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Civil Engineering Journal

Vol. 6, No. 4, April, 2020

Rational Hybrid Analytical Model for Steel Pipe Rack Quantification in Oil & Gas Industries

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Received 06 January 2020; Accepted 16 March 2020

Abstract

The objective of this work is to develop an analytical model to overcome the shortfalls in current engineering practices that are being used to estimate the pipe rack steel quantities during the pre-bid engineering phase in Oil & Gas industries. The research methodology consists of performing data analysis of past projects and devising a new system by developing suitable structure formulation techniques, loading system creation, structural stability analysis and LRFD design calculations, along with steel quantification procedures, which are completed in a single run. Then this rational hybrid analytical model is applied to examine a real-time project pipe rack structure module. As research findings, the results of the analytical model are compared with the outcome of both the conventional methods as well as the bench mark detailed engineering calculations. It is found that the quantity obtained using the new method is extremely close to the detailed engineering quantity with the least time consuming. Hence, this novel analytical model has proved to be a boon to structural engineers working in Oil and Gas industries since the crux of pre-bid engineering is to process voluminous data and calculate the quantities more precisely within a shorter time frame to be a successful bidder.

Keywords: Steel Pipe Racks; Steel Quantity Estimation; Oil and Gas Industries.

1. Introduction

The energy sector is the key factor in the economic growth of any country. The production process is highly based on the growth of energy sectors in a country, and due to this fact, the economic development of all countries has a strong correlation with high energy consumption levels. The per capita Gross National Product (GNP) is naturally having a relationship with the energy consumption activity. Countries with higher per capita GNP obviously consume a lot of energy per person. As an illustration, the per capita energy consumption in the United States is around 16 times that of India. Similarly, Japan's energy consumption is almost 8 times that of India.

The energy industry represents all the forms of industries in total, which are occupied in the production and sale of energy, covering drilling and extraction of crude fuel, processing, refining and distribution to the retail market. Civilized mankind uses huge quantities of fuel, and the energy sector plays a crucial part in the development of infrastructure and maintenance of the societal needs in almost all nations. Oil and gas are vital to many factories and are very important for the creation and development of industrial civilization, and thereby are a real concern for all countries.

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http://dx.doi.org/10.28991/cej-2020-03091497

The total energy consumed in a year is measured for the entire human civilization and is known as the world energy consumption. This indicates the overall energy obtained from all energy resources. This accounts for all the humanity's efforts across every single technological and industrial domain of all the nations in the world. Coal was the main source of energy from 2000 to 2012. The energy consumption by the entire world population has a straightforward impact on the socioeconomic political field. The development of oil and natural gas has had tremendous growth, followed by hydropower and renewable energy. The development of nuclear energy has slowed down due to the nuclear disaster incidents such as Three Mile Island 1979, Chernobyl 1986, and Fukushima 2011.

Total global energy (9,694 Mtoe) consumption from various energy sources is depicted in the form of pie chart in Figure 1 as per the International Energy Agency (IEA) Publication [1].

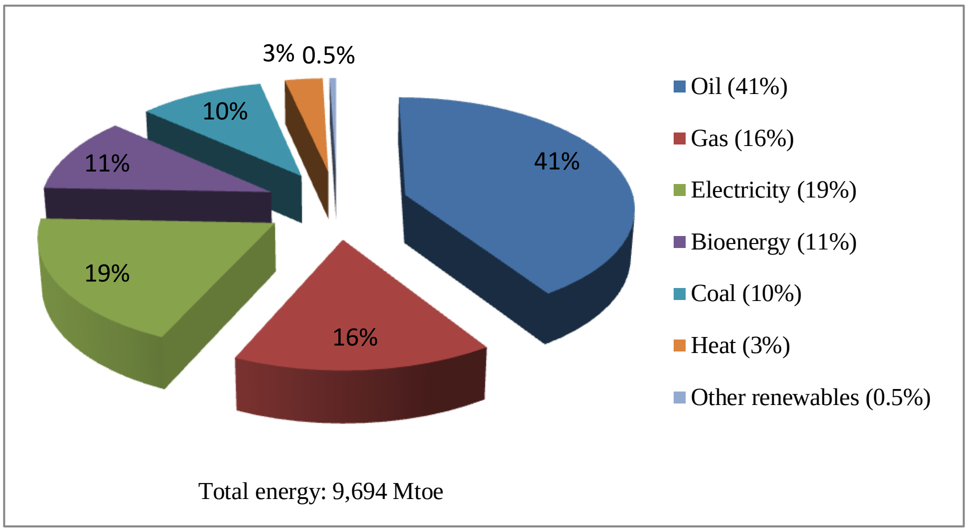

Figure 1. World energy consumption from various energy sources

From Figure 1, it is evident that more than 50% of the world's primary energy needs are fulfilled by the Oil and Gas industries, where Mtoe stands for Million Tonnes of Oil Equivalent.

