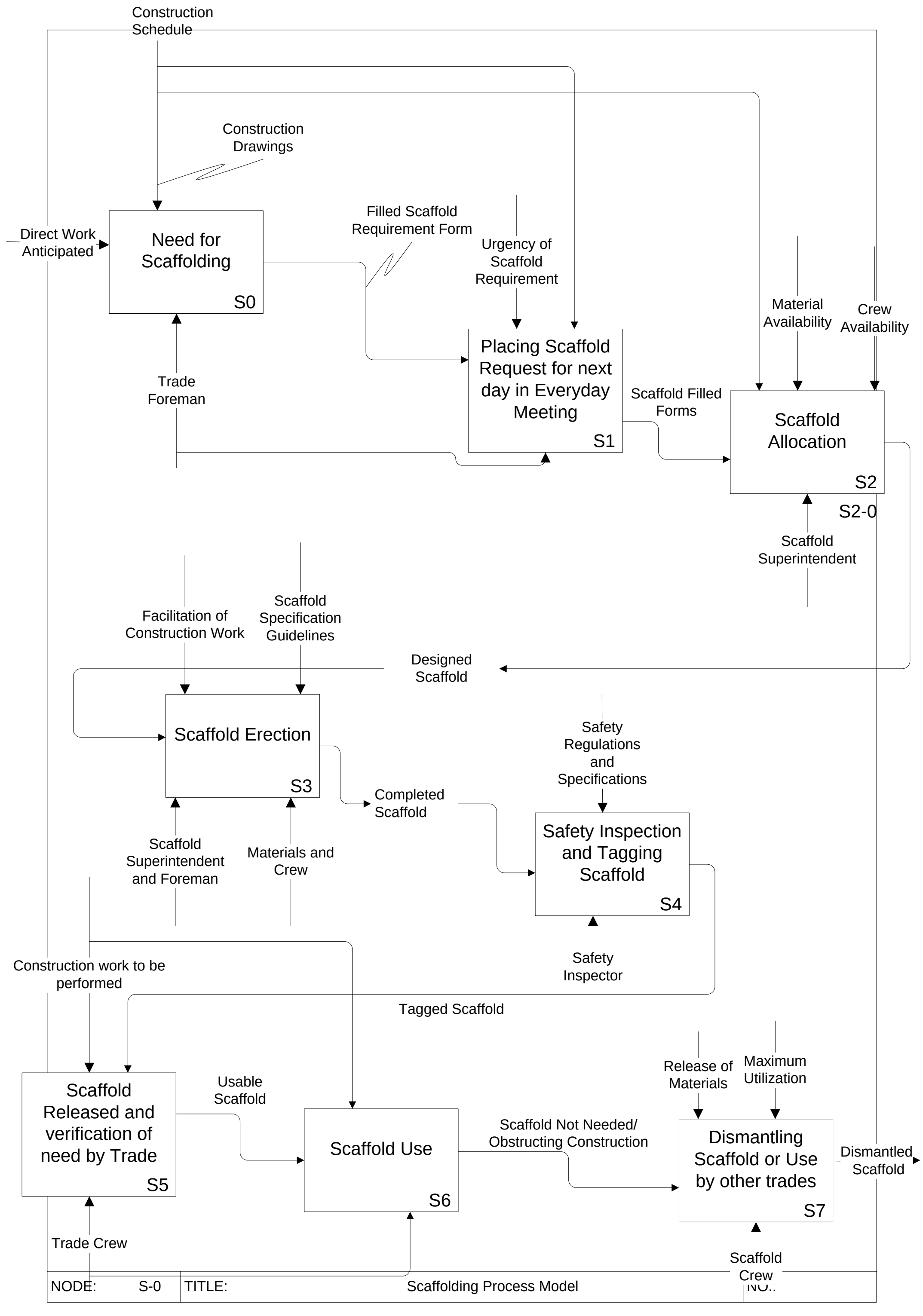


a) Scaffold process full model — Company A

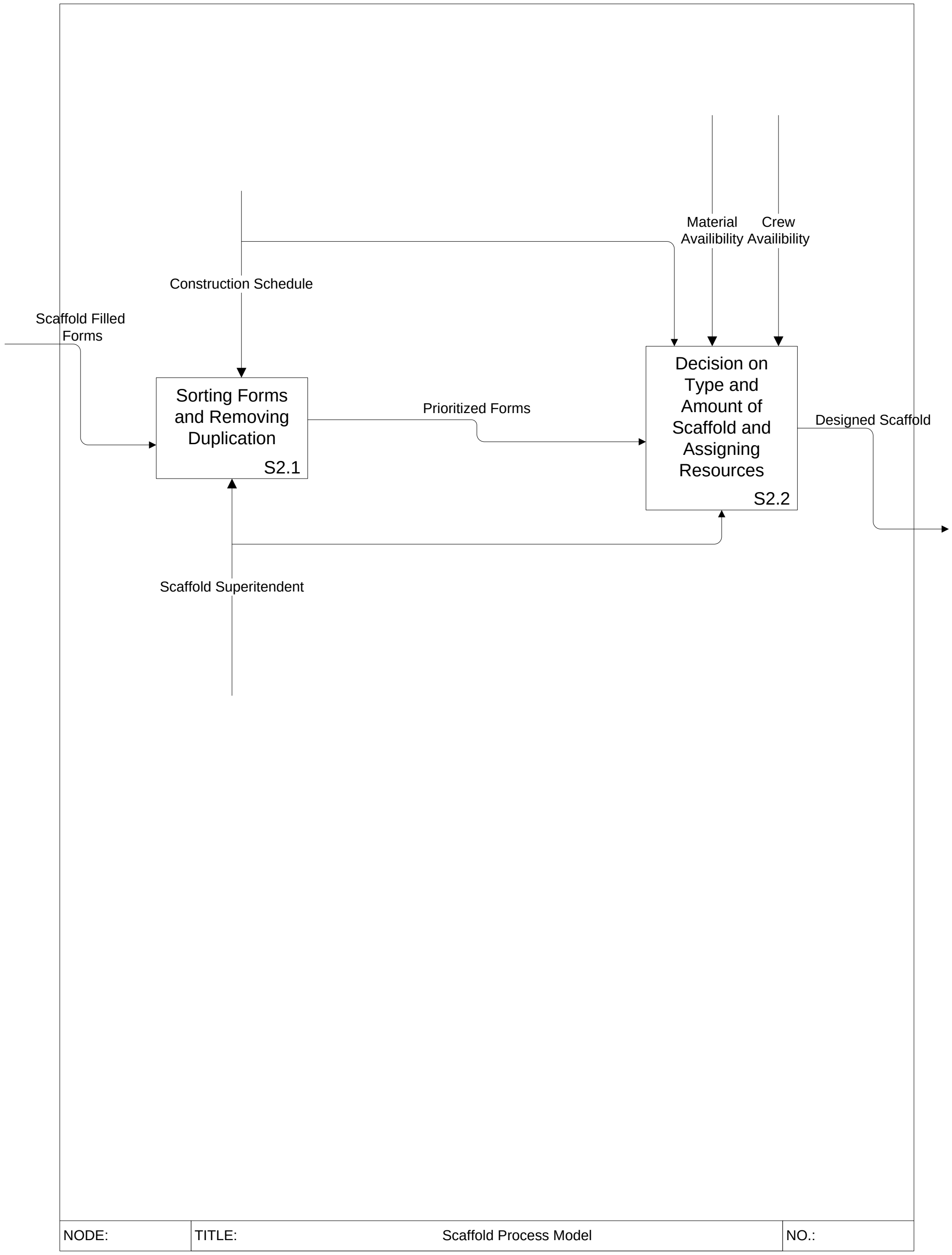


b) Scaffold allocation—Company A

Figure 3-4 Scaffold process flow model —Company A



a) Scaffold process full model —Company B



b) Scaffold allocation —Company B

Figure 3-5 Scaffold process flow model —Company B

Chapter 4 — Data Collection

4.1 Introduction

This chapter explains the concepts in data collection for performing analysis and determining required relationships between associate parameters and scaffold erection man-hours of work. The chapter includes details about the design and implementation of a Navisworks API required for automatic extraction of data from 3D models and the available scaffold database collected from Company A which contains relevant data from one of the previous completed projects.

4.2 Background - Navisworks API

API or Application Programming Interface is a way to perform useful operations or extract relevant information from software that supports external add-ins. It gives the user the chance to extend the boundaries of the software. The codes for such add-ins are written as a Class Library in C#, Visual Basic or other programming languages. For the purpose of this research, .NET programming is performed in Visual Basic template of Microsoft Visual Studio 2010.

Autodesk products like AutoCAD and Navisworks allow users and developers to write API codes and add to the software as tab in the software.

> "Autodesk® Navisworks® project review software helps architecture, engineering, and construction professionals holistically review integrated models and data with stakeholders to gain better control over project outcomes.

> Integration, analysis, and communication tools help teams coordinate disciplines, resolve conflicts, and plan projects before construction or renovation begins."[25]

There are three versions of Autodesk Navisworks –

- Autodesk Navisworks Manage
- Autodesk Navisworks Simulate
- Autodesk Navisworks Freedom

API for Navisworks is not supported in Navisworks Freedom version and can only be added to the other two versions. For the purpose of this research, Autodesk Navisworks Manage is used as the software platform as this software is free to download for students from the Autodesk Students website.

4.3 Why Navisworks and Need of API

Autodesk products are most common among companies for the purpose of designing and visualizing projects. Company A uses Navisworks Simulate for examining the project models in 3D space and a model exists for the Project 1 database which is the source of all data for this research purpose. The free availability of the software is also one major reason for its selection. The Navisworks file contains the 3D model of the project with associated parameters. Each element in the model is characterized by a set of attributes like the name of the element, type, its coordinates on the project space etc. While it is possible to check the model parameters by individually clicking the model elements, a method in the software to extract geometrical data from the model is missing. Also, as the 3D model developed is the primary basis of construction activities, it constitutes the most accurate information about constituting elements. Hence, an API code is needed to select and export the data needed for the data mining model or simulation inputs. There are commercial software tools like Navistools, Profox etc. which could attempt to perform the similar functions; however, they are not suitable for the purpose of this research. They are paid commercial software and cannot be used in academia for further research and development as the source codes of such software are not made public. Hence, it's difficult to understand the working principle and inherent working algorithm for such software.

4.4 Navisworks API Functions

The code is written as a Class Library in Visual Basic programming language in Microsoft Visual Studio 2010. Once the code is completed, the program is saved as a .dll (dynamic link library) file format and the file is copied in the Plug-ins folder of the Navisworks Installation folder. Now each time Navisworks is opened, the plug-in would be present in the Menu Bar and can be used at will. The following figure shows the selection of Class Library as the input type in Microsoft Visual Studio 2010 and the Plug-in tab in Navisworks.

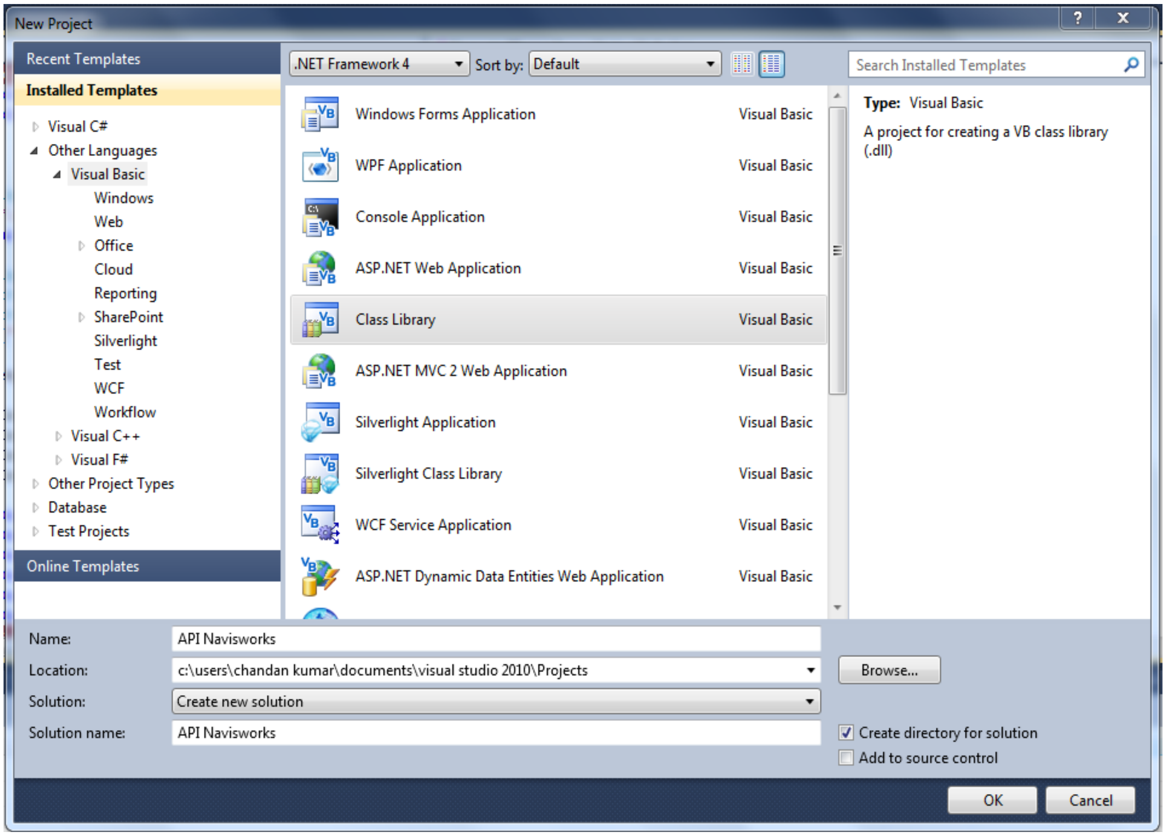


Figure 4-1 Selection of Visual Basic class library template

The following flowchart describes the working algorithm of the application code in Navisworks.

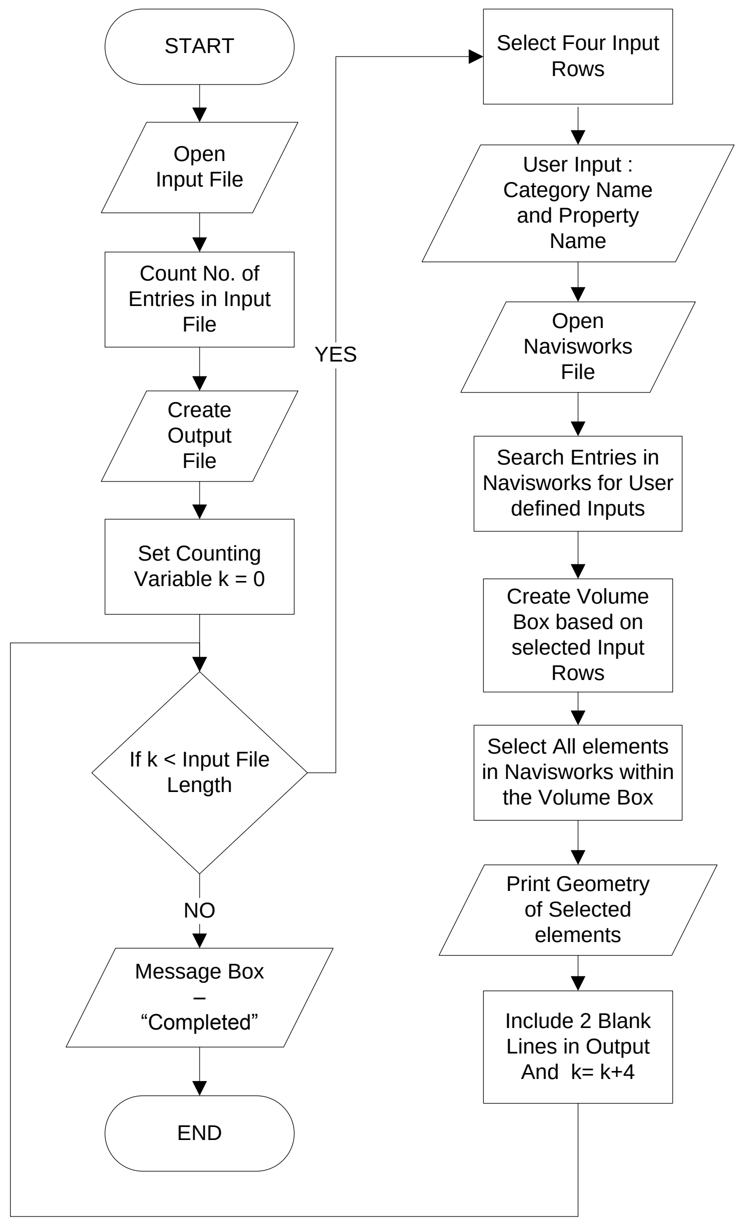


Figure 4-2 Working flowchart of Navisworks API

4.4.1 Input File Preparation

The API is also a semi-automatic link between the 2D and 3D model of the project drawings. The 2D drawing in most companies isdone using Autodesk AutoCAD software. Also as mentioned earlier, Autodesk products allows users to develop plug-ins to perform useful operations from the model. Hence, AutoCAD was used as a source of 2D plot plan of the project. The following flowchart shows the preparation process of input file.

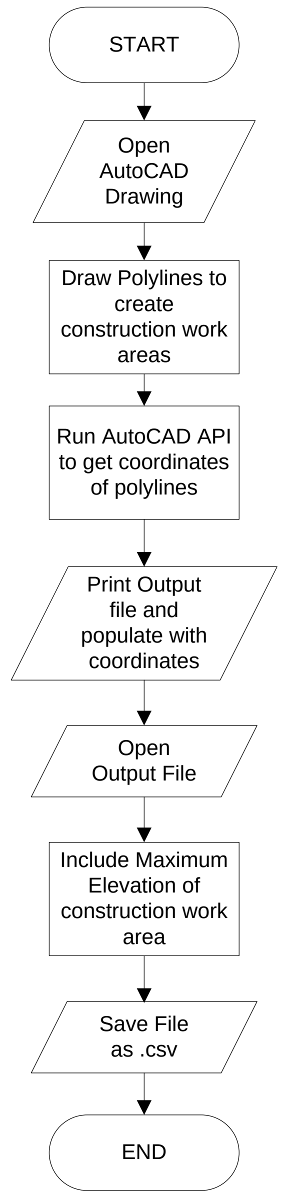


Figure 4-3 Input file preparation for Navisworks API

- The AutoCAD API mentioned in the flow chart is an existing tool with Company A.
- The output file of this process serves as the input file for the Navisworks API.
- The polylines should be drawn in a systematic way and named to keep track of them when the output file is generated. This helps in visualizing the outputs on the AutoCAD file.

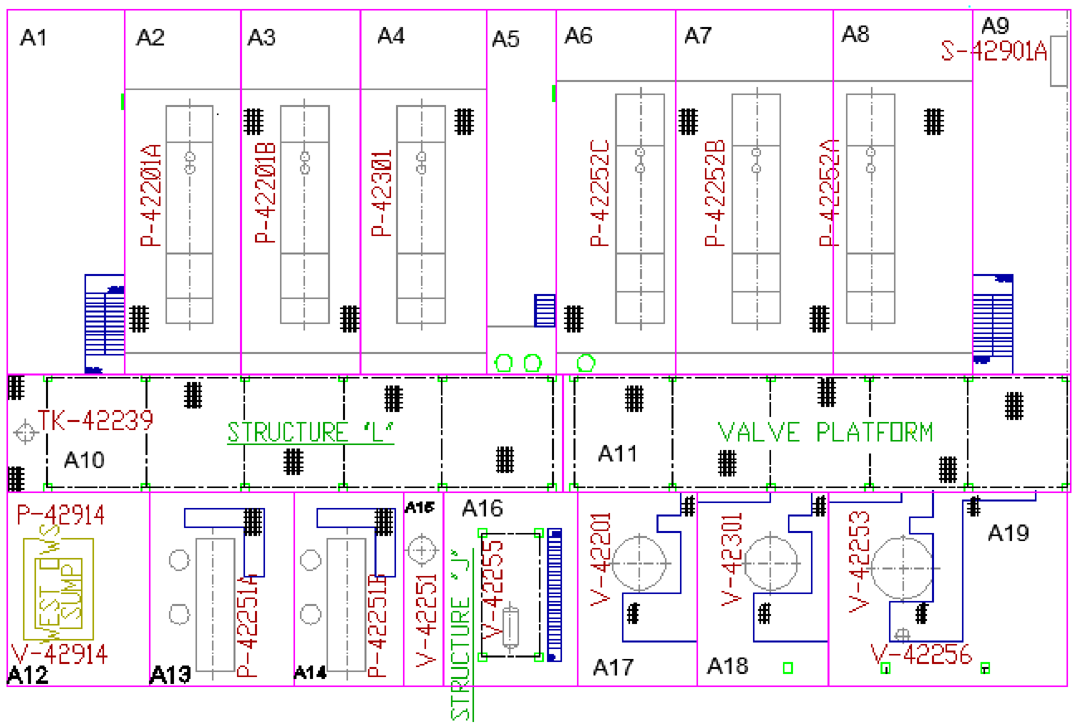


Figure 4-4 Polylines in 2D plot plan

- Each polyline or construction work area generates four (X, Y) coordinates from the 2D plot plan. The output file has to be manually populated with the Z coordinate which is to be kept as zero. The height column would be the maximum elevation of the respective construction work area. To avoid finding the maximum elevation of each construction work area, the value of height can be kept to be the maximum elevation of the whole project.

- The name of the polyline has the nomenclature ISBLi (i = 1,2………..n) according to Company A's standards.

Name	X	Y	Z	Height
ISBL17	2098	3910	615	75
ISBL17	2105	3910	615	75
ISBL17	2098	3920	615	75
ISBL17	2105	3920	615	75

Figure 4-5 Sample input file for Navisworks API

The whole process is basically performed to get the 3D coordinates of the construction work areas in a project. At present there is no way to automatically draw the construction work areas. The main hindrance in automating the process is the asymmetric nature of an industrial construction site. One important point while preparing the input table is to maintain consistency of the units. The units of measurement for AutoCAD, input file, Navisworks file and output file should be selected as the same unit to avoid any confusions or undesired results.

4.4.2 Output File

As described in the flow chart (Figure 4-2) the output file contains the following properties associated with the selected element:

- Name of the Element
- Min. X Coordinate
- Max X Coordinate
- Min Y Coordinate
- Max Y Coordinate
- Min Z Coordinate
- Max Z Coordinate

The output file is saved as a .csv file and needs to be converted intoMicrosoft Excel format to perform further calculations. This activity can be performed by simply saving the file inMicrosoft Excel using ‘Save As’ function. A simple calculation operation can be performed to get the length, breadth and height of the selected element:

Length = Max (X) – Min (X)

Breadth = Max (Y) – Min (Y)

Height = Max (Z) – Min (Z)

One wonders why the length, breadth and height of the selected element were note calculated in the API itself before printing the output file. The reason is that an element in the Navisworks project file consists of elements that are broken down into smaller pieces when designed and transformed to a Navisworks file. So, for the same name of the element more than one output element is selected. To calculate the length of the whole structure, the minimum and maximum X coordinate of all those elements is needed. The same process holds true for breadth and height of the selected structure. For e.g., Figure 4-6 below shows a selected structure in the Navisworks file. This vessel V-1234 contains over one hundred elements each called V-1234, which in totality form the actual vessel V-1234.

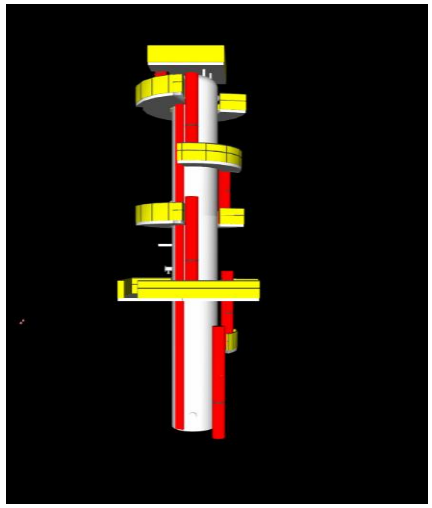


Figure 4-6 A selected vessel from Navisworks file

The Navisworks project file for the case study willbe described in detail in Chapter 5. The model contains no other relevant information which could be useful for the data mining model. Other information that is relevant to the data mining model is the weight of the module and the type of structure. Certain companies do maintain a certain set of nomenclature to define a particular type of equipment or module and it can be deciphered from the output file. However, if the companies have that data as a property of the structure itself, a minor modification in the API can be done to extract that information. A portion of the sample output file is shown in Figure 4-7 describing the constituents of each individual element in the Navisworks file.

Name	MaxX	MinX	MaxY	MinY	MaxZ	MinZ
DisplayString:V-42214	1956.447	1945.853	3865.947	3863.053	626.9469	623.825
DisplayString:V-42214	1953.144	1953.056	3864.544	3864.456	628.0999	625.0999
DisplayString:V-42214	1947.932	1947.608	3864.662	3864.338	628.0999	626.9
DisplayString:V-42214	1947.815	1947.595	3864.61	3864.39	624.3	623.7
DisplayString:V-42214	1950.879	1950.711	3864.584	3864.416	624.1	623.7
DisplayString:V-42214	1945.617	1945.417	3865.072	3863.928	626.072	624.928
DisplayString:V-42214	1956.883	1956.683	3865.072	3863.928	626.072	624.928
DisplayString:V-42214	1956.67	1956.07	3865.071	3863.929	626.0714	624.9285
DisplayString:V-42214	1954.629	1954.171	3864.729	3864.271	628.0999	625.45
DisplayString:V-42214	1950.609	1950.521	3866.25	3864.5	625.7444	625.6555
DisplayString:V-42214	1952.249	1952.161	3866.25	3864.5	625.7444	625.6555
DisplayString:V-42214	1947.594	1947.506	3866.25	3864.5	626.0694	625.9805
DisplayString:V-42214	1954.744	1954.656	3865.95	3864.5	624.3944	624.3055
DisplayString:V-42214	1948.674	1948.586	3864.544	3864.456	628.0999	626.9
DisplayString:V-42214	1949.354	1949.266	3866.25	3864.5	626.0694	625.9805
DisplayString:V-42214	1947.594	1947.506	3866.25	3864.5	624.3944	624.3055
DisplayString:V-42214	1949.354	1949.266	3866.25	3864.5	624.3944	624.3055

Figure 4-7 Sample output file

The code is used for different elements in the project data and the use, inputs and outputs relevant to the case study are explained in detail in Chapter 4. The code itself with all comment statements and details is shown in Appendix A.

4.5 Working Example – Navisworks API

This section describes a case study to demonstrate the working process and results of the Navisworks API.

4.5.1 Navisworks File

The filename is library.nwd and is part of the sample example files that come with the Navisworks Manage Installer package. The location of the file is C:\Program Files\Autodesk\Navisworks Manage 2012\Examples\library. The model units are inches, however, the display units are in meters. The category and property name to be searched for is “Item” and “Name,” respectively. The model is an .nwf file and is saved as .nwd for implementing the API.

Figure 4-8library.nwd

4.5.2 Input File

The requirement is to get all elements within the boundary length of 16000 inches, breadth of 16000 inches and height of 16000 inches. The input .csv file is shown as a picture below.

Boundary1	0	-16000	0	16000
Boundary1	16000	-16000	0	16000
Boundary1	0	0	0	16000
Boundary1	16000	0	0	16000

Figure 4-9 Input file for sample problem

4.5.3 Output

The output contains 336 selected entries and is attached as Appendix B. The selected area is shown in the Navisworks file as in Figure 4-10.

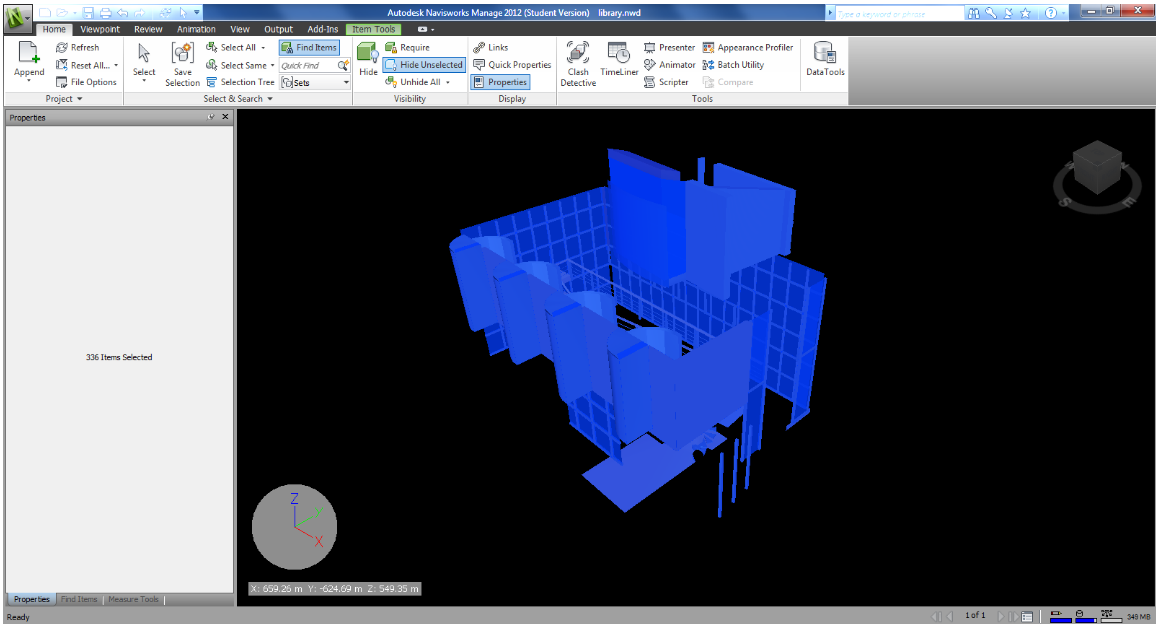


Figure 4-10 Output from Navisworks API

4.6 Available Project Database

The available database is the project data from Project 1 constructed by Company A. The whole project spanned over three years of construction. The project is divided into twenty five[5]major areas with nomenclature ranging from 421A onwards. Area 421R is the most prominent one as it contains the pipe rack modules and related equipment. The following types of structures consume the most part of the project:

- Vessels
- Modules like cable trays, valve decks
- Pre-fabricated structures like stairs etc.
- Supplementary equipment like heating or electrical equipment
- Pipe racks

[5]The number of areas is changed for confidentiality reasons.

A scaffold database was maintained for most of the project, which contains relevant information pertaining to the development of a data mining model. Each entry in the scaffold database represents a scaffold request placed by trade foremen on site. The database contains over 15000 entries. A Scaffold Coordinator was appointed in development of the database, however, there are many problems associated with the database, which willbe explained in detail later in this chapter. The following are the input columns and their description from the existing scaffold database:

- ScaffoldID – Named in sequence of A-001 and so forth, this column represents the major construction area and their scaffold requests.
- Comment – General comments about the request like if it is cancelled etc.
- Date Requested – The date on which the request for the scaffold has been made.
- Date Required – The date on which the completed scaffold is required.
- Requested by Trade_Purpose – The trade who submits the scaffold request like Ironworkers, Electricians etc.
- Area_Location – The description of the area, module, vessel etc. related to the scaffold request.
- Elevation – The elevation at which the scaffold is required.
- Priority No – Priority of request.
- Superintendent – The Scaffold Superintendent collecting the request.
- Foreman to build – The Foreman who supervised the erection of scaffold.
- Actual Volume – The volume of scaffold constructed.
- Units – The unit of volume of scaffold.
- Cost Code – The cost code of the project which governs the request.

- Erection Mhrs A – The total erection man-hours of work for constructing the scaffold.
- Mhrs Dismantle A – The total dismantling man-hours of work, if the scaffold is dismantled.
- Completion Date – the completion date of the scaffold construction.
- Status – The current status of the scaffold.
- Reason for Dismantle – Comments about the dismantling conditions of the scaffold.
- Date Dismantled – The date on which the scaffold dismantling started.
- IWP- The work package with which the request is associated.

A sample section from the database is shown in Figure 4-11.

ScaffoldID	Comment	Date Reque	Date Requir	Requested by Trac	Area_Location	Elevation	Superintendent	Actual Volur	Units	Erection Mhrs A
A-001		25/09/2008	12/09/2008	Pipefitters and Painters	West Oily Sump near A	629.25	Sachin	21	m3	10
A-002		12/09/2008	26/09/2008	Pipefitters	West Oily Sump near B	630	Saurabh	18	m3	16
A-003		20/09/2008	29/10/2008	Labourers/Carpenters/Masons	P-42251A/B Area AB	623.2	Sachin	1240	m3	1112
A-004		24/02/2009	11/02/2009	Pipefitters	Module 421AR-201 to AR-202	627.8	Saurabh	418	m3	1021
A-005		07/03/2009	18/03/2009	Pipefitters	Module 421A R-2021	629.500	Sachin	124	m3	351
A-006		03/03/2009	31/03/2009	Boilermakers	V-423014/422012	637.000	Saurabh	119	m3	126
A-007	Cancelled	24/04/2009	02/04/2009	Millwrights	P-42251AB	640	Sachin	10	m3	1
A-008	Safe Out Mod.	13/04/2009	29/04/2009	Electricians	421A-S102	637.000	Saurabh	10	m3	18
A-009	Safe Out Mod.	14/04/2009	07/04/2009	Electricians	421A-S101	637.000	Sachin	10	m3	18
A-010		06/04/2009	07/04/2009	Pipefitters	V-42301/42201	638.000	George Robinson	12	m3	321

Figure 4-11 Sample from scaffold database

Other than the database itself, an equipment list exists which contains the names of all the vessels and modules in the project along with some other relevant data. The figure below shows the data collection components in the thesis.

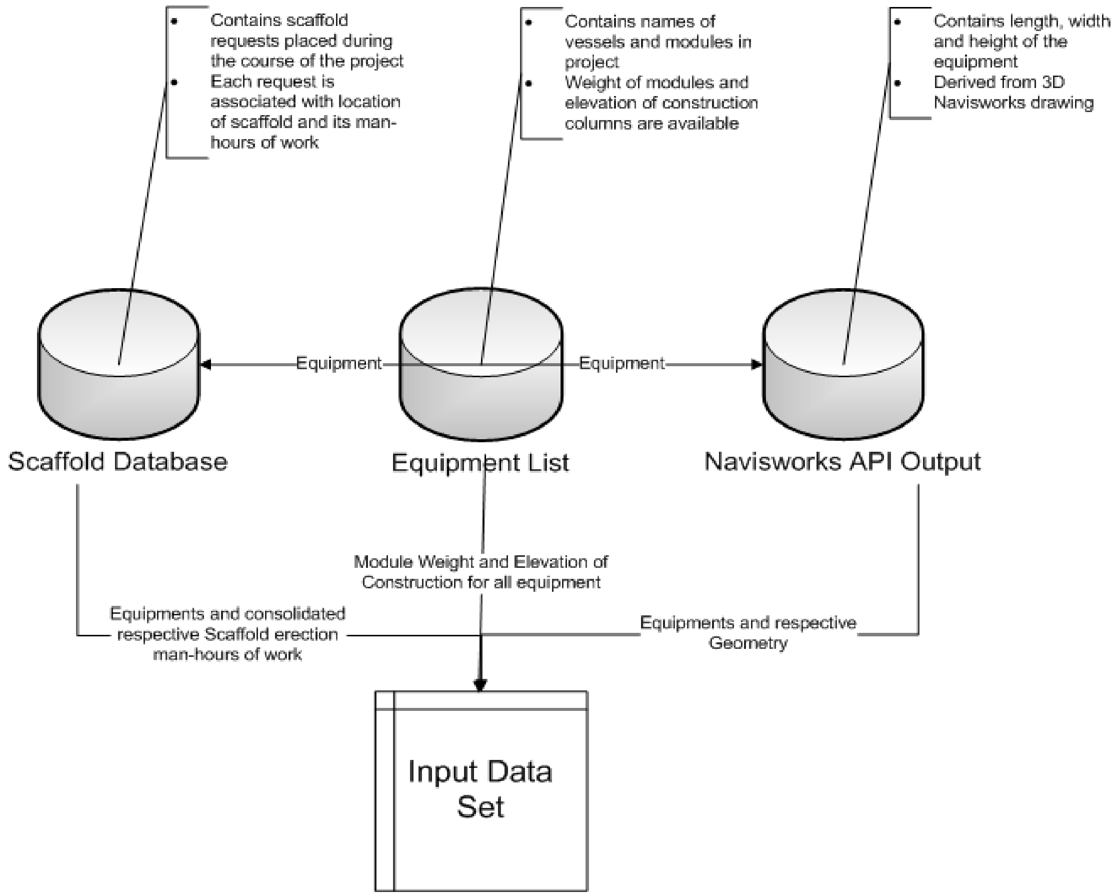


Figure 4-12 Different datasets in the project

Chapter 5 — Data Analysis and Modeling

5.1 Introduction

The present chapter contains details about the problems associated with the available database and all analysis performed on the data set. The chapter also suggests an improved scaffold process flow model derived from the two company models described in Chapter 3, which focuses on advanced planning of scaffold resources on site. The data mining analysis shows trends of different input factors in relation of corresponding scaffold requirements for modules and vessels and linear regression models developed using WEKA software to quantify the existing trends.