The various phases in any Oil and Gas Engineering, Procurement, Construction and Commissioning (EPCC) project are listed below:

- Conceptual/Feasibility Studies
- Pre-Bid Engineering
- Front End Engineering Design (FEED)
- Basic Engineering and
- Detailed Engineering.

Among the various phases of Oil and Gas EPCC projects, the Pre-Bid engineering phase plays the most crucial part on Contractor's side to bid and win the project. The crux of pre-bid engineering is to process volumes of data and calculate the quantities more precisely within a shorter time frame to be the successful bidder. In Oil and Gas plants, steel pipe racks generally quantify more than 50% of the total steel quantities. Pipe rack structural steel quantification poses many challenges to the structural engineers working in this domain.

Parameters affecting the design and thereby the quantities of Pipe racks are:

- Structural Configuration
- Design Loads
- Load Combinations
- Material Grades
- Client Standards
- Design Specifications
- Country Code
- Column Base Connection Types

Generally, the time span available for pre-bid engineering is between two and three months, whereas detailed engineering activities can last twelve to eighteen months. Hence, in just one - sixth of the time, structural engineers have to carry out all the necessary structure formation activities, loading calculations, analysis, design and quantification so as to ascertain as accurately as possible the steel quantities that will be obtained after the detailed engineering calculations. Moreover, the availability of input data, such as structure configuration and loading data, would also be very much incomplete during the pre-bid engineering phase. Conventional methods which are being currently used have many drawbacks, such as a lack of inability to deal with incomplete input data, the lack of proper analysis and stability design calculations, a lower degree of accuracy of quantified data, and a more time consuming process. Therefore, a new rational hybrid analytical model is developed in this study to overcome the shortfalls and difficulties present in the existing conventional methods.

2. Materials and Methods

2.1. Conventional Procedures

Presently there are two methods being adapted for the steel quantification during pre-bid engineering in the Oil and Gas industries, which are:

- Statistical data method
- Rigorous software method

The first method is less accurate and the second is more time consuming. Statistical data analysis may not be applicable for all cases under consideration, and in conventional rigorous structural steel design, apart from structural configuration, modeling and load calculations and the preliminary selection of the optimum member size itself is a highly complicated and tedious process. It is also to be noted that during the pre-bidding process, quantification is done with some bias due to the many assumptions that need to be made because of the limited, incomplete data and time constraints.

This study aims to devise a novel method to overcome the difficulties of the existing methods. To accomplish this, a customized analytical tool is required to carry out the load calculation, configuration modeling, analysis, design and quantity estimation in a single run. Therefore, through a grounded theory study, a theoretical framework will be introduced to enhance the steel pipe rack quantity estimation process in pre-bid engineering in the Oil and Gas industries by analyzing the important factors that influence the steel estimation process and to provide a hybrid rational design strategy to enhance the quantification process by taking into account the best parts of the two existing methods. This area has still not been significantly explored, and not much research has been carried out to cater to this need. A systematic research study and possible solution methodology for this problem is needed, and it would be of immense use to verify the steel incidences obtained from statistical data, or to deduce them in the absence of such statistical data. Based on literature review, it is determined that no universally accepted design procedures, standards, or codes of practices are available currently for the design of steel pipe racks [2, 3].

The challenge is to overcome the difficulties posed due to incomplete input data, a lack of proper analytical and design methods, and the much shorter periods of time available.

2.2. Research Method

The goal of this study is to develop a hybrid rational analytical model to enhance the steel pipe rack quantity estimation process in pre-bid engineering in the Oil and Gas industries by analyzing the important factors that influence steel estimation. This model will take into account the best conceptual parts of the two existing methods and incorporate new analytical procedures for load calculations and define a new set of primary load cases, load factors and load combinations, suitable analysis method (DAM), stability design calculations, and rational estimation with the capability of dealing with incomplete input data. The new hybrid rational analytical model will function in an integrated platform so that all activities such as model creation, analysis and material quantification are performed in a single run. Due to this, there is a considerable reduction in overall time consumption. Thus, the new method can overcome all challenges that are faced in the pre-bid engineering phase.

In the new hybrid model, proper loading data is estimated by means of qualitative data analysis by calculating the minimum and maximum pipe diameter with a permuted arrangement, along with blanket loading and various primary load cases, as per the detailed engineering design format, which enhances the level of optimization of the quantities of primary and secondary steel. Primary frame members would be designed as a 2D frame with proper loading effect from secondary members with rigorous analysis.