5.2 Comparison of Scaffold Process Flow Models

Process models described in Chapter 3 are similar in their functionality and bring on the basics in scaffold planning. The requests are made in meetings held with all the trade foremen and the Scaffold Superintendent together. The requests are studied by the Superintendent to avoid any duplications and a scaffold is designed based on his/her experience to suit the needs of maximum trades. The meetings are on daily basis, however, in Company A, it was found that the trades are instructed and encouraged to submit requests a week in advance. The Scaffold Superintendent then allocates manpower and materials for the construction of the scaffold. This is one of the points where the scaffold estimating tool would come to be useful, to provide the Superintendent with a quick, reliable and user friendly means of estimating scaffolding. After the scaffold is erected, it is safety tagged. The tagging is performed by either the Scaffold Superintendent or safety personnel on site. The trades can then use the scaffold to perform operations. After the scaffold has served the purpose, the trades would inform the Superintendent about it, and the dismantling of the scaffold can take place to release the materials, which can be used at other scaffolds on site. This is a general area of concern in the field, as in most situations, the trades fail to mention to the Superintendent about the completed use of the scaffold, and the structure stands erected even though it is not being used. This also holds up the material resources on site and as most scaffold materials are on rental basis, this leads to increment in inventory even though it might not be required. Both these models are working principles that guide the companies in performing scaffold operations and are tried and tested methods. However, there isroom for improvements to avoid duplications of scaffolds and consequently increasing productivity of project operations.

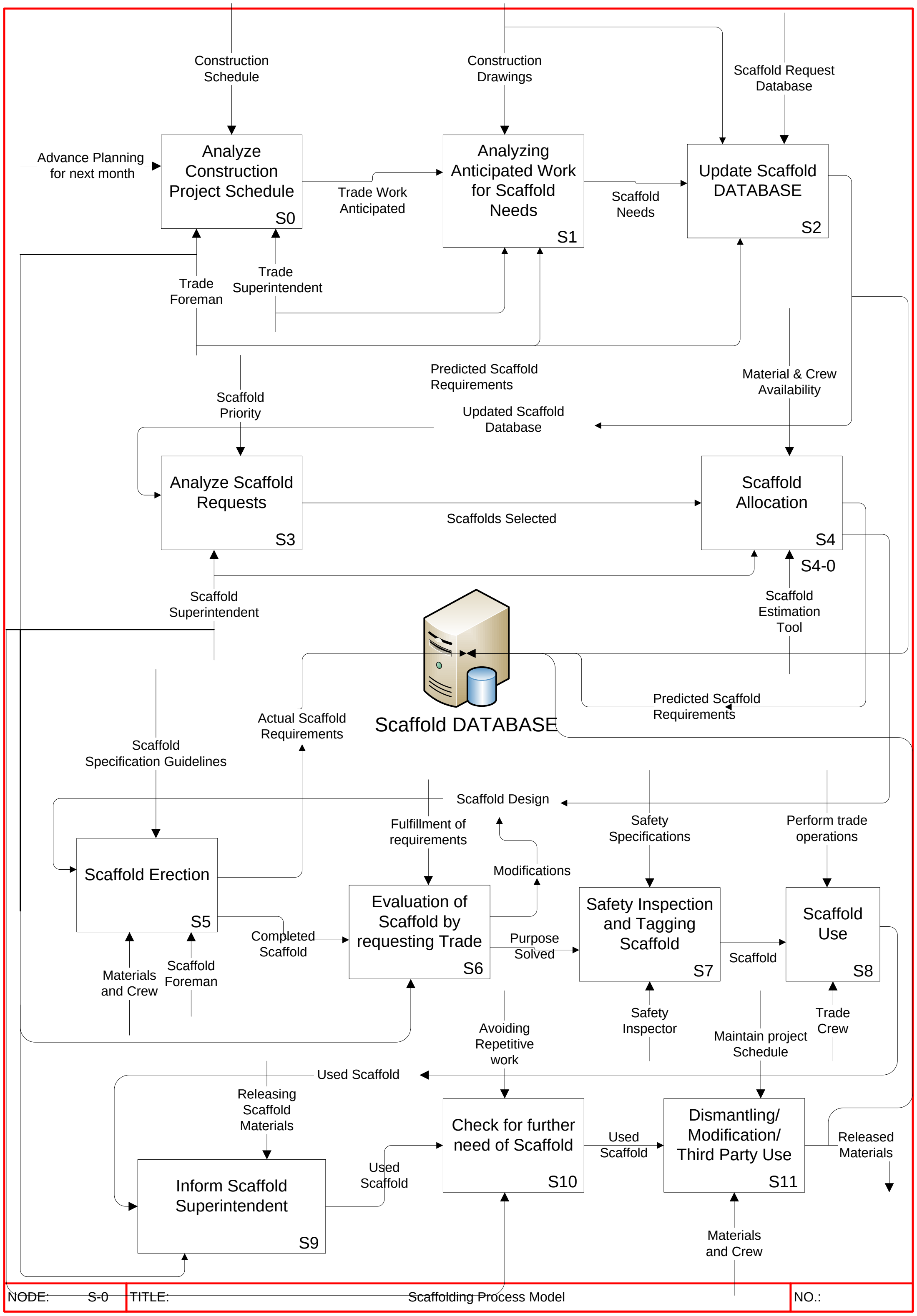


Figure 5-1 Modified scaffold process flow model

Figure 5-1 represents a modified scaffold process flow model that would be ideal to maintain consistency and achieve desired productivity in scaffolding planning. It is to be noted that one of the most common causes of decreased scaffolding productivity is the repetition of jobs on site. The same scaffold at a location can be created and dismantled several times in a location based on scaffold requests generated. The only way to overcome such a situation is the effective planning of scaffolding needs at an initial stage of the project and assigning materials and labor crews accordingly to the site. Now, as industrial construction is a diversified construction scenario, a pre plan of all scaffolding needs at the start of the project is highly unlikely. Hence, effort has to be made to plan a sufficient amount of time in advance, if not for the entire project. As the direct work schedule is approximately a firm schedule in construction processes, they are to be used to predict scaffolding requirements for the next month in advance. This allows sufficient time to order and receive materials in case of prediction of any shortage, if anticipated. Also, planning a month in advance would enable the Scaffold Superintendent to assess the need of each constructed scaffold at a location and the possibility to combine requests of different trades together to construct one unified scaffold serving all needs. Materials in scaffold construction are normally rented, and this can help in maintaining inventory of existing and future needs. Labor is the most costly aspect of a construction project and a look ahead would enable optimization of the labor needs of the project.

The other important aspect of the scaffolding process flow on sites is the failure of trades to promptly inform the Scaffold Superintendent when they are finished using the scaffold. This leads to hold up of the materials in the erected scaffold, where they could have been used in construction someplace else and saved the company on rental costs.

Maintenance of scaffold request database would serve the purpose for eliminating such conflicts. The Trade Foreman can just update the database as to when they have finished using and the Scaffold Superintendent can look into the matter for further considerations.

The third aspect of this modified model is the maintenance of Scaffold Requirement Database. The database is to be maintained by the Scaffold Superintendent at two stages of the project:

1. Predicted scaffold requirements when the scaffold is being allocated to a trade request, like total man-hours of work, amount of materials etc.
2. Actual scaffold requirement when the scaffold is erected, like man-hours of work, amount of materials etc.

The database also contains details about the scaffold requests, and hence, trades making such requests also fill in required sections of the database. Such a database would serve extremely beneficial to the company in future as well as during the course of the project. This database can be used to update and improve the data mining models developed and used in the scaffold estimation tools as well as to understand the triggers and needs of different scaffold construction. The database should be regularly updated with actual site data to maintain its accuracy and usability in future. The productivity of scaffold crew and any further conclusions like addition or deletion of crew would also be a major usability of such a database.

The flow process ends when the scaffold is dismantled or certain permissible modifications can be done to satisfy future needs. At some locations, some third party agencies working on site may also need scaffolding and such scaffolds can be loaned to them for use before they are completely dismantled.

5.3 Scaffold Database Design

As discussed in the previous section, the database is to be maintained by the Scaffold Superintendent and trade personnel, or if required, assigned to a knowledgeable Scaffold Coordinator. The reason I recommend somebody knowledgeable about the scaffolding process and the construction in general is that would eliminate certain uncertainties and errors in database management.

The following inputs would constitute an effective database, which can be used later on for analysis and estimating models for any future projects:

1. Identifier for Construction Area – This would help the scaffold to be linked to major construction work areas in the project. It needs to be a pre-defined list of areas and selection can be from a drop down menu.
2. Identifier for Equipment – This would associate the scaffold with particular equipment on site. This input needs to be a pre-defined list as a consistent nomenclature is required in any analysis on the dataset collected. The user would be able to add or delete from the list; however, a general predefined nomenclature technique has to be maintained. The database should have the ability to prompt the user if he/she is trying to populate the database with some inconsistent entry.
3. Scaffold Request Number – This would help in identifying and tracking the scaffold request. This can be a string comprised of construction area and numerical entity.

4. Scaffold Request Date – This would be the date the request is placed for the scaffold.
5. Trade Requirements – Trades who request the scaffold.
6. Estimated Trade Hours of Work – The trades making the request should include an estimate if hours of operation on the scaffold.
7. Actual Trade Hours of Work – The actual amount of hours spent using the scaffold by the requesting trade.
8. Comments by Trade – Reason for any unforeseen circumstances which might have led to considerable difference in estimated and actual trade hours of work.
9. Predicted Scaffold Requirements – Based on the scaffold request, the Superintendent should populate the database with predicted scaffold requirements which are the following:
   - I. Scaffold man-hours for erection of scaffold.
   - II. Materials required, either in volumetric units or number of pieces.
   - III. Elevation of construction of scaffold access.
   - IV. Scaffold crew ID
10. Actual Scaffold Requirements – Based on actual construction after completion of work, the Superintendent should populate the database with actual scaffold requirements:
    - I. Scaffold man-hours for erection of scaffold.
    - II. Materials required, either in volumetric units or number of pieces.
    - III. Elevation of construction of scaffold access.
    - IV. Actual start date of construction.

V. Actual finish date of construction.

11. Comment by Scaffold Superintendent - Reason for any unforeseen circumstances which might have led to considerable difference in estimated and actual scaffold erection man-hours of work.
12. Type of Scaffold – The type of scaffold to be constructed.
13. Attribute of the Scaffold – Whether the scaffold is a new erection from ground up or modification of existing scaffold. If modified, which scaffold requests it is linked to and the input entry has to be in the form of drop down menu to select the scaffold request number to avoid errors.
14. Dismantling Requirements – This would include the following attributes:

    I. Actual dismantling man-hours of work – This attribute would not be associated with all scaffolds as not all scaffolds would be fully dismantled. As the request are linked with previous requests for modifications etc. this would only be required for the last scaffold request.

One thing of utmost importance here is the database is not to be maintained for each individual request coming from the trades. The Scaffold Superintendent would scrutinize all the requests and would only consider the ones based on urgency of requirement, available resources and project schedule constraints. Appendix F shows a simple form in Microsoft Access which can be used to construct this kind of database. Also, one section in the database has to filledin by trade personnel and the other by scaffold personnel, hence, the form can be developed over company server to facilitate smooth operations and automatic data collection.

5.4 Problems with available Scaffold database – Project 1

There are certain problems associated with the available database explained in the previous chapter which makes an extremely accurate data mining model extremely difficult to predict. The pitfalls of the database are described as follows:

1. The first entry in the scaffold database is of a date which is more than a year into the project. This makes the database likely to miss some relevant project data. This is also evident from the total erection scaffold hours collected from the database which is72% of the total as seen from as built schedule of the project.
2. The nomenclature maintained in the Area_Location column which enables pin pointing the scaffold to a particular structure is not unified and clear. A lot of typos exist, which makes it difficult to write an algorithm to extract relevant data. All the data have to be manually seen, verified from 3D and 2D drawings and then used for data mining experiments.
3. Dismantling hours are not recorded for all scaffold requests, which might be due to modifications in existing scaffolds hence, accurate modeling of dismantled scaffold hours is not possible.
4. There are night shift hours for erecting scaffold as separate entries in the database. They have not been associated with any major area which makes it difficult to incorporate them into final extracted data.
5. The calculation of scaffold volume required is quite unclear from the database. When talkingwith the Scaffold Coordinator for the project, she mentioned that the volume represents the area of the scaffold platform multiplied by the height of the

hand rails for the scaffold. This method of calculating volume is highly ambiguous and would not clearly visualize the scaffold requirements of a request.

6. The actual date of construction of scaffold is missing from the database, which hinders the possibility of predicting crew sizes for scaffold construction.
7. The original Scaffold Coordinator for the project left the project in between and someone else took over to type data entries. The transition would have also misplaced or missed entries.
8. When manually extracting information, it was found that some Area_Location entries have been put under the wrong construction work areas, which have been manually corrected while formatting the data mining model.

A lot of effort has been put in to extract relevant data from the database and use it in developing the data mining model. The data has to be cleaned and verified, if possible, before being used for further analysis.

5.5WEKA Analysis

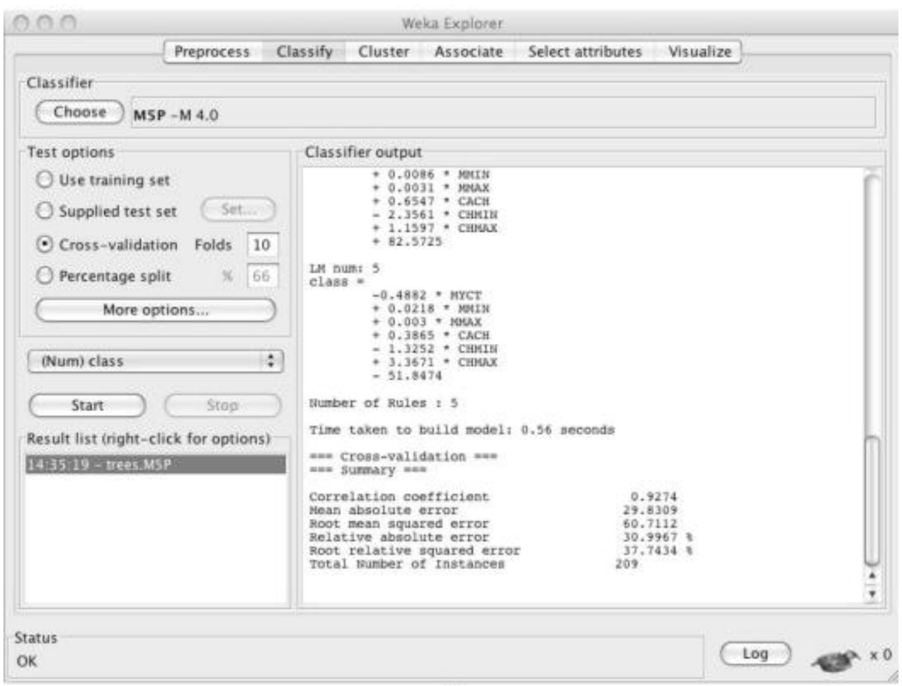
> "Weka is a collection of machine learning algorithms for data mining tasks. The algorithms can either be applied directly to a dataset or called from your own Java code. Weka contains tools for data pre-processing, classification, regression, clustering, association rules, and visualization. It is also well-suited for developing new machine learning schemes."[26]

5.5.1 Preparation of data

The data has to be prepared in the form of a spreadsheet or database. The input file format for Weka is .csv (Comma-Separated Value) or .arff (Weka's native data storage method). For the purpose of this analysis, the input file is prepared as a .csv file which can be easily generated by using the "Save As" function in Microsoft Excel 2007. The input file will contain all the columns required to run the learning algorithm like Linear Regression or Neural Networks including with the first row naming the columns. Figure 38 shows a typical input file for Weka Analysis.[26]

5.5.2 Explorer Tab in Weka

The explorer tab in Weka is the main graphical user interface of Weka. It contains all the methods to perform the analysis and show the outputs desired. Figure 5-2shows the Explorer functionalities in Weka.[26]



(b)

Figure 5-2 The Explorer interface in Weka

5.5.3 Training and Testing Data

The classifier to perform the analysis can be selected from the 'choose' dropdown menu, which includes a number of algorithms for data analysis like Linear Regression, Bayes

Algorithm, ZeroR method etc. For the purpose of this research, Linear Regression is used as a classifier to train and test input data. In the test options 10-fold cross validation method is used to generate the best possible relationship model between the input and output fields. An important reason for this is the availability of considerably less amount of data for breaking down the dataset into training and testing parts.

> “In k-fold cross validation, the initial data are randomly partitioned into k mutually exclusive subsets or “folds”, `D1 …Dk, each of approximately equal size. Training and testing is performed k times. In iteration ‘i’, partition Di is reserved as the test set, and the remaining partitions are collectively used to train the model. Each sample is used the same number of times for training and once for testing.”[27]

A 10-fold cross validation technique is used for performing the analysis. Hence, all the data has been used to train the model 9 times while once serving as the testing part of the analysis. It also means that each fold would use 90% of the data to train the model while the remaining 10% would serve as the test data. The use of this method enables self-validation of the models, which is very important in this case study as separate data from other projects is not available to validate the models.

5.5.4 Outputs

In Linear Regression as a classifier, Weka generates a linear model or equation which predicts the output as a linear function of all input columns. The linear regression technique in Weka also has the functionality of attribute selection. The attribute selection function allows the program to automatically select the attributes from the input table which would perform the best in the analysis leading to minimum errors. This would serve useful when a large number of input columns exist and the user is uncertain to what extent an input affects the final output.

> "*LinearRegression* performs standard least-squares multiple linear regression and can optionally perform attribute selection, either greedily using backward elimination or by building a full model from all attributes and dropping the terms one by one, in decreasing order of their standardized coefficients, until a stopping criteria is reached."[26]

In the context of this research, no attribute selection algorithm is selected as the inputs have been logically selected after discussions with experienced professionals in the industry.

5.6 Trends in Existing Scaffold Database

The following section presents the trends existing in the scaffold database. This helps in visualizing the effect of certain parameters on scaffolding requirements as well as deriving useful conclusions from the same.

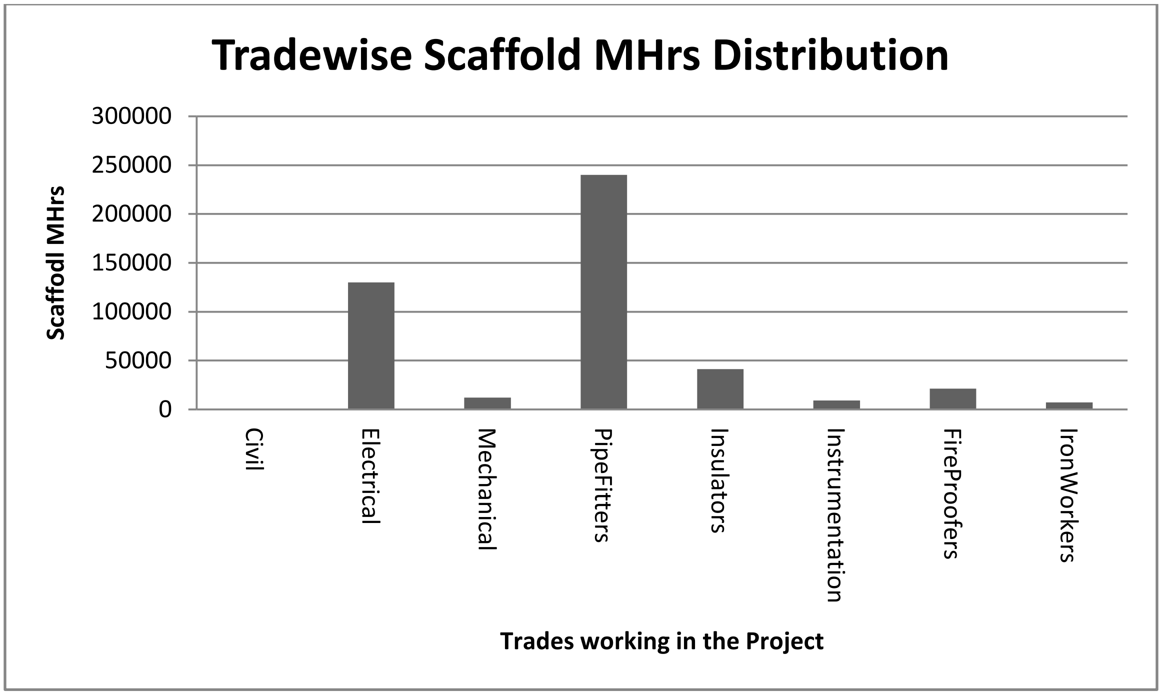


Figure 5-3Trade distribution in Project 1 w.r.t. Scaffold MHrs requirement

Figure 5-3shows the amount of Scaffold Mhrs of work associated with different trades in Project 1. The project required a lot of piping and rack installations, and hence, as seen from the graph, Pipefitters consume the most scaffold man-hours of work. The first concept to derive from this analysis is that distribution of scaffold man-hours is not quite evenly distributed in a project, and secondly, the distribution ratio would vary depending on the type of project. The Scaffold Coordinator for Project 1 mentioned that the scaffold requests had to be made at least a week in advance by the different trades. The graph shown in Figure 5-4 does not, however, show the indicated pattern. Up to 50% of the entries in the database show a request date of 5 days and less for the required scaffold.

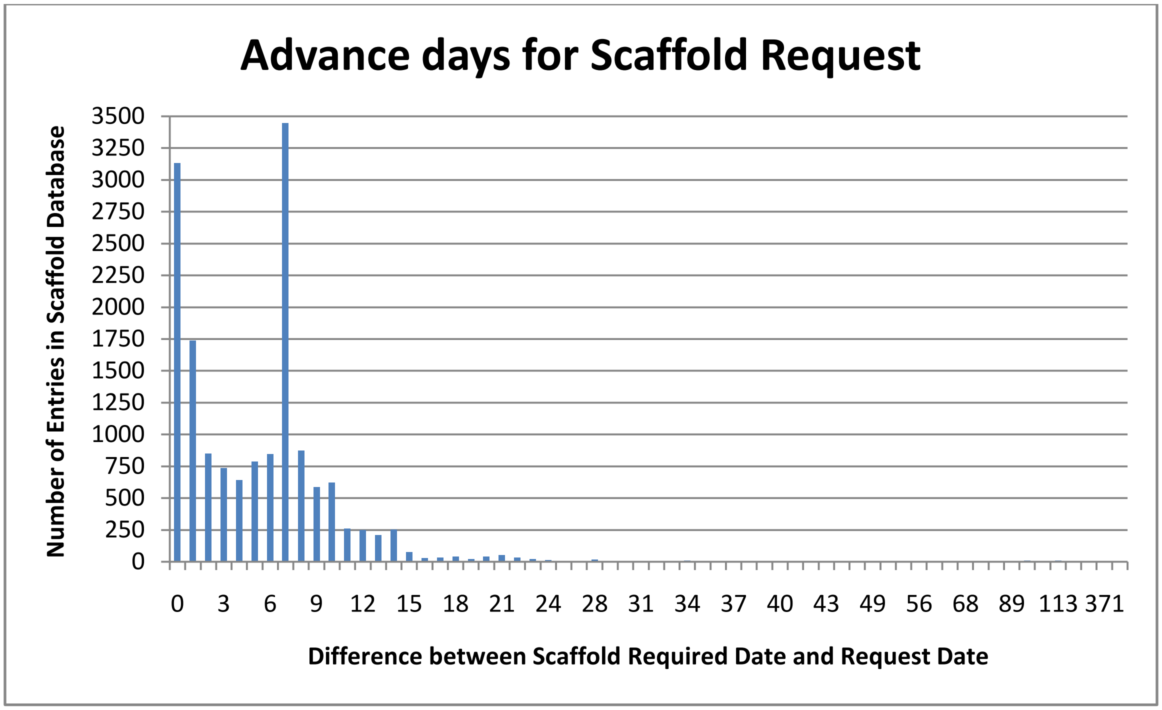
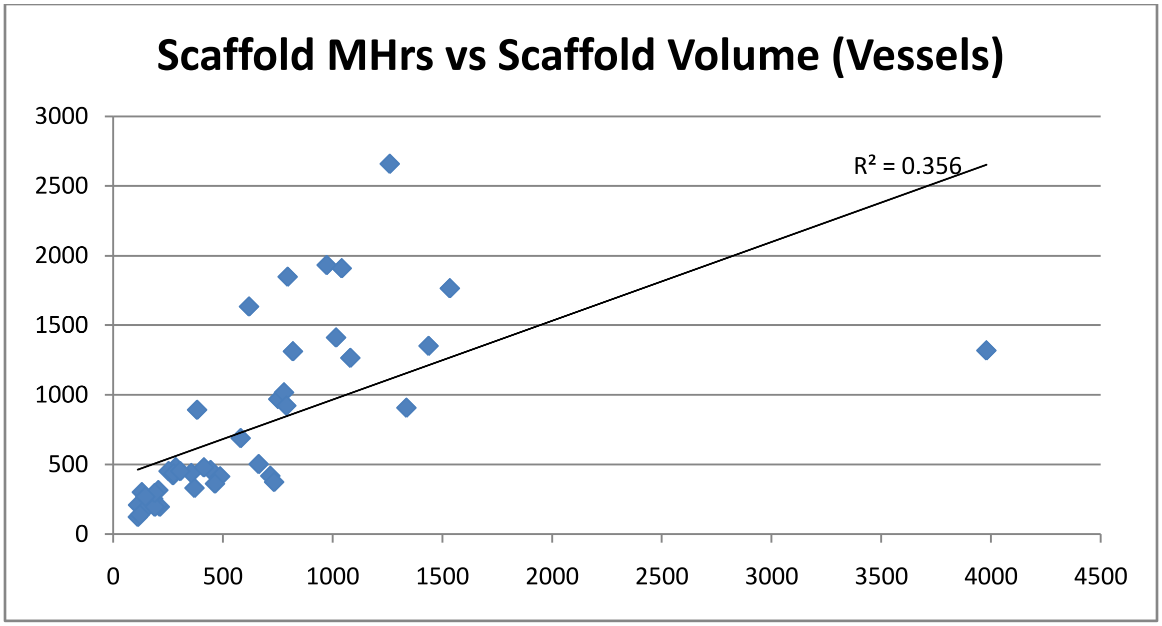
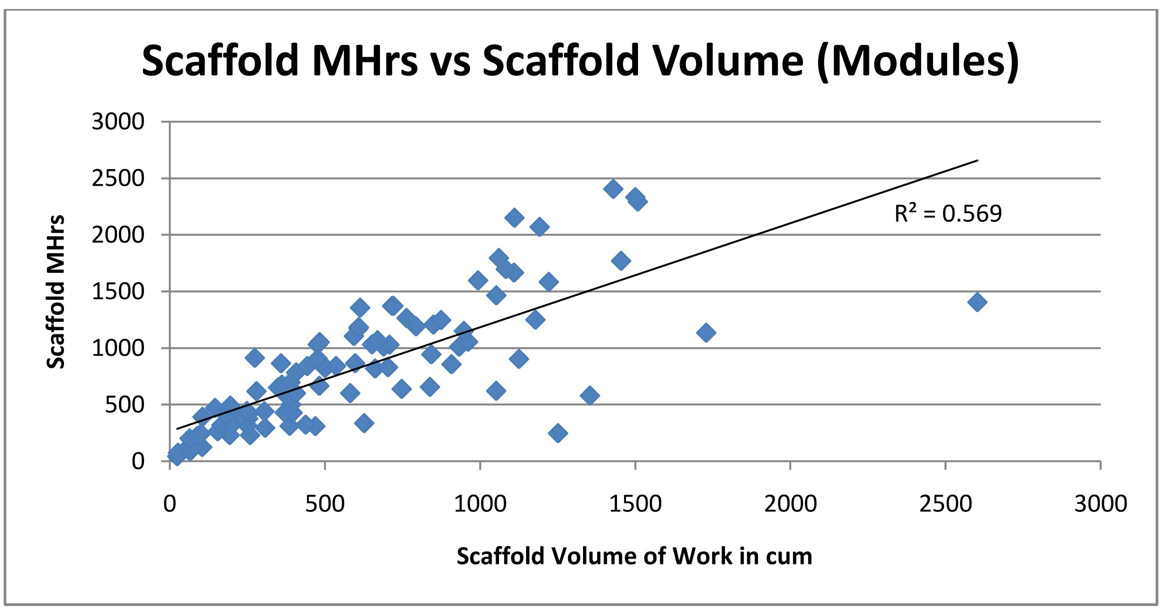


Figure 5-4 Count of entries for each difference between scaffold required date and scaffold request date

The Scaffold database consists of a column providing the amount of volume the scaffolding constructed for the respective request consumed. This volume, in most entries, is the measure of the deck area required multiplied by the height of hand rails. Although such a measurement would not be helpful in finding the amount of materials needed for the scaffold at this stage of project, a graph between scaffold volume and scaffold man-hours of work does show a certain level of dependence.



(a) Vessels in project



(b) Modules in project

Figure 5-5 Scaffold man-hours of work vs. scaffold volume for equipment in project

From the above figure, it can be seen that in most cases there does exist a direct linear relationship between the scaffold man-hours of work and scaffold volume of work. The correlation coefficient for vessel is around 60% and for the modules is around 75%.

5.7Extraction of Vessel Information

A list of all the vessels is prepared from the scaffold database for which the scaffold erection man-hours of work is available and is extractable. All the vessels are then manually searched in the database to extract the total scaffolding man-hours of work for respective vessels. A table of 58 vessels have been collected from the database and included in the input file. However, relevant information about all the vessels cannot be gathered from the scaffold database and the 3D models which led to a selection set of 42vessels. The input columns are – Type of Structure, Length, Breadth, Height, Elevation of Construction, Scaffold Volume of work, and Scaffold Man-hours of work. All the vessels are erected at ground elevation; hence, they all have the same value — zero.Scaffold Man-hours of work is the desired output from the analysis and Weka analysis is run for the same. Linear Regression without attribute selection was used for analysis using 10-fold cross validation technique. For any scaffold requests which have been tagged with more than one vessel, the scaffold man-hours of work have been equally divided among the vessels. A sample input data extracted from the scaffold database for a particular vessel has been shown in Figure 5-6.

ScaffoldID	Date Requested	Date Required	Requested by Trade_Purpose	Area_Location	Elevation	Actual Volume	Units	Erection Mhrs A	Completion Date
A-299	15-Oct-09	19-Oct-09	Electricians	V-42201-01-H	Various	29.25	m3	67	10/20/2009
A-006	30-Mar-09	31-Mar-09	Boilermakers	V-42301/42201	637.000	19	m3	26	04/02/2009
A-011	08-Apr-09	08-Apr-09	Boilermakers	V-42201/42301	636.000	0	m3	6	04/08/2009
A-010	06-Apr-09	07-Apr-09	Pipefitters	V-42301/42201	638.000	12	m3	32	04/08/2009
A-031	19-May-09	27-May-09	Electricians	South of V-42201/42301	630.000	0	m3	0	n/a
A-034	20-May-09	29-May-09	Electricians	V-42201	637.500	13.5	m3	75	07/02/2009
A-057	02-Jun-09	25-Jul-09	Electricians	V-42201	630.000	12	m3	29	07/22/2009
A-058	09-Jun-09	22-Jun-09	Fireproofers	V-42201	Grade	583.8	m3	310	07/07/2009
A-275a	29-Sep-09	12-Oct-09	Insulators	V-42201	630.000	72	m3	145	10/06/2009
A-065	16-Jun-09	25-Jun-09	Electricians	V-42201/42301	636.000/638.000	168	m3	219	06/26/2009
A-072	25-Jun-09	29-Jun-09	Electricians	V-42201	640.000 to 644.000	13.5	m3	47	07/02/2009
A-397	26-Nov-09	01-Dec-09	Heat Tracing	V-42201	647.500	68.75	m3	69	1/7/2010
A-452	12-Jan-10	13-Jan-10	Electricians	V-42201	50.002	9	m3	30	1/18/2010
A-616	30-Apr-10	03-May-10	Instrumentation	V-42301/V-42201	623.000	64	m3	18	5/3/2010
A-650	07-Jun-10	08-Jun-10	Electricians	V-42201	644.000	0	m3	0	n/a
A-658	08-Jun-10	14-Jun-10	Electricians	V-42201	640.000	0	m3	0	n/a
A-651	08-Jun-10	10-Jun-10	Electricians	V-42201	631.000	0	m3	0	n/a
A-654	08-Jun-10	09-Jun-10	Electricians	V-42201	631.000	18	m3	35	6/16/2010
A-657	08-Jun-10	15-Jun-10	Electricians/HT	V-42201	634.000	51	m3	46	6/17/2010
A-696	28-Jun-10	28-Jun-10	Electricians	V-42201	629.000	6	m3	11.5	7/2/2010
A-749	27-Jul-10	29-Jul-10	Electricians	V-42201	622.000	15	m3	22	8/3/2010
A-771	11-Aug-10	13-Aug-10	Electricians	V-42201	631.000	20	m3	14	8/12/2010
A-789	17-Aug-10	18-Aug-10	Electricians	V-42201	631.000	8	m3	10	8/18/2010
A-861	13-Sep-10	13-Sep-10	Electricians	V-42201	637.000	56	m3	63	9/23/2010
A-955	04-Oct-10	07-Oct-10	Boilermakers	V-42201	622.500	3.5	m3	7	10/5/2010

Figure 5-6 Sample extracted data from database

Autodesk Navisworks API generated over the course of the project is used to derive the geometrical parameters of the vessels. No file or separate database could be found to determine the weights of the vessels, and hence, weight has not been chosen as an input factor for the vessel analysis. Figure 5-7shows the set of all the vessels in Navisworks 3D file for the project.

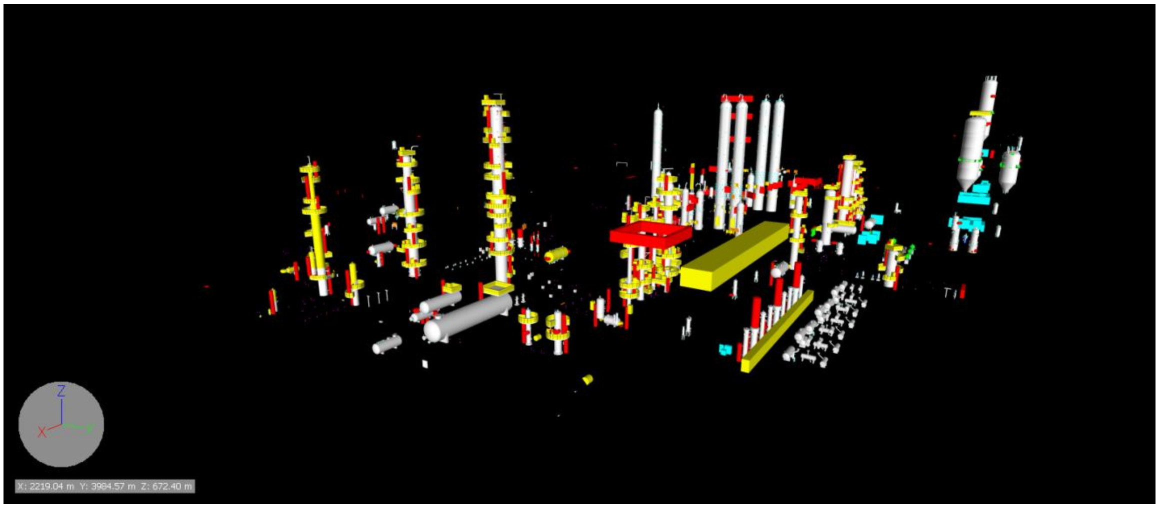


Figure 5-7 Vessels in the project

The volume of work which is the geometry calculated from the API Navisworks for vessel analysis was plotted against the scaffold man-hours of work from the database to see the dependence of parameters on the output.