Steel design is performed using the LRFD (Load and Resistance Factor Design) method, incorporating the rational stability method of analysis (Direct analysis method – DAM surpassing the currently used effective length method) as stipulated in AISC specification 360 – 2010.

Secondary members, such as longitudinal beams and secondary beams along the length of the pipe rack, are also designed with the LRFD approach with proper load combinations. Then, tertiary members are quantified using statistical data, which will be applied on the primary and secondary steel, which are quantified by the hybridized rational analytical model.

Thus, the new model developed applies the new design approach by employing DAM with rational quantification parameters. Because of the fact that it employs the basic concepts of both conventional methods, this is a hybrid as well.

The new Hybrid model is designed to overcome the drawbacks existing in the conventional methods, and has been found to be more effective, as detailed in Table 2. This new rational hybrid model is capable of working with limited input information by assuming suitable data derived from a statistical database and relevant calculations. It is intended for use in low seismic zones where wind loads are governing. The analytical model's automated calculations are developed in the MS-Excel platform and by using Visual Basic Application. This model is developed such that it satisfies all design requirements of steel members as per the following standards / codes and Saudi Aramco best practices. It also satisfies other major international codes of practices along with Process industry practices (PIP) standard PIP STC 01015:

- AISC LRFD Manual
- ASCE-07-2005- Minimum Design Loads for Buildings and Other structures
- ASCE Task Committee report – Wind Loads for Petrochemical and Other Industrial Facilities
- SABP-M-006 - Wind Loads on Pipe racks and Open Frame Structures and
- SABP-M-007- Steel Pipe rack Design

Table 1. Comparison of the existing methods with the new rational hybrid analytical model

Sl. no.	Parameter	Statistical data method	Rigorous software method	Rational hybrid analytical model
1	Load calculation	Not done	Approximate load is calculated	Detailed load calculations are carried out based on qualitative inputs with necessary permutations
2	Analysis	Not done	Analysis is done using sophisticated software package	Analysis is done using stiffness matrix method
3	Structural design	Not done	Design using sophisticated software package	Rational stability design method is adapted
4	Steel quantification calculations	Using statistical percentages for all primary, secondary and tertiary steel quantities	From software output for primary steel and allied percentages for secondary and tertiary steel quantities	Based on calculations for primary and secondary steel members and using statistical percentages for tertiary members. The statistical percentages are applied on calculated primary and secondary steel quantities
5	Procedure to deal with incomplete input data	Not available	Not available	Available
6	Time consumption	Less	More	Least
7	Steel quantities optimization level	Low	Medium	High