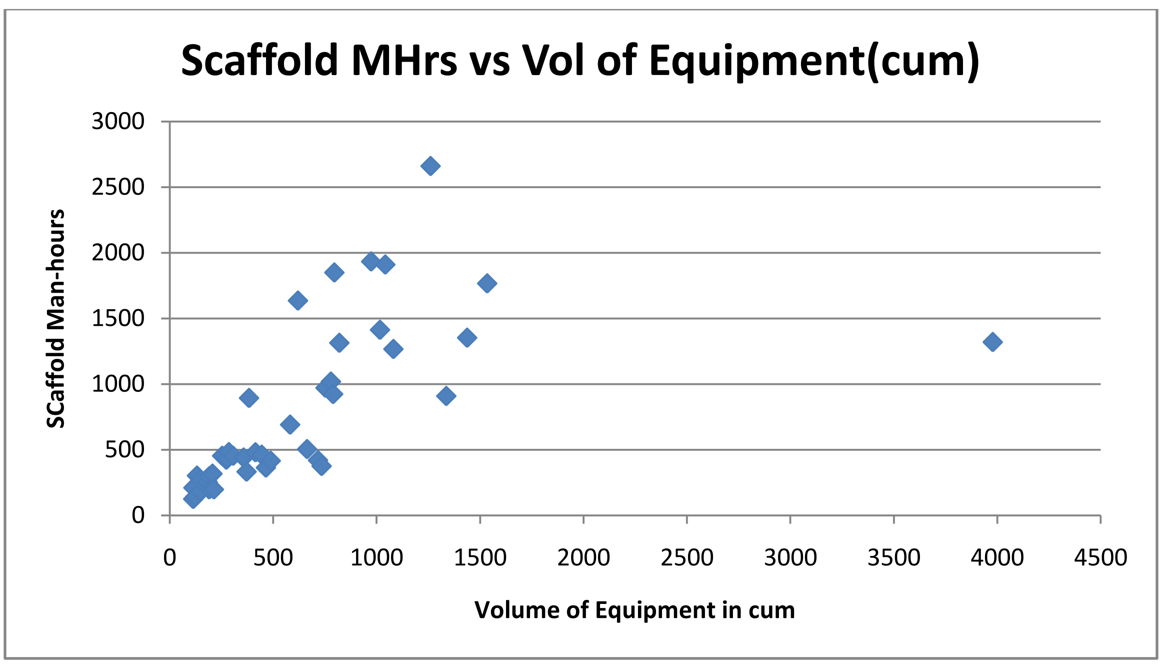


Figure 5-8 Scaffold man-hours vs. volume of work for vessels

As seen from the above figure, scaffold man-hours of work follows almost a linear pattern as the volume of the vessel in cum. This predicts that for the vessel analysis, geometry of the equipment is the major affecting factor. The weight of the vessels was not available to be used and checked if the model performs better or not and all vessels are constructed from ground level, hence, elevation of construction is not a determining factor in vessel analysis.

5.7.1Vessel Data Mining Model

Figure 5-9shows the output of Weka analysis on the vessel input data. The correlation coefficient is 85.91%; however, the error rates are quite high.

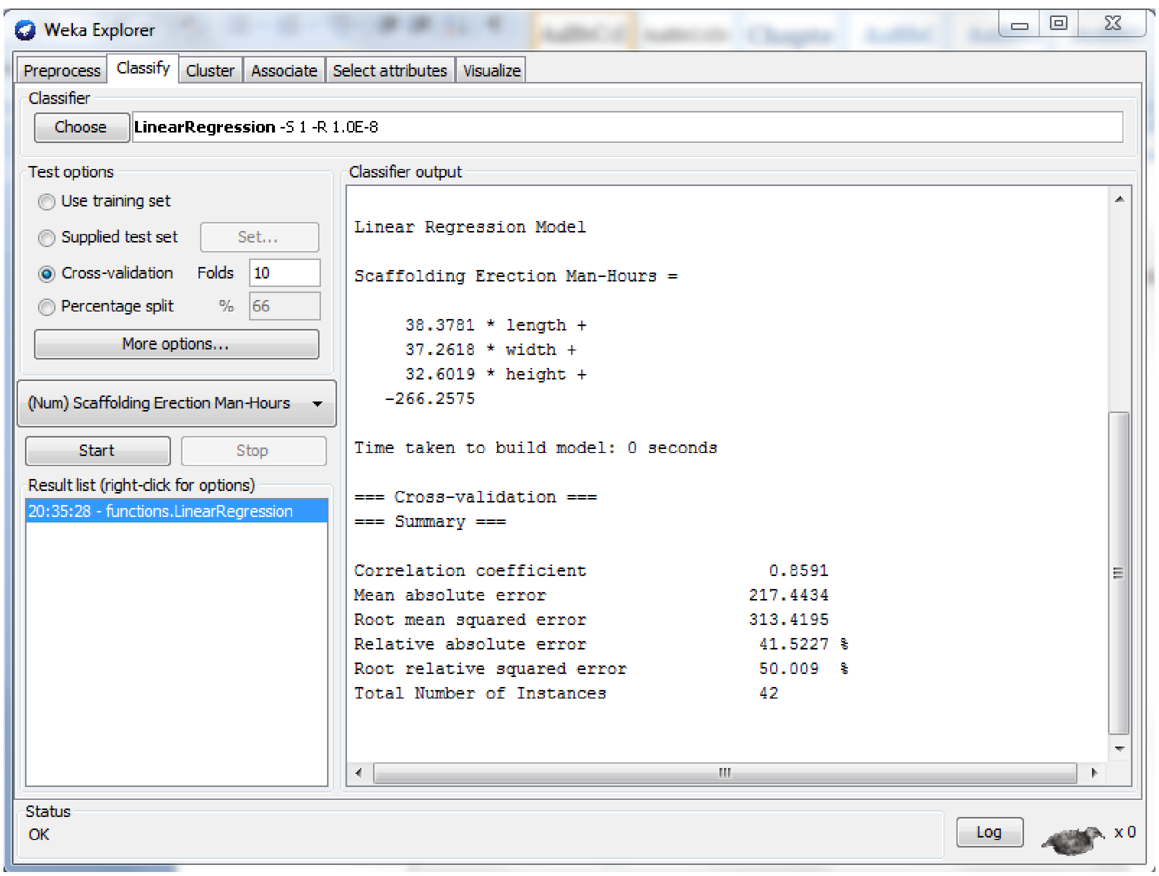


Figure 5-9Wekamodel for vessels

Predicted scaffold man-hour outputs are tabulated against the actual man-hour outputs and the average error for the model is calculated. The average error comes to be approx.33%. This error, however, seems large; some of it can be attributed to the errors in the database itself, which have been explained earlierin this chapter. Appendix C[6]contains the compared values and error analysis for vessel data mining model.

5.8Extraction of Module Information

Extraction of module information was also performed in the same manner as vessels. A list of 124 modules was listed in the equipment list of the project. As was the case in vessels, the information in the scaffold database seemed too inaccurate for a lot of these, most of them were found to be using zero man-hours of work, as per the database.Hence, a selection set of only 95 modules was selected and used for analysis. Unlike vessels, it is difficult to confirm the reliability and accuracy of scaffold man-hours data.Scaffold man-hours of work and scaffold volume of work were extracted for the modules from the scaffold database. This, however, was a more complicated procedure than for vessels. The nomenclature of vessel is straightforward which is simple like “V-12345” and it is easy to maintain in the database. The same for modules is more error prone when maintained. A typical module is named like ‘421A – R201.’ The first part of the nomenclature depicts the major construction area to which the module belongs while the second part points out the module number. Now the error arises from the fact that a module named, for e.g.R201, can exist in two different construction work areas. So there are two entries, for e.g. a module called 421A-R201 and an entry called 421R-R201. This generates the possibility of errors when maintaining data for the modules. The same was

[6]Data is scaled for confidentiality reasons.

also discovered when manually extracting information about the modules. Sometimes it is not possible to predict what exact module is being talked about and to which construction work area it belongs. However, a considerable amount of time was spent to extract the best possible data from the database using the 3D and 2D models of the project site. A lot of entries in the database predicted zero man-hours of work for certain modules. There could be two different reasons for such entries, one being an error in maintenance of relevant data in the database, and the other being special case of modules which do not require scaffolding. Either case, such entries were removed from the final selection set of modules as the inclusion was resulting in negative predictions.

The Navisworks API generated over the course of this research work was used to derive the geometric parameters of the modules. The weight information for the modules was provided in another database maintained by Company A for lift design studies and is called the Equipment List. The input table columns are Type of structure, Length, Width, Height, Weight, Scaffold Volume of work, Scaffold Man-hours of work. Figure 5-10shows the 3D Navisworks file containing all the modules in the construction work site.

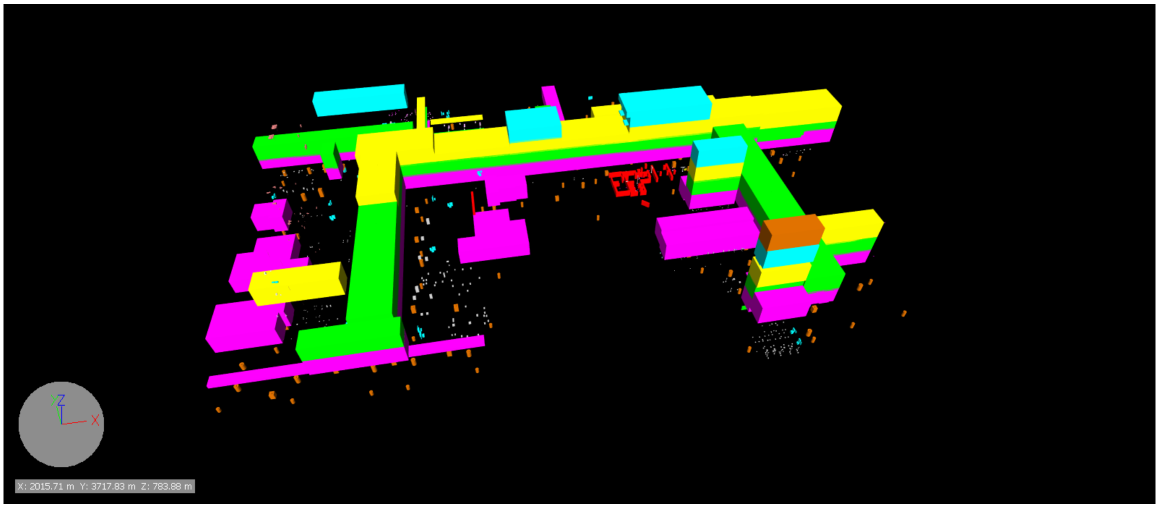


Figure 5-10 Modules in the project

The volume of the envelope surrounding the vessel which provides the length, width and height of the module for the data mining analysis was plotted against the scaffold man-hours of work from the scaffold database. Figure 5-11shows the comparative diagram. It can be seen from the figure that the geometry alone cannot be deemed the single most factor that affects scaffolding. This justifies the use of other factors like weight and elevation of construction in the data mining exercise performed on the available data set.

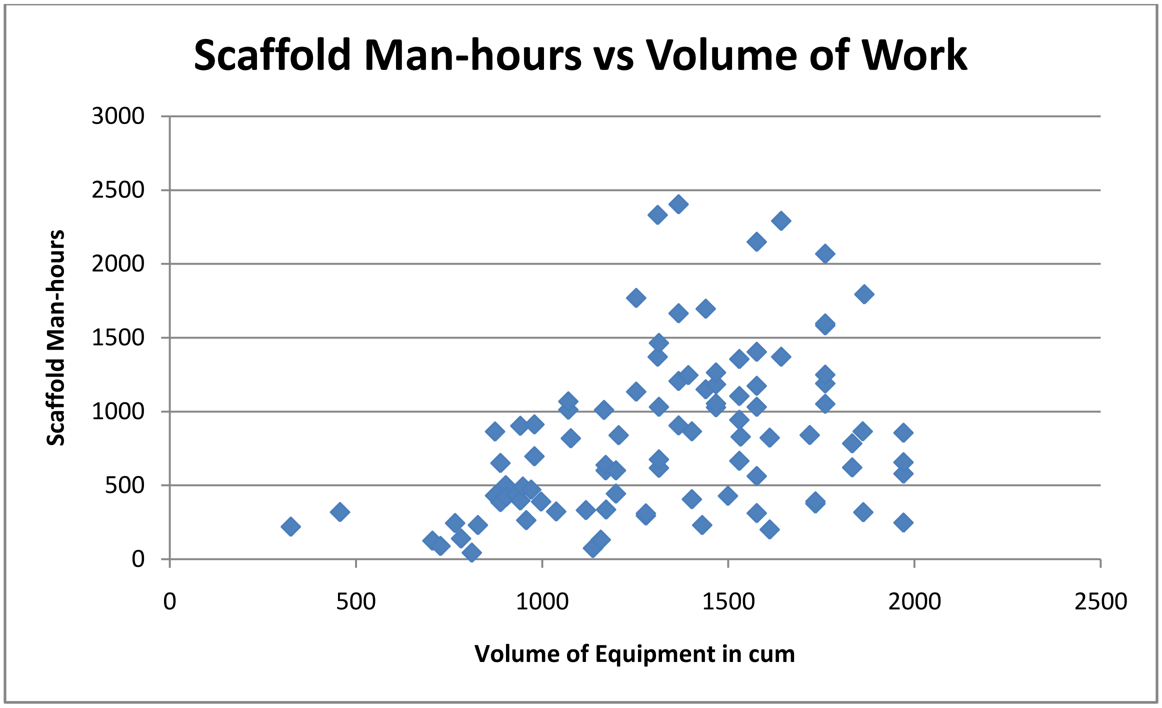


Figure 5-11 Scaffold man-hours vs.volume of work for modules

Figure 5-12shows the dependence graph of scaffold man-hours of work on the weight of the equipment. As seen from the figure, it is difficult to set a pattern especially linear relationship between just the weight and scaffold man-hours of work for the modules.

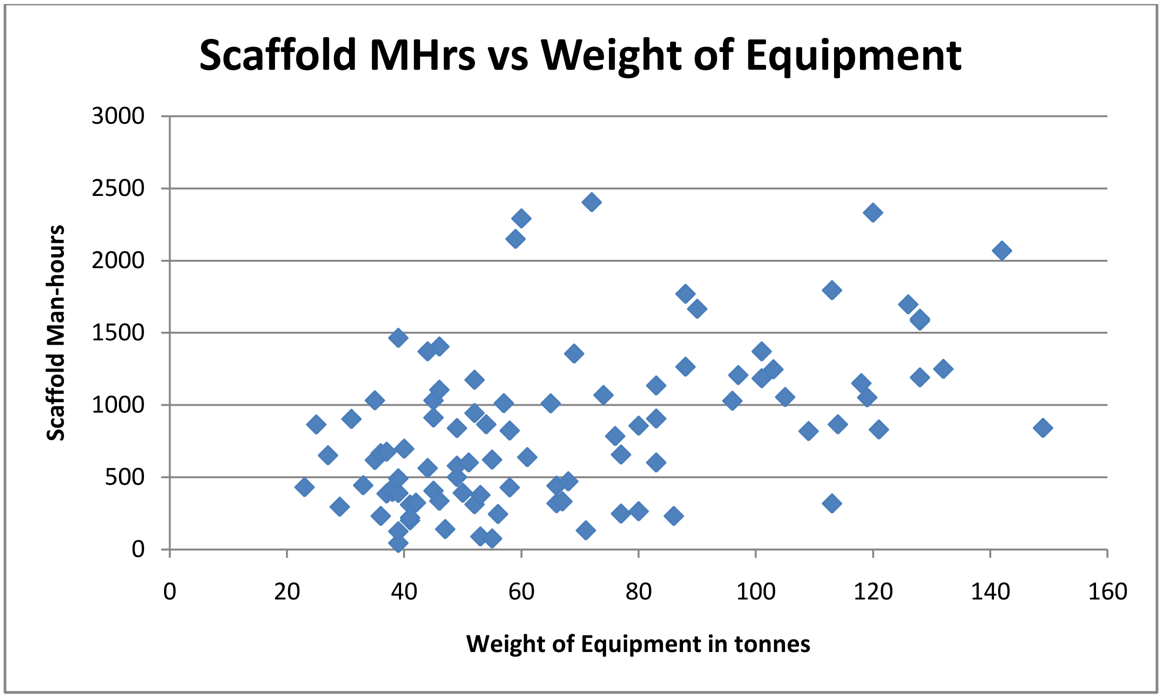


Figure 5-12 Scaffold man-hours vs.weight of equipment

Figure 5-13shows the amount of scaffold man-hours of work consumed by each type of module over the total scaffold hours taken by all modules, as per the extracted database. It can be seen from the graph that pipe racks consume the most amount of man-hours, which was also evident from the trade wise man-hour distribution graph.

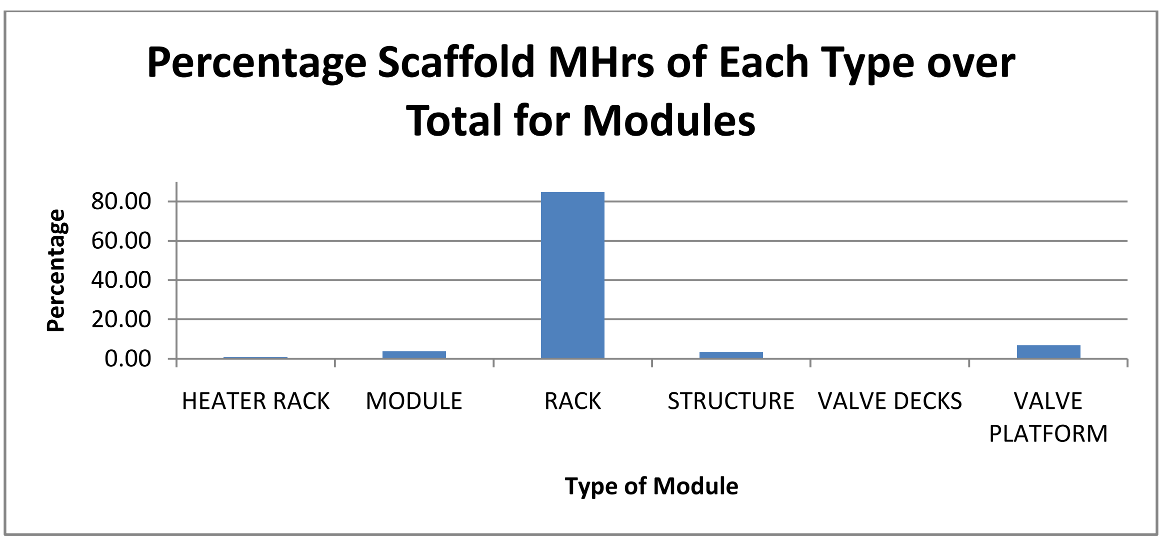
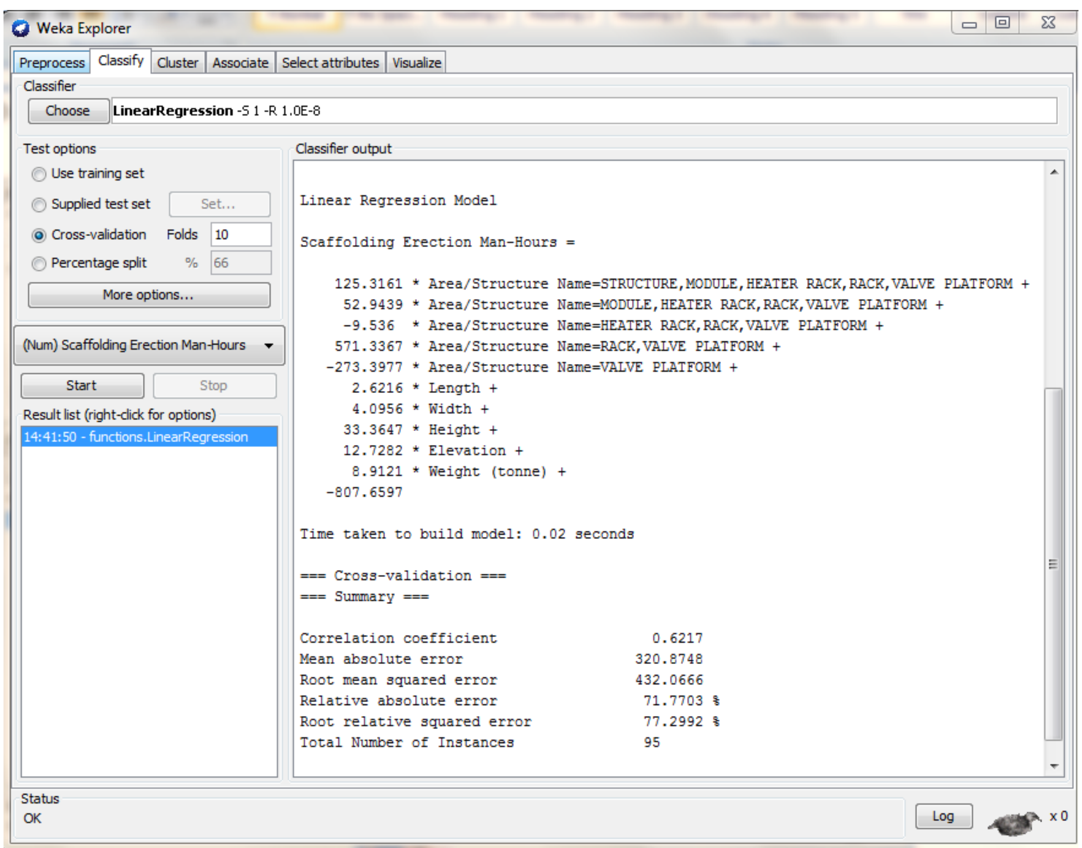


Figure 5-13 Percentage of hours consumed by individual equipment type over total value for modules

5.8.1 Module Data Mining Model

Figure 5-14shows the output of Weka analysis on the module input data. The correlation coefficient is 62.17%; however, the error rates are quite high as was the same in vessel analysis. The reason for the same is the inaccuracies in module data extracted from the scaffold database. Predicted scaffold man-hour outputs are tabulated against the actual man-hour outputs and the average error for the model is calculated. The average error comes to be approx. 54%. This error, however, seems large; it can be attributed to the errors in the database itself, which have been explained earlierin this chapter. Appendix D[7]contains the compared values from the model for error analysis.