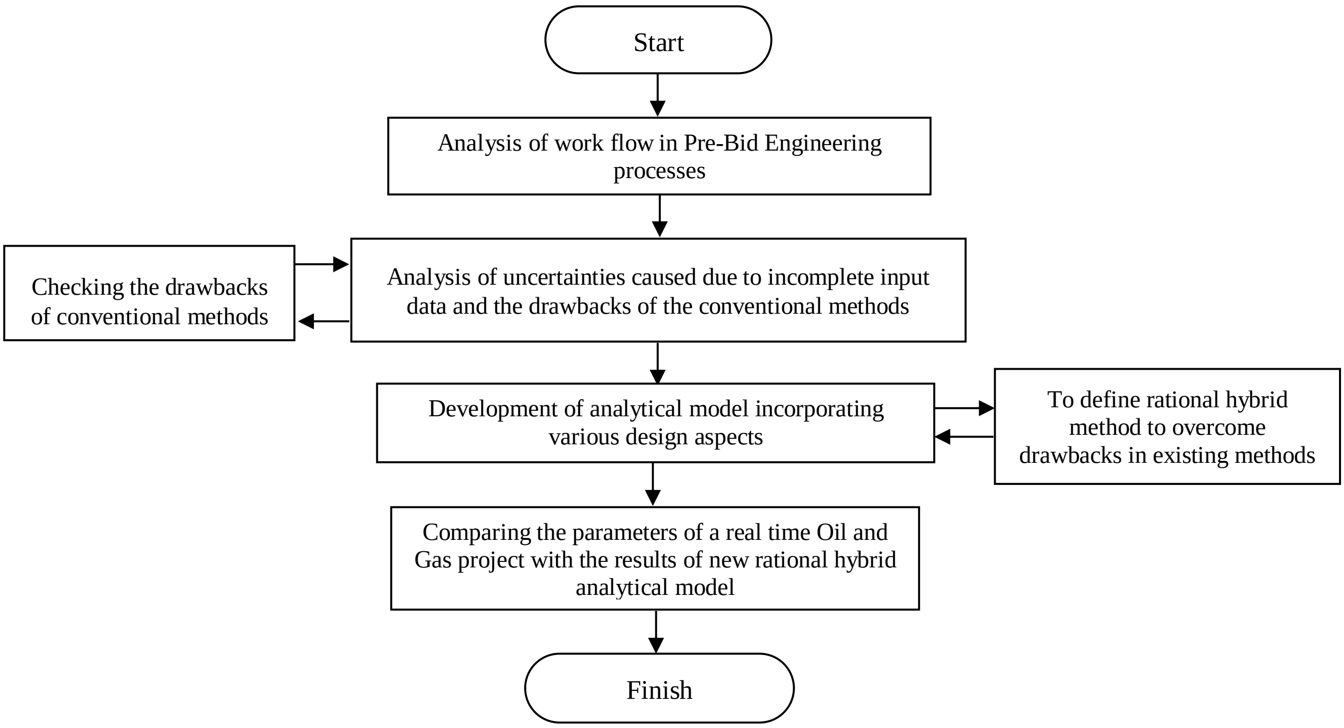

Figure 2. Flowchart for the Research Method

2.3. Problem Statement

In this work, a real time project structure was considered for the analysis, design and steel quantity estimation, and the results are compared against two parameters, namely accuracy and time consumption. Generally, after considering a real time problem for the study, the problem parameters are to be normalized to suit the working philosophy of the analytical method.

The problem presented here is normalized accordingly. In this problem, a single bay three - storied pipe rack is considered with a bay width of 9 m. The spacing of pipe rack frames is 6 m. There are eight frames in the pipe rack module considered. Vertical bracings are provided in the central bay along the longitudinal direction at both alignments. Plan bracings are considered as shown in the 3D view.

Shear connections would be considered along the longitudinal direction, where vertical bracings (Non-sway frame) are provided. Moment connections would be considered along the transverse direction of the pipe rack, where vertical bracings are provided only in the bottom storey (Sway frames).

Longitudinal girt beams are considered to reduce the effective length of the columns about the minor axis in the bottom tier. Secondary beam projections in the form of cantilever-type beams are considered at both ends of the pipe rack module for a length of 1.5 m to facilitate the piping connections to the adjacent modules. All the main steel structural connections shall be of bolted type only. The three-dimensional view of the pipe rack module is shown in Figure 3. The bottom connections of base plates to the concrete pedestals are pinned type, which do not transmit any moments to the foundations.

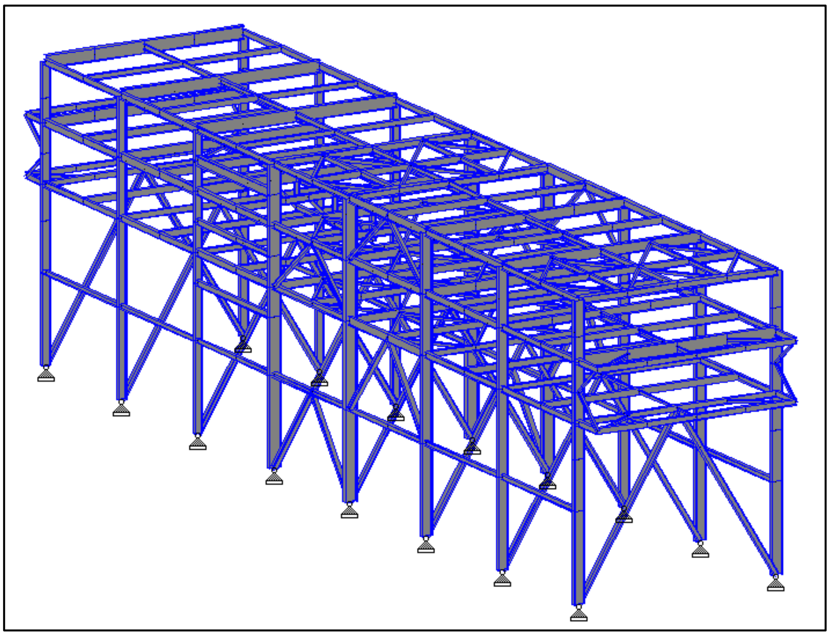

Figure 3. Three-dimensional view of pipe rack module

The bottom tier has a height of 7 m, and the other two tiers each have a height of 2.5 m. Hence, the total height of the pipe rack is 12 m. A photograph of the pipe rack module structure for the present study is shown in Figure 4.

Figure 4. Photograph of the pipe rack module under consideration

General Input Data:

The input parameters required for the analysis are:

1. Steel grade
2. Steel prefabrication requirement
3. Number of bays
4. Number of storeys
5. Number of frames
6. Bay width
7. Bottom storey height
8. Overall height of the pipe rack
9. Spacing of frames
10. Initial indicative sizes for all members
11. Column support conditions
12. Tier load
13. Wind speed
14. Wind exposure category
15. Seismic building category
16. Seismic zone
17. Air coolers availability

Pipe Loading Data:

In all projects, the loading data on the pipe racks from the piping discipline are not available or are incomplete during the pre-bid engineering phase. To handle this, proper loading data is estimated by means of qualitative data analysis by calculating minimum and maximum pipe diameter with a permuted arrangement along with blanket loading. There are three qualitative pipe diameters identified, which are designated as Low, Medium and High, which correspond to 12", 18" and 30" pipe diameters, respectively. Based on pipe diameter, insulation thickness and minimum gap requirements between pipes, the permutations are carried out to find the worst load case scenario.

The pipe loading data generation based on the pipe rack span and spacing is developed to determine the appropriate pipe diameter which would cause the worst load case scenario as shown Figure 5.

Piperack span	Length of pipe (Spacing)	Pipe Dia	Pipe Dia	Pipe thickness	Pipe thickness	Pipe weight	Insulation thickness	Overall diameter of pipe	Min. Safe gap	C/c dist	Insulation weight	Total dead load for one pipe	No of pipes	Intermediate Spacing	End spacing	Beam self weight	Total dead load per m run of beam	Total live load per m run of beam	Total load per m run of beam	Load per unit area
m	m	in	m		m	kN/m	in	m	m	m	kN/m	kN/m		m	m	kN/m	kN/m	kN/m	kN/m	kN/m2
9	6	12	0.3048	1	0.0254	1.72	2	0.4064	0.1	0.5064	0.148	1.864	8	0.72	0.36	2	11.9	2.65	14.59	2.43
9	6	14	0.3556	1	0.0254	2.03	2	0.4572	0.1	0.5572	0.169	2.198	7	0.83	0.41	2	12.3	3.34	15.60	2.60
9	6	16	0.4064	1	0.0254	2.34	2	0.5080	0.1	0.6080	0.190	2.531	7	0.78	0.39	2	13.8	4.55	18.36	3.06
9	6	18	0.4572	1	0.0254	2.65	2	0.5588	0.1	0.6588	0.211	2.864	6	0.94	0.47	2	13.5	5.09	18.55	3.09
9	6	20	0.508	1	0.0254	2.97	2	0.6096	0.1	0.7096	0.232	3.197	6	0.89	0.45	2	14.8	6.44	21.23	3.54
9	6	22	0.5588	1	0.0254	3.28	2	0.6604	0.1	0.7604	0.253	3.531	5	1.14	0.57	2	13.8	6.63	20.40	3.40
9	6	24	0.6096	1	0.0254	3.59	2	0.7112	0.1	0.8112	0.274	3.864	5	1.09	0.54	2	14.9	8.02	22.90	3.82
9	6	26	0.6604	1	0.0254	3.90	2	0.7620	0.1	0.8620	0.295	4.197	5	1.04	0.52	2	16.0	9.54	25.53	4.26
9	6	28	0.7112	1	0.0254	4.21	2	0.8128	0.1	0.9128	0.316	4.530	4	1.44	0.72	2	14.1	8.96	23.04	3.84
9	6	30	0.762	1	0.0254	4.53	2	0.8636	0.1	0.9636	0.337	4.864	4	1.39	0.69	2	15.0	10.39	25.36	4.23
9	6	32	0.8128	1	0.0254	4.84	2	0.9144	0.1	1.0144	0.358	5.197	4	1.34	0.67	2	15.9	11.93	27.79	4.63
9	6	**34**	0.8636	1	0.0254	5.15	2	0.9652	0.1	1.0652	0.379	5.530	4	1.28	0.64	2	16.8	13.57	30.32	5.05
9	6	36	0.9144	1	0.0254	5.46	2	1.0160	0.1	1.1160	0.401	5.863	3	1.98	0.99	2	13.7	11.49	25.22	4.20
																Dia of pipe which would give worst loads (in) :				**34**

Figure 5. Pipe load data generation

Wind Load Calculations:

A wind load calculation template is developed to calculate the forces on members as per ASCE 07 (Minimum design loads for buildings and other structures). Basic wind speed is taken from the relevant project design data. The Directionality factor, Topographic factor and Importance factor are considered as per the guidelines provided in the ASCE 07.