[7]Data is scaled for confidentiality reasons.

Figure 5-14Wekamodel for modules

5.9 Uncertainties in Models

The linear expression derived for equipment, either vessel or module, can be represented as:

$$y = A0 + A1(x1) + A2(x2) \ldots\ldots Ap(xp);$$

'y' being scaffold man-hours of work and x1,x2…..xp being the input parameters like length, weight etc. The coefficients A0, A1…Apdo however share a level of uncertainty. Monte Carlo Simulation techniques can be used as a means to reflect the uncertainty inherited in thesefactors derived for the linear expression. Software like @RISK or EasyFit, can be used to fit the derived sample set of factors individually into probabilistic distributions like Normal, Beta etc. This representation would present a more accurate picture on the usability of the model for different companies and can be researched and implemented in future work.

In addition to the coefficients, some of the parameters in the linear expression derived for vessels and modules cannot be used as deterministic inputs. Factors like trade hours of work or weight of the equipment are at most times uncertain. Hence, the model demands the inclusion of stochastic nature in the inputs. This is resolved in the present research by developing the final estimation tool as a simulation template. This allows the user to input values in some of the major probability distributions, the final output derived from the template would now be a range estimate. A range estimate enables the tool to be closer to reality than a deterministic number.

5.10Comparison with Other Estimation Methods

The results obtained from the above analysis are compared with other estimation methods found from existing literature works. The existing methods are described in Chapter 2—Literature Review. The closest estimating method that can be used for multiple scenarios in industrial construction is the Technical Calculation and Estimator's Man-Hour Manual by Marko Bulic[19]. The manual computes the volume of scaffold required as a function of the weight of the structure to be erected on site. The volume is then mapped to the man-hours of work needed through some tables. The tables for man-hour calculation are shown in Figure 2-17, and the volumetric estimating procedure is discussed in Appendix E[8]. The figure below describes the comparison done for all the modules from the total list. The same cannot be done for vessels as the weight of vessels are not available.

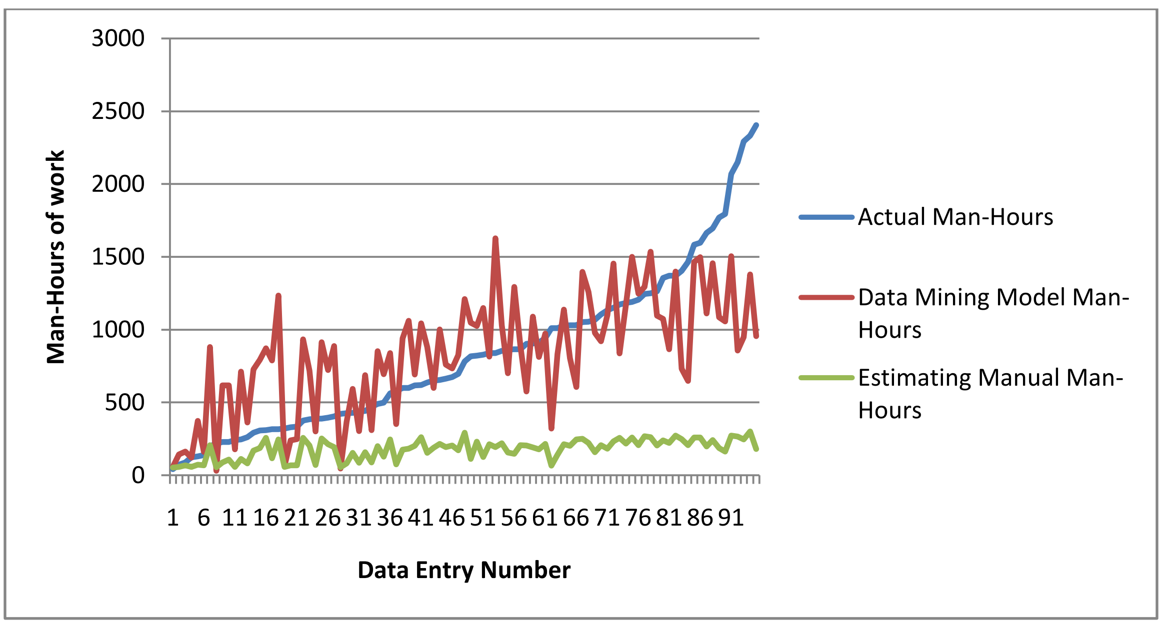


Figure 5-15Comparison of results

As seen from the above comparison, the man-hours calculated from the estimator's manual do not come close to the actual man-hours of work, while the module analysis

[8]Values are removed as the manual is not free to be used.

still predicts a very close value. This can be attributed to the fact that the estimator's manual is quite unclear about the concept of weight of the structure. The weight can be the overall weight of the structure when it is installed or the weight of the structure when all the piping, insulation, electrical works have been performed on the module and it is fully erected. Also, weight as sole factor for determining scaffolding requirements does not seem justifiable, as small equipment can have the same weight as large equipment, while the scaffolding requirements for both would be considerably different in most cases.

5.11Scaffold Template — Introduction

This section explains in detail the objective, functionality and working of the Scaffolding Simulation Template. The use of a simulation platform for the development template opens the door for any further development in the line of this research. Any new functionality can be added to the template without changing the core of the operating algorithm. The section explains the scope of the template, the inputs, the modeling principles and techniques and the outputs generated.

5.11.1Scope

There are two methods of estimation in the scaffolding template:MACRO and MICRO level of estimation, as has been described in Chapter 3. The MACRO level of estimation is based on the data mining experiments conducted by Ms. Lingzi Wu on the same scaffold data, as described in Chapter 5. The parameters have been used based on her research predictions and used as a separate estimating tool within the template.

The second part of the template and the objective of this research work is the MICRO estimation. This is a more generic way of estimating scaffolding requirements for industrial construction and can be generalized for any company. The working styles of different companies in performing the scaffolding process can be quite different, and hence, the values obtained from data mining analysis that are part of this template would have to be modified to suit the needs of other companies. The template in its present form contains relationships and values based on the data mining analysis performed in this chapter and for works for vessels and modules on an industrial construction site. With new data, the scope for other aspects of construction like process equipment, stair towers etc. can also be added into the functionality of the template. At present, sufficient relevant data is not found to do the same.

The template takes the inputs from the user, relates it to the inherent values already existing in the template from data mining exercises,and predicts the desired output. The type and nature of inputs and outputs are explained later in the section. The user can decide on the available inputs at hand and input values in the type of estimate that seems more suitable, i.e. MICRO or MACROestimate. The outputs for both estimates are separately depicted in the template for easy understanding. The overall look and the nature of the template have been kept simple and user friendly for this to be easily understandable and usable for a novice user as well.

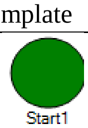
5.11.2Opening the Template

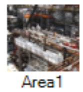
The template has been coded in Simphony 4.0 simulation platform, version 4.0.0.114. The coding is done in C# programming language under .NET 4.0 frameworks. The program is written as a Class Library which creates a .dll (Dynamic-Link Library) file after the program is saved. The file can be just copied and pasted into the Simphony 4.0 installation folder. The link of pasting the .dll file is C:\Program Files (x86)\Simphony.NET 4.0\Templates. However, the location of the final folder can be different in other computers. Simphony UI is then opened and the scaffolding template is added to it for use. Once the template has been opened in Simphony UI, the elements of the template can be dragged onto the modeling window for use. The modeling elements have to be connected with arrows for the model to work. Any incomplete model would result in errors. When an element on the modeling window is selected, the right side of the template shows all the associated properties, inputs, outputs etc. for that modeling element.

5.11.3Modeling Aspects

There are three basic elements in the modeling of a construction scenario. These elements, when joined together, allow the user to complete the construction of a model in the Simphony 4.0 user interface.Table 5-1shows the three modeling elements and their description.

Table 5-1 Modeling elements

Name of Element	Symbol in Template	Purpose
Start		• Generates an entity and starts the simulation process.
End		• Simulation ends when the entity reaches this element.

Area		• Represents a construction area in a project. • An area element can represent one structure on site or a whole construction area depending on the type of estimate selected. • Takes a set of inputs, maps them using relationships already fed in the element to produce outputs. • The outputs can be derived by selecting the element after the simulation is complete.

Any model would contain one Start element and one End element while there can be any number of AREA elements in between. All the elements have to be connected with connecting arrows to allow the movement of entities from start to end. A simple model in the template is depicted in Figure 5-16.

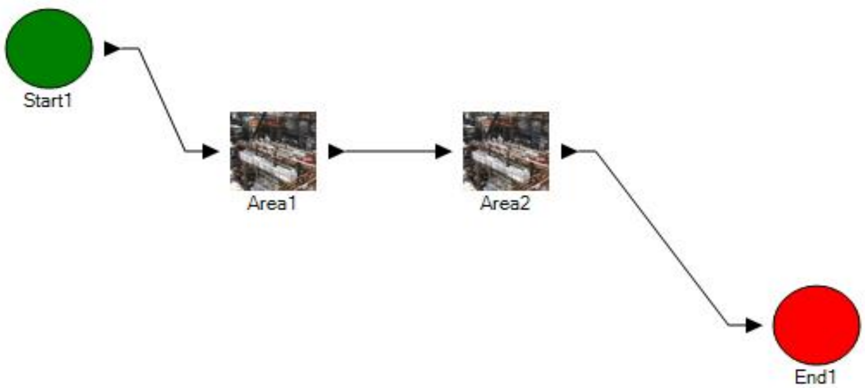


Figure 5-16 Sample model

5.11.4Inputs

There are two sets of inputs which the user enters for the modeling of a construction area in an industrial site. The first is if the estimate is desired for MACRO estimation scenario and other for the MICRO estimation scenario. The inputs have been separated from each other under separate headings and the user can simply enter the values for the desired estimating method. The AREA element in the modeling window is the main element in the model. The area elements on the modeling window can be selected and the relevant inputs be entered. The model is capable of taking stochastic inputs for numerical values in the form of common probabilistic distributions. Simulation for the model containing stochastic inputs needs to be run for more than one time to get a range estimate of outputs. The number of runs can be changed under RunCount tab in the modeling parameters. The following section describes the type and nature of inputs for both levels of estimation.

5.11.4.1MACRO Estimation Inputs

Inputs for generation ofMACRO estimate are put under the section titled "MACRO ESTIMATION INPUTS" in the scaffolding template. The list of inputs and their relationships has been derived based on a set of data mining experiments conducted on the scaffold data, described in Chapter 4[28].The following inputs are required for the generation of a MACROestimate through the simulation tool:

- Trades – The name of all the trades that work in a construction work area. There is a selection list of 8 trades for the user to select from the menu. These are:
    1. Civil
    2. Electricians
    3. Fire Proofers
    4. Instrumentation
    5. Insulators
    6. Iron Workers

7. Mechanical

8. Pipe Fitters

- Trade Hours – Each selected trade in a construction work area is assigned the estimated amount of trade hours that would be assigned or used in that area. The use of simulation template allows the user to input these values in the form of all major probability distributions. Figure 5-17 shows the input window for trades and their working hours.

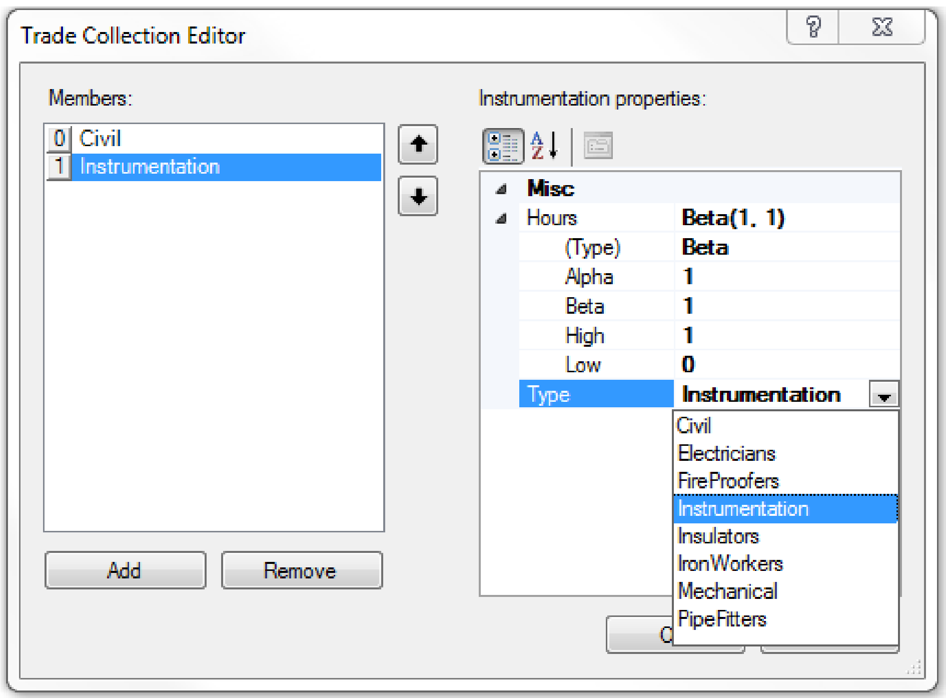


Figure 5-17 Sample trade input window

- AreaDefn – This defines the size of a construction work area. The user can select from the following three choices:

1. Small

2. Medium

3. Large

- Complexity – This defines the complexity of a construction work area. The user can select from the following two choices:
    1. Simple
    2. Complex
- Congestion – This defines the congestion of a construction work area. The user can select from the following three choices:
    1. Less_Congested
    2. Congested
    3. Not_Congested

5.11.4.2MICROEstimation Inputs

Inputs for generation of MICRO estimate are put under the section titled "MICRO ESTIMATION INPUTS" in the scaffolding template. The list of inputs and their relationships has been derived based on a set of data mining experiments conducted on the scaffold data described in Chapter 5. The following inputs are required for the generation of a MICROestimate through the simulation tool:

- Equipment – This contains the list of all types of equipment for which the simulation template can predict outputs. The user can select the equipment from an inbuilt dropdown menu from the following options:
    1. Plane Module
    2. Structure
    3. Valve Decks
    4. Rack Module

5. Valve Platform

6. Heater Rack

7. Vessel

- Geometry of the Equipment – This contains the cubical dimensions of the envelope surrounding the modules or vessels. The three parameters are length, width and height of the equipment. The unit of measurement is meters.
- Elevation – The elevation of construction of the equipment above the ground level of the project site. This is in meters. This input can be entered in the form of major probability distributions.
- Weight – The weight of the equipment to be erected. The unit of measurement is metric tonnes. This input can be entered in the form of major probability distributions.

Figure 5-18shows the input window for the MICRO estimation part of the template.

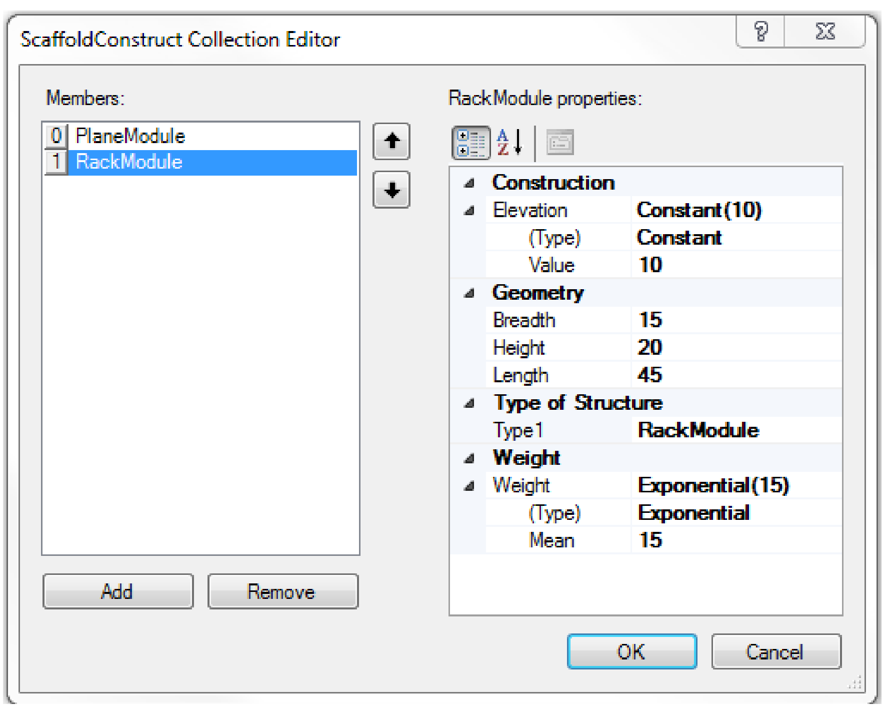


Figure 5-18 Sample MICROinput window

5.11.5Outputs

The template produces scaffold man-hours of work as the output from any kind of estimating mechanism selected in the template. The output for MACRO estimate and MICRO estimate is kept under separate tabs for easy understanding. The outputs are collected as statistics and present the user with all relevant statistical parameters for scaffold man-hours of work like mean, standard deviation etc. This sample set would comprise of the number of runs the user inputs for the simulation model to run. The program also provides the cumulative distribution graph of all runs of the simulation model. Interpretation and usability of the output would largely depend on the user and the scenario for which the analysis is performed. For e.g. at a bidding stage of the project, say a 90 percentile value can be selected as the number to bid for or some user can use the mean of all runs as the estimating output from the template. A sample output is shown inFigure 5-19.