Earthquake loads are generally not considered in the pre-bidding analysis, and following primary loads, load combinations and load conditions are considered in the analysis.

Loads and Load combinations:

- Dead Load (D)
- Live Load (L)
- Temperature Load (T)
- Wind Load (W)
- Member Local Check Load (LC)

Sample wind pressure intensity calculation is presented below.

Wind Pressure Calculations as per ASCE 7-05

$q_z = 0.613\ K_z\ K_{zt}\ K_d\ V^2\ I$ (Cl 6.5.10 - ASCE7-05

Directionality factor, K_d	0.85		(Table 6-4 - ASCE7-05)
Topographic factor, K_{zt}	1		(Cl 6.5.7.1 & 6.5.7.2 -ASCE 7-05
3s Gust wind speed ,V	160	km/h	= 44.44 m/s (From Project Data
Importance Factor , I	1.15		(Table 1-1 & 6-1 - ASCE7-05

K_z (Exposure catagory-D) (Table 6-3- ASCE7-05)

Height (m)	K_z
0-4.6	1.03
4.6 - 6.1	1.08
6.1-7.6	1.12
7.6-9.1	1.16
9.1. - 12.2	1.22
12.2 - 15.2	1.27

Wind Pressure (Eq.6.15-ASCE 7-05)

Height (m)	qz (kN/m2)
0-4.6	1.22
4.6 - 6.1	1.28
6.1-7.6	1.33
7.6-9.1	1.37
9.1. - 12.2	1.44
12.2 - 15.2	1.50

Design Load Cases/Conditions:

- Erection / Shutdown
- Operation
- Hydro - Testing

Various load combinations are adapted in the design of structural steel pipe racks under the following heads when they are considered for each of the three Load cases:

1) Load Combinations for Global Steel Design

2) Load Combinations for Local Member Steel Design

Analysis, Design and Steel Quantification:

Using the first method, the inputs are very minimal and the final steel quantities can be found and tabulated.

For the second method, which involves the use of sophisticated software, the analysis and design would be carried out and an estimate would be created, then the steel quantification results would be tabulated.

The stiffness method of analysis is carried out in the Hybrid rational analytical model using the direct analysis method as per AISC 360 – 2010. Structural steel design follows the LRFD approach. Then, the steel quantification results are tabulated for comparison.

3. Results and Discussion

The final steel structural design is mainly checked for strength and serviceability load combinations. For serviceability, the vertical deflections of beams and horizontal drifts of columns are checked against the permissible limits as per steel design code. The unity ratio is checked for strength load combinations for all structural members.

For steel quantification purposes the overall steel incidence in kg/m^3 is the key factor. The steel incidences obtained from various methods and the detailed engineering process are tabulated in Table 2. From this table it is clearly seen that the rational hybrid model produces closest result to the detailed engineering (DE) value, and comes out higher, so as to remain conservative. These details are depicted by the chart in Figure 6.

Table 2. Steel incidences

	Steel incidences			
	Statistical	**Rigorous**	**Hybrid model**	**Detailed Engg.**
Incidence (kg/m^3)	23	20	17	16

The overall steel quantities from each method are further split into four categories such as light steel, medium steel, heavy steel and extra heavy steel based on their weight per meter run. The weight ranges are less than 25 kg/m, 25 kg/m to less than 70 kg/m, 70 kg/m to less than 125 kg/m, and above 125 kg/m, respectively, to ease the procurement planning. Tertiary members are quantified as percentages of main frame members based on improved statistical data analysis. The Medium steel and Heavy steel classification of steel quantities do not have many practical implications, and many contracting firms have three classifications only, namely Light steel, Medium steel and Heavy steel.

Finally, after the detailed engineering calculations are done, the quantities are checked and compared to find the difference and which method is closest to the detailed engineering outcome. Keeping the detailed engineering quantity as the benchmark with 100% accuracy, the incidences arrived from the two conventional methods and rational hybrid analytical model are calculated in percentages. Thus, the degree of accuracy of the steel quantity calculations in percentage terms are tabulated in Table 3 for comparison. A chart depicting the values provided in the quantification accuracy percentage comparison table is shown in Figure 7.

The time taken for the quantity calculations using each method is also compared and is provided in Table 4. A bar chart showing the time taken using each method is illustrated in Figure 8.