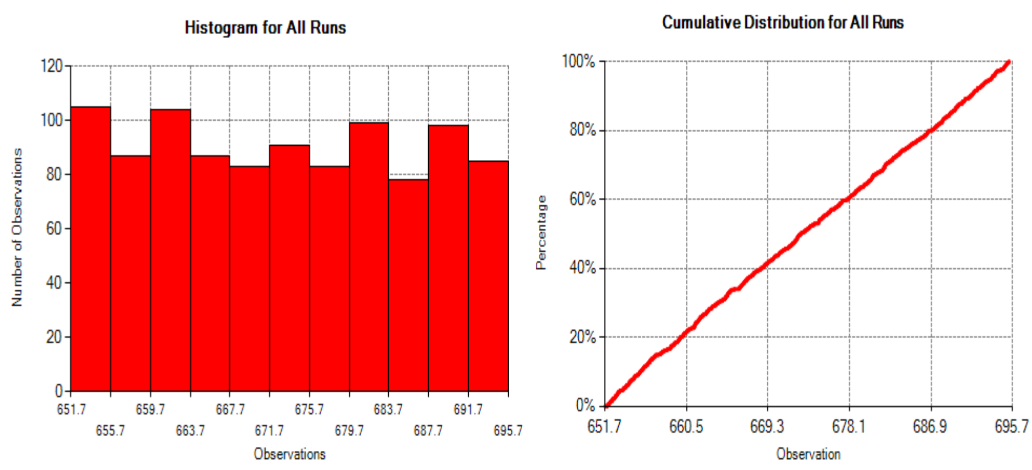


Figure 5-19 Sample output

Chapter 6 — Conclusions and Recommendations

6.1 Summary of Work

Estimating and planning scaffolding for industrial construction is a widespread concern in the construction industryand this is research is one of its kind in addressing the problem at hand. The first objective in this research was to find out the loopholes from construction research point of view in the scaffolding processes existent in companies. Then, the question to be addressed was, “what could be done to manage such concerns and what tools or mechanisms are needed?” The analysis and template developed over the course of this project try to address the main concerns and provide a way to tackle them. All companies have different way of analysing scaffolds needed in their construction projects, and hence, one set of values or methods is difficult to address for all, in a wholesome manner. However, the generic algorithm for MICRO estimation developed over the course of this research is applicable to one and all. The values for relationships of input parameters to concerned outputs can be derived for companies based on any existent data they have. The research also analyzes the scaffold process flow on site and provides a more systematic and productive flow chart for effective planning and construction of scaffolds on site. The values derived from the database for the case study are not accurate, which led to considerable higher error rate in vessel and module analysis. However, properly maintained and accurate data would allow for a better relationship model. The process of effectively gathering and maintaining data is also described in earlier chapters.

6.2 Permanent Scaffold

Scaffolds are temporary structures that facilitate the workers to work on higher than ground elevations at a construction site. However, it can be argued in some situations "why isn't the scaffold made part of the original structure itself?" These situations would occur based on the following conditions:

- The point of access on a structure has to be added several times over the course of the project and lifetime like regular maintenance operations.
- There is extra room for the addition of scaffold structure and would not hamper site installation.
- Structural integrity of the assembled structure would not fail due to the addition of scaffolding access.
- The addition of scaffold access is cost effective and would be within the cost scope of the project.

Such scaffolding construction would involve the Construction Engineers and even the Scaffold Superintendent to be involved in the design phase of the project to eliminate any confusion at the site. This can also significantly increase productivity and save labor hours of work.

6.3Future Developmentin Industrial Scaffold Research

The template is the stepping stone to develop a simple yet versatile estimating tool to predict industrial construction scaffolding parameters. The use of probabilistic inputs allows the user to predict values even if the exact level of surety does not exist for the input values. Future research in the field of industrial construction scaffolding would lead to enrichment of the template in different aspects other than what it does at present status. The first thing is the incorporation of material estimate in the template. Material data has to be maintained over the course of the project to link the volumetric or linear amount of scaffolding to the amount and list of materials it would need to construct. This would be possible by closely analyzing the type and amount of materials that are normally available in an industrial construction site and the building procedures used on site for construction of scaffolds. Also, the type of scaffolds to be constructed can be something that can be incorporated into the template outputs. The user would be able to select the type of scaffold and be able to compare it with other types to get the best construction scenario. This would also lead to savings in overall project cost by formally optimizing the type and materials used for a particular scaffolding need on the construction site.

The last option,thoughprogress is certainly not limited to it, would be the linking of the template with the project schedule. This would allow the efficient planning of the scaffolding needs of the project. The schedule would be able to predict at what dates a particular vessel or module etc. is supposed to start getting erected on site, and since scaffolding is needed to support such processes, the need and amount of scaffold would be known beforehand. This would also allow maintaining an optimized number of scaffold crews and checking available rental materials to minimize any construction delays. The scaffolding estimation tool is the need of the hour for industrial construction and the present template presents the much needed platform to reach the final objective.

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Appendix A— Navisworks API Code

```
Option Explicit On
#Region "TestAPI"
Imports Autodesk.Navisworks.Api

Imports Autodesk.Navisworks.Api.Plugins
Imports System.Windows.Forms
Imports System.IO

' Naming the API and adding as a Plugin in Navisworks
<PluginAttribute( _
        "Model1.MyAddIn", _
         "Company A", _
         ToolTip:="Navisworks Selection Model", _
DisplayName:="API Model.net", _
         Options:=PluginOptions.None)> _
<AddInPluginAttribute(AddInLocation.AddIn)> _
Public Class Model1
   Inherits AddInPlugin


   Public Overrides Function Execute(ByValParamArray parameters As String()) As Integer

      'Open Input File
      Dim Readdialog = New OpenFileDialog()
Readdialog.Filter = "CSV files (*.csv)|*.csv|Text files (*.txt)|*.txt"
Readdialog.RestoreDirectory = True

      Dim linecount As Integer
      If Readdialog.ShowDialog() = DialogResult.OK Then

         'Count the number of entries in Input File
linecount = File.ReadLines(Readdialog.FileName).Count()
      End If

      'Initialize temporary Arrays that save the input file entries
      Dim temp As String() = New String(linecount - 1) {}
      Dim XCoord As Double() = New Double(linecount - 1) {}
      Dim YCoord As Double() = New Double(linecount - 1) {}
      Dim ZCoord As Double() = New Double(linecount - 1) {}
      Dim HCoord As Double() = New Double(linecount - 1) {}

      'Reading the input file and saving as an array
      Using stream1 = New FileStream(Readdialog.FileName, FileMode.Open, FileAccess.Read)
         Using reader = New StreamReader(stream1)

            Dim iAs Integer = 0
            While Notreader.EndOfStream
               Dim line = reader.ReadLine()
               Dim cells = line.Split(","c)

temp(i) = cells(0)
```

```
XCoord(i) = Double.Parse(cells(1))
YCoord(i) = Double.Parse(cells(2))
ZCoord(i) = Double.Parse(cells(3))
HCoord(i) = Double.Parse(cells(4))

i += 1
            End While
         End Using
      End Using

      'Initialize temporary arrays to save four entries from the input file
      Dim X1 As Double() = New Double(3) {}
      Dim Y1 As Double() = New Double(3) {}
      Dim Z1 As Double() = New Double(3) {}
      Dim H1 As Double() = New Double(3) {}

      Dim k As Integer = 0

      'User inputs the output file name and location
      Dim dialog = New SaveFileDialog()
dialog.Filter = "CSV files (*.csv)|*.csv|Text files (*.txt)|*.txt"
dialog.RestoreDirectory = True

      If dialog.ShowDialog() = DialogResult.OK Then
         Using stream = New FileStream(dialog.FileName, FileMode.Create, FileAccess.Write)
            Using writer = New StreamWriter(stream)
               writer.WriteLine("""{0}"",""{1}"",""{2}"",""{3}"",""{4}"",""{5}"",""{6}""", "Equip Name",
"MaxX", "MinX", "MaxY", "MinY", "MaxZ", "MinZ")

               'While loop runs till it has exhausted all entries in the Input File
               While k <temp.Length

                  'Copy four entries from Input file to temporary array
Array.Copy(XCoord, k, X1, 0, 4)
Array.Copy(YCoord, k, Y1, 0, 4)
Array.Copy(ZCoord, k, Z1, 0, 4)
Array.Copy(HCoord, k, H1, 0, 4)

                  'Calculate the coordinates of the Cuboid Volume Box
                  Dim maxX As Double = X1.Max()
                  Dim maxY As Double = Y1.Max()
                  Dim maxZ As Double = Z1.Max()
                  Dim minX As Double = X1.Min()
                  Dim minY As Double = Y1.Min()
                  Dim minZ As Double = Z1.Min()
                  Dim Height As Double = H1.Max()

                  Dim CategoryName, PropertyNameAs String

                  'User inputs the Category and Property that needs to be searched
CategoryName = InputBox("Enter the name of the category")
PropertyName = InputBox("Enter the name of the property")


' gets the current Navisworks document
                  Dim oDoc As Document = Autodesk.Navisworks.Api.Application.ActiveDocument

                  'Creates a new search
                  Dim search As New Search()
```

```
search.Selection.SelectAll()

            'Adds a new search condition
search.SearchConditions.Add(SearchCondition.HasPropertyByDisplayName(CategoryName, PropertyName))

            'Gets the resulting collection

            Dim SearchResults As ModelItemCollection = search.FindAll(oDoc, True)

oDoc.CurrentSelection.CopyFrom(SearchResults)

            'creates the volume box from cuboid coordinates
            Dim oNewBox As New BoundingBox3D(New Point3D(minX, minY, minZ), New
Point3D(maxX, maxY, maxZ + Height))

' check the items whose boxes are within the specified bounding box above. Concept taken from
"http://adndevblog.typepad.com/aec/2012/05/search-model-items-within-a-volume-and-apply-
transformation.html"dated 01/04/2013

            Dim items As IEnumerable(Of ModelItem) =
SearchResults.DescendantsAndSelf.Where(Function(x) oNewBox.Contains(x.BoundingBox()))


' Select the items in the search results based on above operation
oDoc.CurrentSelection.CopyFrom(items)

' Save the Geometry and name of all the selected item
            For Each Item In items

              If (Item.HasGeometry = True) Then



                Dim FirstProperty As DataProperty =
Item.PropertyCategories.FindPropertyByDisplayName(CategoryName, PropertyName)
                Dim temporary As String = FirstProperty.Value.ToString()

                Dim length As Double = Item.BoundingBox.Max.X - Item.BoundingBox.Min.X
                Dim breadth As Double = Item.BoundingBox.Max.Y - Item.BoundingBox.Min.Y
                Dim heightofstr As Double = Item.BoundingBox.Max.Z - Item.BoundingBox.Min.Z

writer.WriteLine("{0},{1},{2},{3},{4},{5},{6}", temporary, Item.BoundingBox.Max.X,
Item.BoundingBox.Min.X, Item.BoundingBox.Max.Y, Item.BoundingBox.Min.Y, Item.BoundingBox.Max.Z,
Item.BoundingBox.Min.Z)
              End If
            Next
            'Write two blank lines before reading next set of coordinates
writer.WriteLine()
writer.WriteLine()
            k = k + 4
          End While
        End Using
      End Using
    End If

    'Api function is complete
MessageBox.Show("completed!")
    Return 0
  End Function
```

End Class
#End Region

Appendix B— Sample Output

Equip Name	MaxX	MinX	MaxY	MinY	MaxZ	MinZ
DisplayString:LIGHTWOOD2	10850.74	7550.736	-7143.83	-14043.8	200	200
DisplayString:LIGHTWOOD3	2024.487	250.7359	-9543.83	-12314.5	7200	6900
DisplayString:LIGHTWOOD4	14450.74	250.7363	-10593.8	-14043.8	7200	6900
DisplayString:LIGHTWOO13	11916.45	8822.331	-10487.7	-12022.8	11601	11601
DisplayString:DULLSTEE27	10850.74	10319.37	-8376.54	-8913.28	200	150
DisplayString:DULLSTEE28	10850.74	10231.06	-8603.39	-8913.28	400	350
DisplayString:DULLSTEE29	10850.74	10230.97	-8913.28	-9213.96	600	550
DisplayString:DULLSTEE31	10828.4	10291.67	-8913.96	-9445.32	800	750
DisplayString:DULLSTEE32	11448.08	10828.4	-8913.96	-9223.84	1600	1550
DisplayString:DULLSTEE33	11129.08	10828.4	-8913.96	-9533.73	1200	1150
DisplayString:DULLSTEE34	11359.77	10828.4	-8913.96	-9450.69	1400	1350
DisplayString:DULLSTEE35	11365.14	10828.4	-8382.59	-8913.96	2000	1950
DisplayString:DULLSTEE36	11448.17	10828.4	-8613.28	-8913.96	1800	1750
DisplayString:DULLSTEE37	10828.4	10518.52	-8913.96	-9533.63	1000	950
DisplayString:DULLSTEE38	11138.29	10828.4	-8294.27	-8913.96	2200	2150
DisplayString:DULLSTEE39	10828.4	10527.73	-8294.18	-8913.96	2400	2350
DisplayString:DULLSTEE40	10828.4	10297.03	-8377.22	-8913.96	2600	2550
DisplayString:DULLSTEE41	10828.4	10208.72	-8604.07	-8913.96	2800	2750
DisplayString:DULLSTEE42	10828.4	10208.63	-8913.96	-9214.63	3000	2950
DisplayString:DULLSTEE43	10806.07	10269.33	-8914.63	-9446	3200	3150
DisplayString:DULLSTEE44	10806.07	10496.18	-8914.63	-9534.31	3400	3350
DisplayString:DULLSTEE45	11106.74	10806.07	-8914.63	-9534.4	3600	3550
DisplayString:DULLSTEE47	250.7363	150.7363	-13093.8	-13193.8	10500	3600
DisplayString:DULLSTEE48	8268.52	8168.519	-14143.8	-14243.8	6900	3600
DisplayString:DULLSTEE49	9468.521	9368.521	-14143.8	-14243.8	6900	3600
DisplayString:DULLSTEE50	10668.52	10568.52	-14143.8	-14243.8	6900	3600
DisplayString:DULLSTEE52	7982.105	7541.845	-10175.2	-11402.3	3800	3750
DisplayString:DULLSTEE53	7684.224	7243.963	-10210.8	-11437.9	4000	3950
DisplayString:DULLSTEE54	7386.343	6946.083	-10246.4	-11473.5	4200	4150
DisplayString:DULLSTEE55	7088.462	6648.202	-10282	-11509.1	4400	4350
DisplayString:DULLSTEE56	6790.582	6350.321	-10317.6	-11544.7	4600	4550
DisplayString:DULLSTEE57	6492.701	6052.44	-10353.2	-11580.3	4800	4750
DisplayString:DULLSTEE58	6194.82	5754.56	-10388.8	-11615.9	5000	4950
DisplayString:DULLSTEE59	5896.939	5456.679	-10424.4	-11651.5	5200	5150

DisplayString:DULLSTEE60	5610.922	4253.29	-10360.7	-11893.2	6300	5350
DisplayString:DULLSTEE61	4407.534	3967.274	-10602.3	-11829.5	5600	5550
DisplayString:DULLSTEE62	4109.653	3669.394	-10637.9	-11865.1	5800	5750
DisplayString:DULLSTEE63	3811.773	3371.513	-10673.5	-11900.7	6000	5950
DisplayString:DULLSTEE64	3513.892	3073.632	-10709.1	-11936.2	6200	6150
DisplayString:DULLSTEE65	3216.011	2775.751	-10744.7	-11971.8	6400	6350
DisplayString:DULLSTEE66	2918.13	2477.87	-10780.3	-12007.4	6600	6550
DisplayString:DULLSTEE67	2620.249	2179.989	-10815.9	-12043	6800	6750
DisplayString:DULLSTEE68	2322.368	1882.108	-10851.5	-12078.6	8100	6950
DisplayString:DULLSTEE71	1150.736	1050.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE121	250.7363	150.7363	-12193.8	-12293.8	10500	3600
DisplayString:DULLSTE122	250.7363	150.7363	-11293.8	-11393.8	10500	3600
DisplayString:DULLSTE123	250.7363	150.7363	-10393.8	-10493.8	10500	3600
DisplayString:DULLSTE124	250.7363	150.7363	-9493.83	-9593.83	10500	3600
DisplayString:DULLSTE125	250.7363	150.7363	-8593.83	-8693.83	10500	3600
DisplayString:DULLSTE126	250.7363	150.7363	-7693.83	-7793.83	10500	3600
DisplayString:DULLSTE127	250.7363	150.7363	-6793.83	-6893.83	10500	3600
DisplayString:DULLSTE128	2050.736	1950.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE129	2950.736	2850.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE130	3850.736	3750.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE131	4750.736	4650.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE132	5650.736	5550.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE133	6550.736	6450.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE134	7450.736	7350.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE135	8350.736	8250.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE136	9250.736	9150.736	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE137	10150.74	10050.74	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE138	11050.74	10950.74	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE139	11950.74	11850.74	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE140	12850.74	12750.74	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE141	13750.74	13650.74	-5818.83	-5918.83	10500	3600
DisplayString:DULLSTE142	15985.74	15874.58	-13231.7	-13342.8	6900	3600
DisplayString:DULLSTE144	15878.95	15767.79	-12338	-12449.2	6900	3600
DisplayString:DULLSTE146	15772.17	15661.01	-11444.4	-11555.6	6900	3600
DisplayString:DULLSTE166	11235.49	7550.736	-14143.8	-14243.8	3700	3600
DisplayString:DULLSTE167	11235.49	7550.736	-14143.8	-14243.8	4900	4800
DisplayString:DULLSTE168	11235.49	7550.736	-14143.8	-14243.8	6100	6000
DisplayString:DULLSTE169	250.7363	150.7363	-5943.21	-14043.8	3700	3600
DisplayString:DULLSTE170	250.7363	150.7363	-5943.21	-14043.8	4900	4800
DisplayString:DULLSTE171	250.7363	150.7363	-5943.21	-14043.8	6100	6000
DisplayString:DULLSTE172	250.7363	150.7363	-5943.21	-14043.8	7300	7200