Table 3. Quantification accuracy percentages

	Statistical	Rigorous	Hybrid model	Detailed Engg.
Light steel	35	20	30	20
Medium steel	40	15	17	55
Heavy steel	15	7	53	20
Extra heavy steel	10	58	0	5
Steel Incidence	56.25	75	93.75	100

Table 4. Time consumption

	Statistical	Rigorous	Hybrid model	Detailed Engg.
Time (hours)	4	48	2	200

Detailed engineering man hours generally range from 200 to 300 hours; however, the lower value has been considered in the above comparison. Even though the statistical method consumes less time, its steel incidence results are too far from the detailed engineering calculations, as shown in Table 2, resulting in highly uneconomical values, and leads to over estimation of the steel quantities, which is highly undesirable in the pre-bid engineering calculations.

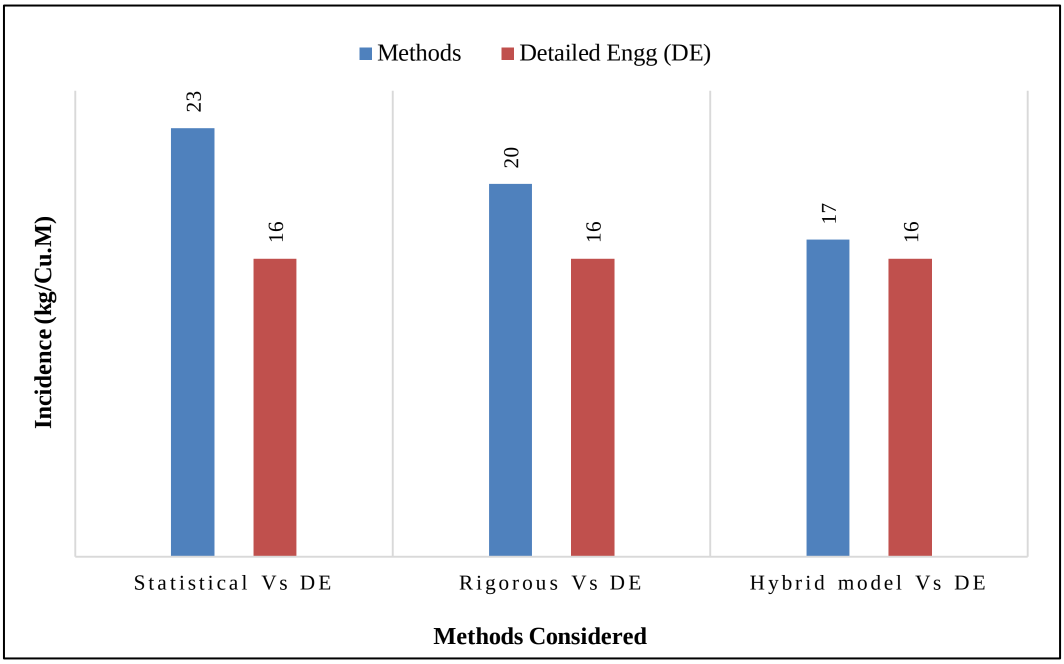

Figure 6. Incidence chart

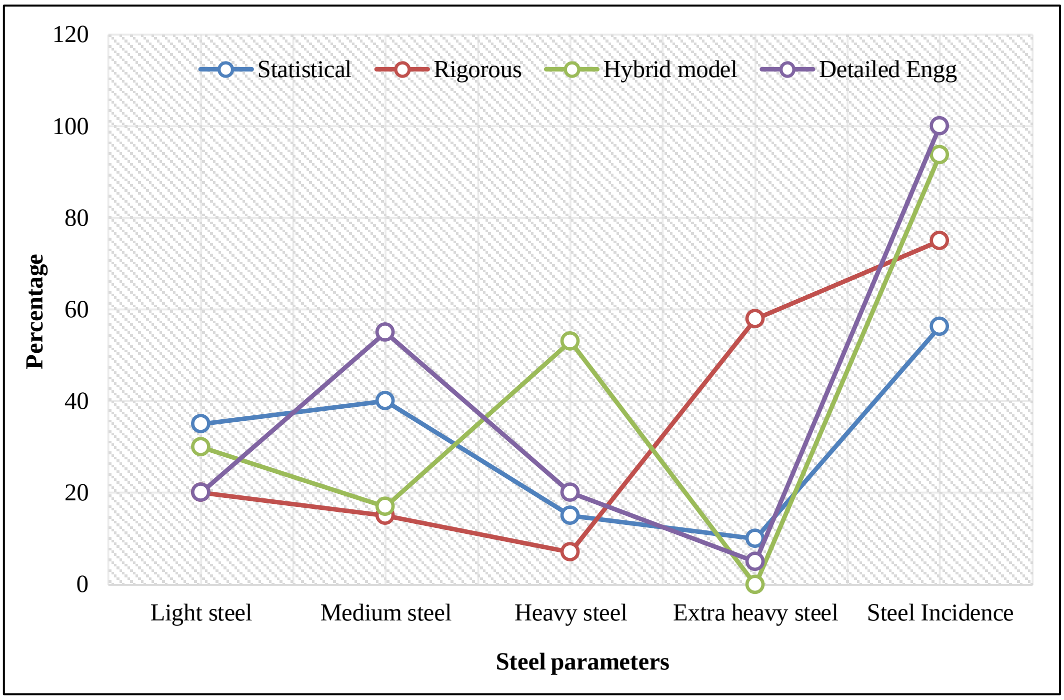

Figure 7. Quantification accuracy chart

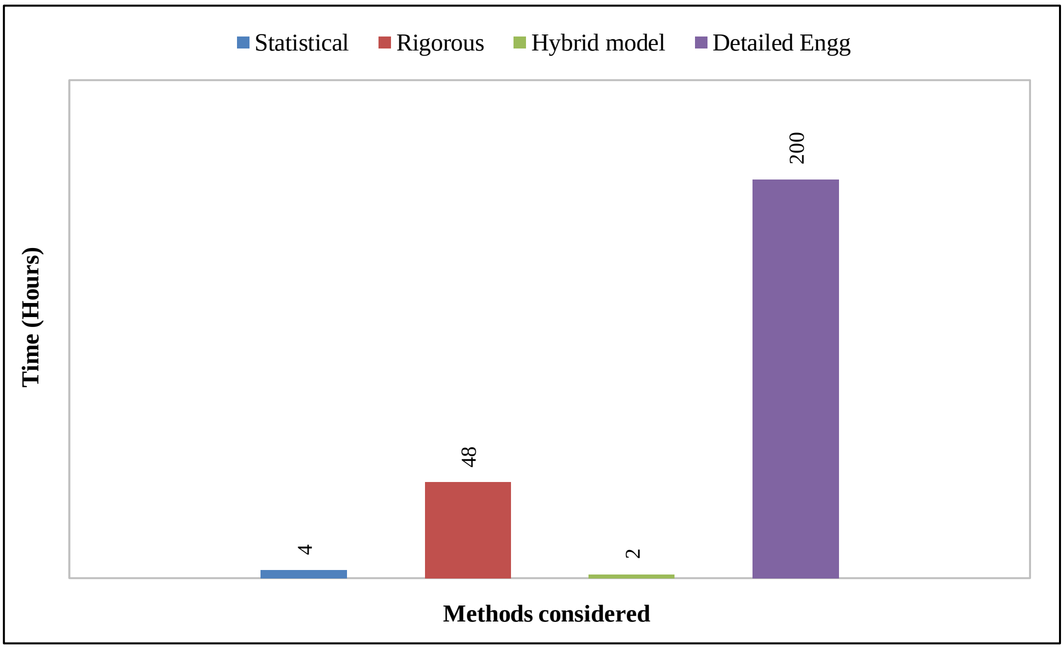

Figure 8. Time consumption chart

4. Conclusion

Based on the results provided in the steel incidences table (Table 2), it is evident that the results obtained through the rational hybrid analytical model are much closer to the actual detailed engineering results in terms of the steel incidence ratio, which is the basis for the quantification and pre-bidding calculations. It is also clear that the hybrid model comes out slightly on the conservative side, which is necessary for the pre-bid engineering phase. It also takes much less time than the rigorous software method.

This work provides a comprehensive solution for the quantification of steel pipe rack structures in Oil and Gas plants, which is necessary as many onshore plants are cropping up around the world to cope with the increased demand for Oil and Gas consumables, as discussed in the Introduction section. Therefore, it is clear that the newly developed hybrid rational model will be a boon to contracting firms involved in the bidding for Oil and Gas EPCC projects worldwide by giving them the ability to quantify the materials needed with more accuracy and within least possible timeframe. It has been discovered that the rational hybrid analytical model will be of much use to structural engineers in calculating steel quantities more accurately and in less time.

The limitations of this method can be viewed as the inability to deal with pipe racks of more than one bay and more than seven stories, which is very rare and seldom occurs in any Oil and Gas onshore plant. In future research, the same analytical model could be further developed to design the structural steel members using the Allowable stress method (ASD), and to check and compare the quantities arrived at using that methodology.

5. Acknowledgements

The Authors are thankful to all the colleagues and family members for their august cooperation and untiring support during the preparation of this manuscript.

6. Conflicts of Interest

The authors declare no conflict of interest.

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