DisplayString:DULLSTE173	250.7363	150.7363	-5943.21	-14043.8	8500	8400
DisplayString:DULLSTE174	250.7363	150.7363	-5943.21	-14043.8	9700	9600
DisplayString:DULLSTE175	14450.76	350.7366	-5818.83	-5918.83	3700	3600
DisplayString:DULLSTE176	14450.76	350.7366	-5818.83	-5918.83	4900	4800
DisplayString:DULLSTE177	14450.76	350.7366	-5818.83	-5918.83	6100	6000
DisplayString:DULLSTE178	14450.76	350.7366	-5818.83	-5918.83	7300	7200
DisplayString:DULLSTE179	14450.76	350.7366	-5818.83	-5918.83	8500	8400
DisplayString:DULLSTE180	14450.76	350.7366	-5818.83	-5918.83	9700	9600
DisplayString:DULLSTE189	11916.45	8822.331	-10487.7	-12022.8	11600	11300
DisplayString:DULLSTE198	14650.74	14550.74	-6043.21	-7043.21	7300	7200
DisplayString:DULLSTE199	14650.74	14550.74	-5943.21	-7143.21	10500	3600
DisplayString:DULLSTE249	14550.74	14450.74	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE250	12750.74	12650.74	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE251	10950.74	10850.74	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE252	9150.736	9050.736	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE253	7350.736	7250.736	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE254	5550.736	5450.736	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE255	3750.736	3650.736	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE256	1950.736	1850.736	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE257	150.7363	50.73633	-7043.83	-7143.83	8100	7000
DisplayString:DULLSTE259	14550.74	14450.74	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE260	12750.74	12650.74	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE261	10950.74	10850.74	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE262	9150.736	9050.736	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE263	7350.736	7250.736	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE264	5550.736	5450.736	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE265	3750.736	3650.736	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE266	1950.736	1850.736	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE267	150.7363	50.73633	-9543.83	-9643.83	8100	7000
DisplayString:DULLSTE271	3727.025	3615.866	-11775.9	-11887.1	8100	7000
DisplayString:DULLSTE272	5514.31	5403.151	-11562.3	-11673.5	8100	7000
DisplayString:DULLSTE273	7301.595	7190.436	-11348.8	-11459.9	8100	7000
DisplayString:DULLSTE274	9088.881	8977.723	-11135.2	-11246.3	8100	7000
DisplayString:DULLSTE275	10876.17	10765.01	-10921.6	-11032.8	8100	7000
DisplayString:DULLSTE276	12663.45	12552.29	-10708	-10819.2	8100	7000
DisplayString:DULLSTE277	14450.74	14339.58	-10494.5	-10605.6	8100	7000
DisplayString:DULLSTE278	1956.493	1844.976	-10565.1	-10676.7	8100	7000
DisplayString:DULLSTE279	14579.69	14468.53	-9220.18	-9331.34	4500	3400
DisplayString:DULLSTE330	14650.74	14550.74	-9357.31	-9457.31	10500	3600
DisplayString:DULLSTE331	14650.74	14550.74	-10457.3	-10557.3	10500	3600
DisplayString:DULLSTE332	14650.74	14550.74	-9457.31	-10457.3	7300	7200

DisplayString:DULLSTE337	7608.661	7497.502	-11513.5	-11624.6	4725	3775
DisplayString:DULLSTE338	7454.415	7343.257	-10222.7	-10333.8	4725	3775
DisplayString:RUSTYSTEE7	11876.78	8822.331	-10983.6	-12022.8	15541.99	14999.8
DisplayString:RUSTYSTEE9	11184.21	10850.74	-9477.68	-9811.16	6800	3600
DisplayString:RUSTYSTE10	11150.74	10850.74	-7143.83	-7443.83	6900	3600
DisplayString:RUSTYSTE18	350.7363	50.73632	-5643.83	-5943.83	10500	6900
DisplayString:BRUSHEDST1	13910.08	11892.53	-10726.9	-11185.5	14940.67	11300
DisplayString:BRUSHEDST2	13607.07	9496.201	-6823.38	-7449.4	14100	11600
DisplayString:BRUSHEDST3	13333.94	12763.74	-7405.54	-10818.6	14940.67	11600
DisplayString:BRUSHEDST4	8622.993	8499.387	-6743.63	-7050.65	14100	11600
DisplayString:CONCRETE.7	14750.74	13229.16	-10557.9	-14343.8	10500	6900
DisplayString:CONCRETE.8	4837.518	2429.158	-14043.8	-14343.8	10500	6900
DisplayString:CONCRETE.9	8437.517	6029.158	-14043.8	-14343.8	10500	6900
DisplayString:CONCRETE10	12037.52	9629.158	-14043.8	-14343.8	10500	6900
DisplayString:CONCRETE18	14550.74	14550.74	-5643.83	-7443.83	3600	3300
DisplayString:STUCCO.02	12691.95	10850.74	-7443.83	-9513.28	3499	3499
DisplayString:SHINYSTEE0	2729.158	1237.517	-14343.8	-15535.5	10800	6900
DisplayString:SHINYSTEE1	2729.158	1237.517	-12852.2	-15384.4	10500	7200
DisplayString:SHINYSTEE2	6329.158	4837.518	-12852.2	-15384.4	10500	7200
DisplayString:SHINYSTEE3	9929.158	8437.517	-12852.2	-15384.4	10500	7200
DisplayString:SHINYSTEE4	13529.16	12037.52	-12852.2	-15535.5	10800	7200
DisplayString:SHINYSTE11	6329.158	4837.518	-14343.8	-15535.5	10800	6900
DisplayString:SHINYSTE12	9929.158	8437.517	-14343.8	-15535.5	10800	6900
DisplayString:SHINYSTE21	12431.73	10850.74	-7143.83	-8263.28	4300	3600
DisplayString:SHINYSTE37	7901.795	2116.663	-11517.6	-12027	7420	3800
DisplayString:SHINYSTE38	7747.552	1769.365	-9606.46	-10743.3	7420	3800
DisplayString:SHINYSTE39	14445.99	2017.369	-10534.2	-12038.9	7420	7400
DisplayString:SHINYSTE46	14549.55	1769.364	-9585.27	-9606.46	7420	7400
DisplayString:SHINYSTE47	14445.99	2017.369	-10534.2	-12038.9	7620	7600
DisplayString:SHINYSTE48	7901.795	2116.662	-11517.6	-12027	7620	4000
DisplayString:SHINYSTE49	7747.551	1769.364	-9606.46	-10743.3	7620	4000
DisplayString:SHINYSTE50	14549.55	1769.364	-9585.27	-9606.46	7620	7600
DisplayString:SHINYSTE51	14445.99	2017.369	-10534.2	-12038.9	7820	7800
DisplayString:SHINYSTE52	7901.795	2116.662	-11517.6	-12027	7820	4200
DisplayString:SHINYSTE53	7747.551	1769.364	-9606.46	-10743.3	7820	4200
DisplayString:SHINYSTE54	14549.55	1769.364	-9585.27	-9606.46	7820	7800
DisplayString:DARKWOOD.2	12431.73	10550.74	-6843.83	-8263.28	4550	4500
DisplayString:DARKWOOD23	13611.06	9520.127	-6773.54	-7150.36	11700	11600
DisplayString:DARKWOOD24	13611.06	9520.127	-6773.54	-7150.36	12900	12800
DisplayString:DARKWOOD25	8626.98	8523.312	-6693.79	-6751.61	11700	11600
DisplayString:DARKWOOD26	8626.98	8523.312	-6693.79	-6751.61	12900	12800

DisplayString:DARKWOOD34	7752.296	1733.545	-9643.83	-10787.8	8150	4500
DisplayString:DARKWOOD35	14550.74	1721.596	-9543.83	-9643.83	8150	8100
DisplayString:DARKWOOD36	14450.74	2012.622	-10494.5	-12078.6	8150	8100
DisplayString:DARKWOOD37	7906.541	2111.916	-11477.9	-12066.8	8150	4500
DisplayString:GLASS.01	11235.49	7550.736	-14192.8	-14193.8	6900	3600
DisplayString:GLASS.04	201.7363	200.7363	-5943.21	-14043.8	10600	3700
DisplayString:GLASS.05	14450.94	350.7363	-5867.83	-5868.83	10600	3700
DisplayString:GLASS.10	11892.53	8822.331	-10786.7	-12022.8	15241.99	11600
DisplayString:GLASS.20	14601.74	14600.74	-6043.21	-7043.21	10500	3600
DisplayString:GLASS.25	14601.74	14600.74	-9457.31	-10457.3	10500	3600
DisplayString:WIRE.01	12034.04	8603.613	-11750	-12136.9	14400	11400

Appendix C— Error Analysis for Vessel Model

	Scaffold Man-hours		
Sl No	**Actual**	**Predicted**	**Error Percentage**
1	1487.2	1476.244	0.74
2	332.2	484.748	45.92
3	527.45	676.599	28.28
4	154.55	171.776	11.15
5	2125.75	1950.861	8.23
6	759	1073.633	41.45
7	2099.9	2247.223	7.02
8	1553.2	1497.067	3.61
9	348.15	367.983	5.7
10	229.35	232.529	1.38
11	498.3	1076.108	115.96
12	465.3	1150.314	147.22
13	231	86.768	62.44
14	998.8	1308.395	31
15	199.1	317.548	59.49
16	553.85	568.656	2.67
17	399.3	504.702	26.4
18	216.7	89.067	58.9
19	1119.8	659.329	41.12
20	456.5	522.72	14.51
21	365.2	334.686	8.36
22	483.45	509.707	5.43
23	480.15	797.742	66.14
24	2033.35	1964.787	3.37
25	460.9	602.349	30.69
26	982.3	548.603	44.15
27	412.5	399.311	3.2
28	1067	503.734	52.79
29	1797.95	1979.615	10.1
30	297	432.036	45.47

31	279.95	576.114	105.79
32	325.6	311.773	4.25
33	1444.3	666.38	53.86
34	1392.6	1873.652	34.54
35	2924.9	1866.678	36.18
36	529.1	1009.316	90.76
37	1015.3	450.637	55.62
38	1942.05	1395.218	28.16
39	507.1	528.88	4.29
40	216.7	208.714	3.69
41	1450.9	1266.012	12.74
42	498.3	543.906	9.15
	Average Error percentage		**33.85**

Appendix D— Error Analysis for Modules Model

	Scaffold Man-hours		
Sl No.	Actual	Predicted	Error Percentage
1	354.2	70.125	80.2
2	904.2	1129.337	24.9
3	1390.4	1204.687	13.36
4	152.9	174.845	14.35
5	364.1	263.67	27.58
6	682.55	1146.629	67.99
7	470.8	403.744	14.24
8	1865.6	1602.821	14.09
9	995.5	1198.967	20.44
10	429.55	1004.762	133.91
11	271.15	781.594	188.25
12	487.3	754.886	54.91
13	1741.3	1611.478	7.46
14	1326.6	1373.042	3.5
15	253	678.007	167.99
16	465.3	51.348	88.97
17	1490.5	1181.862	20.71
18	1174.8	1076.086	8.4
19	2520.65	1043.79	58.59
20	1265	1599.543	26.45
21	473	652.806	38.01
22	96.8	179.036	84.96
23	679.25	761.156	12.06
24	1037.3	1070.454	3.2
25	1214.95	1011.021	16.78
26	924	1790.415	93.77
27	660.55	1034.055	56.54
28	424.05	789.382	86.15
29	136.4	132.253	3.04

30	220	968.022	340.01
31	1544.4	803.209	47.99
32	2364.45	941.028	60.2
33	721.05	1101.397	52.75
34	1370.6	1422.399	3.78
35	922.9	895.807	2.94
36	941.05	1133.198	20.42
37	911.9	1262.349	38.43
38	539.55	937.244	73.71
39	427.9	331.408	22.55
40	1159.4	1383.888	19.36
41	1507.55	1538.042	2.02
42	1134.1	883.278	22.12
43	1156.65	1535.578	32.76
44	899.8	1152.393	28.07
45	1945.9	1194.281	38.63
46	81.4	157.696	93.73
47	861.85	1332.144	54.57
48	1831.775	1221.605	33.31
49	731.5	835.978	14.28
50	951.5	1422.806	49.53
51	1112.65	916.542	17.63
52	701.25	967.868	38.02
53	368.5	273.779	25.71
54	517	340.109	34.21
55	47.3	61.864	30.78
56	715.55	660.308	7.72
57	1003.2	893.508	10.93
58	267.85	194.953	27.21
59	1290.85	920.612	28.68
60	1755.6	1647.976	6.13
61	1973.4	1161.809	41.13
62	765.6	907.148	18.49
63	1373.9	1687.939	22.86
64	660.55	1166.583	76.61
65	342.1	959.189	180.38
66	951.5	981.068	3.11
67	742.5	805.904	8.54

68	2644.4	1050.126	60.29
69	323.4	799.227	147.13
70	253	679.327	168.51
71	289.3	398.816	37.85
72	618.2	923.076	49.32
73	349.8	1357.807	288.17
74	950.4	770.693	18.91
75	445.5	974.864	118.83
76	413.05	1027.29	148.71
77	240.9	33.352	86.16
78	484	332.629	31.27
79	1247.4	1209.802	3.01
80	550	762.949	38.72
81	636.35	385.11	39.48
82	1610.4	712.382	55.76
83	992.75	632.819	36.26
84	1111	351.791	68.34
85	1309	1649.725	26.03
86	1134.1	666.38	41.24
87	1302.4	1290.52	0.91
88	339.9	871.431	156.38
89	1130.8	1252.141	10.73
90	143.55	410.663	186.08
91	2564.65	1517.615	40.83
92	1507.55	951.192	36.91
93	348.7	867.328	148.73
94	2275.35	1654.983	27.26
95	436.15	794.497	82.16
	Average error percentage		**54.88**

Appendix E— Chapter 9, Technical Calculation and Estimator's man-hour manual

IX. ESTIMATES

1. ESTIMATE OF SCAFFOLDS

Quick estimates of scaffolding and the scaffolds are very difficult to make and not reliable. Estimators usually do not have the drawings, the dimensions and what is most important they do not have enough time to perform a proper calculation. Therefore, they have to make quick estimates of the quantities starting first with a decision on who is going to undertake the scaffolding. Will they subcontract this job to a specialist firm or do the scaffolding themselves?

It is also necessary to see who will use the scaffolds. Will they be used for erection only, or for painting and insulation works as well?

If there are several users, the rental period is longer but in that case the expenses can be shared.

1. ESTIMATES OF SCAFFOLDING WHEN CONTRACTED TO A SPECIALIST FIRM

The most usual categorization and the rates of the scaffolding specialist firms are:

a) Scaffold Erection

standing scaffolds	[m^3]	cantilever scaffolds	[m^3]
hanging scaffolds	[m^3]	platform floors	[m^2]

b) Scaffold Dismantling

same categorization as for erection

c) Rental

same categorization per week and month

The price of erection and dismantling of scaffolding varies by its height every ____ : ____ m. When estimating the scaffolding quantity, the quantity for erection in [m^3] and an average erection height are determined.

1.1 PIPING IN PLANTS

Quantity: ____ : ____ [m^3/t] piping weight

Type :
- standing scaffolds ____ : ____ %
- hanging scaffolds ____ : ____ %
- cantilever scaffolds ____ : ____ %
- platforms landings ____ : ____ %

1.2 PIPING ON PIPERACKS

Quantity: Option I Pipe rack surface area ____ [m^2] scaffold
Option II ____ [m^3/t] piping weight

Type :
- standing scaffold ____ %
- hanging scaffold ____ – ____ %
- cantilevel scaffold ____ : ____ %
- platforms floors ____ : ____ %

Height: ____ : ____

Rental: average ____ : ____ months

1.3 STEEL STRUCTURES

Quantity: ____ : ____ [m^3/t] structure weight

Type :
- standing ____ : ____ %
- hanging ____ : ____ %
- cantilever ____ : ____ %
- platforms floors ____ : ____ %

Height: average ____ m

Rental: average ____ : ____ weeks

m^3x 35,32 = cu ft
m^2x 10764 = sq ft

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1.4 EQUIPMENT IN PETROCHEMICAL PLANTS

When estimating the scaffolding for equipment erection one should know who is going to use the scaffolding. For instance, no scaffolding is required for erection of towers, but it is required for erection of connection piping, electrical installations, insulation or painting. The best way is to calculate all the equipment individually for each unit. Similarly, one should also determine the type of scaffolding, its height, and the rental time.

When the scaffolding is used for the equipment erection only, it could be calculated in the following way:

Quantity:	___ : ___ [m^2/ton] equipment weight		
Type:	standing	___	%
	platform floors	___	%
Height:	___ : ___ m		
Rental:	___ month		

2. ESTIMATE OF SCAFFOLDING WHEN DONE BY AN ERECTION COMPANY

This kind of scaffolding erection is used less and less. If used, the scope of scaffolding should be estimated in the same way as for the first case.

2.1 PIPING IN PLANTS: ___ : ___ [m^3/ton] piping quantity

2.2 PIPING ON PIPERACKS: Option I Pipe rack surface area – [m^2] scaffold
Option II ___ [m^3/ton] piping quantity

2.3 STEEL STRUCTURES: ___ : ___ [m^3/ton] structure quantity

2.4 EQUIPMENT IN PETROCHEMICAL INDUSTRY: ___ : ___ [m^2/ton] equipment quantity
(If used for the equipment erection only)

When the scaffolding quantity is calculated in [m^3] or [m^2], which is more or less the same we should estimate the material needed for tubular or patent scaffolding.

2.5 TUBULAR SCAFFOLDING

There are sets of tubular scaffolding with a list of material needed such as tubes and clamps for 500 m^3 (Iron Works Sisak). If it is expected that the scaffolding will be erected and dismantled several times during the works execution, the following calculations should be considered:

2.5.1 Tubular scaffold material

$$\text{Total scaffolding:} \quad \frac{[m^2] + [m^3]}{\_\_\_} = m^2 \text{ or } m^3$$

The scaffolding quantity to round up to hundred (100).

m^3 x 35,32 = cu ft
m^2 x 10764 = sq ft

2.5.2 Planking tops for scaffolding

Scaffold quantity / – m^3 planking tops

2.6 SCAFFOLDING LABOUR

Determine the number of scaffolding hours by calculating:
Erection + dismantling – [Mhr/m^3] or m^3 x elevation factor (for average elevation)

(See "Equipment Scaffolding", page 72 73)

After that, determine the labour needed for scaffolding and the means of transport.

Appendix F— Sample Scaffold Form