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Y.-S. Ma [a] & Q. Hadi [a]

[a] Department of Mechanical Engineering, University of Alberta, Edmonton, T6G 2G8, Canada

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Unified feature-based approach for process system design

Y.-S. Ma* and Q. Hadi

Department of Mechanical Engineering, University of Alberta, Edmonton T6G 2G8, Canada

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Process system design, such as those engineering projects being developed in the global energy sector, involves well-established empirical engineering knowledge, standards and industrial codes. Their effective and efficient implementation has critical consequences to the success of projects. In a mechanical engineering domain, process system design covers process-flow modelling, pressure vessel and piping layout design, detailed structure design, etc. The authors are motivated to investigate an effective method for achieving the knowledge-driven design to address the efficiency drawback in traditional process system design applications. This article proposes a systematic method to embed in-depth engineering knowledge and to realise smart design changes in a unified feature-based approach. To prove the feasibility and effectiveness of the proposed method, a process fuel and water supply system has been comprehensively designed in the conceptual design stage. The findings of this research work are presented with some critical discussions at the end of this article. The authors believe that this approach is easy to implement and is useful to improve the knowledge reusability and engineering design productivity.

Keywords: unified feature-based design; process engineering; parametric modelling; knowledge-based design

1. Introduction

The ever-increasing demand for energy across the globe has sustained the growth of process engineering in the oil and gas and electrical generation sectors. In many underdeveloped and developing nations, there is still a wide gap between the demand and supply of electricity. As the demand for electricity has increased, so has the construction of new power plants. Process system engineering, including the design of processing vessels and piping, is a major effort for such project development and also plays an important role in the economics equations. So far, the engineering practice is very much based on the traditional procedural and iterative engineering code-checking approach, which is time consuming and error prone. In addition, each process system design constantly changes with the advancement in design, installation and construction because of various progressive or unseen factors. Hence, it becomes important that the design details are updated in a system model along with the changes in those process and instrumentation diagrams (PIDs) and layout designs with minimum effort.

The problem is how to generically embed and effectively apply all the established and codified design rules, standards and checking procedures in a computer-aided engineering system with the required design integrity, change management functionality and project scalability. A company's engineering department commonly finds itself repeating some similar design procedures but the engineering models cannot be reused. In the past, there had been a temptation to reuse previous project designs, but the integrity of engineering model became unknown, and it was too tedious to check (Pilhar *et al.* 2002). Such concerns have been particularly strong in the system-conceptual design stage. Although modern computer-aided design (CAD) tools have been widely used in industry, the problem of how to effectively use them when dealing with the challenges of engineering complexity and knowledge embedment has puzzled many companies (Franco *et al.* 2006).

The authors believe that feature-based parametric modelling could play an important role (Allada and Anand 1995). For example, in the machining sequence development, Wang *et al.* (2006) have reported their successful enriched feature implementation that has shown promise. Hence, for processing industry applications, a systematic method to embed in-depth engineering knowledge and to realise smart design changes in an advanced feature-based design is proposed. To prove the effectiveness of the proposed method, a convincing case study is necessary. Via an in-depth project, a pilot software system has been developed to create an efficient and reusable oil and water supply design method for a power plant so that

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*Corresponding author. Email: yongsheng.ma@ualberta.ca

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industrial contractors can enhance their practices by adopting the proposed approach.

2. Literature review

Pressure vessel design in process engineering is a relatively mature subject (Megyesy 2008). Most of the recent research on computer-aided solutions are focused on the physics modelling or finite element analysis (Franco *et al.* 2006); in the discipline of CAD for pressure vessels, many efforts had been directed to medical field (Li *et al.* 2007).

Traditionally, CAD applications are independently developed and applied for expressing geometric design requirements for manufacturing. Over the years, the Standard for the Exchange of Product (STEP) model data has been developed for sharing data among different design and manufacturing systems (Zhou *et al.* 2008). The feature concept was also initiated for manufacturing. For example, machining features were defined as volumes of material removed in machining operations (ISO 1999) and broadly used for computer-aided process planning (Xu *et al.* 2011). A thorough review related to new feature representations and their research states of art are available in Ma *et al.* (2008).

In the process engineering field, features certainly have the potential to represent engineering semantic patterns; hence, researchers from Germany proposed a concept of related modelling schemes such that feature-based knowledge representation and implementation can be more coherently and consistently developed (Pilhar *et al.* 2002).

However, the features defined by the traditional technology were not associated with the engineering constraints that are essential for design intent modelling and safety evaluation. This drawback has limited feature technology to a solution of knowledge bases, geometry generation in the manufacturing sector only. In fact, in feature-based engineering design applications, the incorporation of engineering calculations and the management of evaluation after design changes is a difficult issue so far. One active research attempt is to make various types of features to be more unified under a common scheme such that associative nature of advanced features (Bronsvoort and Noort 2004, Gottipolu and Ghosh 2003), such as cooling channels in plastic injection mould (Ma and Tong 2004), can be modelled and supported for productivity enhancement with certain information management automation. The further development of feature definitions has advanced feature applications.

To design a process supply system with the advanced feature-based approach, there are some challenges. First of all, the definitions of features in such design projects are usually non-standard and have never been explicitly identified. For example, Zhang and Nagasawa (2004) tried to use a manufacturing feature concept, but their work was limited to generating 3D welding structures. Considering the specific process engineering application domain, the piping layout in a diesel fuel supply sub-system could be analogous to the cooling channels in mould design (Ma and Tong 2004). Such features related to conceptual design are even more difficult because of the abstract nature and further detailing in the downstream (Kim *et al.* 2004, Han and Lee 2006). Second, the design cycle involves multiple processes including flow analysis, pressure vessel design and geometry design simulation. Design changes occur repetitively throughout the design cycle. Therefore, effective mechanisms to implement, validate and consistently achieve the updates of downstream changes are essential for knowledge-driven design approach (Ma *et al.* 2008, Subramani and Gurumoorthy 2005). Hence, an in-depth study to identify, verify and prototype advanced features is imperative to beef up the unification and diversification of feature-based knowledge engineering approach. This article highlights the advanced design features that have been identified via a real-world research project, illustrates the representation of them in a feature modelling and development effort, and demonstrates the design feature implementation mechanisms based on the parametric modelling approach. The advantages and drawbacks of this proposed method are discussed.

3. Engineering design aspects

Usually, process system design starts with the process flow design carried out by chemical engineers. Then, the key facilities, such as reaction towers, storage vessels, piping layout, electrical and instrumentation systems, are followed. Finally, operation control and management systems are selected and implemented. After many iterations of testing operations, the fully integrated process system is ready for commercial operation. Process system engineering consists of multidisciplinary associative design and coherent real-time system integration. The built-in dependency and concurrency of multiple-domain design engineering is always present throughout any project life cycle. Therefore, multiple views of engineering and management consideration have to be fully integrated and validated cyclically via effective procedures. The usual engineering domains involved are process engineering, mechanical engineering, electrical and electronic engineering and system engineering. In addition, the operation management aspect is also constantly evaluated. From a mechanical engineering point of view, pressure vessel design and piping layout design are the most dominant tasks involved.

3.1. Pressure vessel design

Many different pressure vessels serve as an indispensable part of the process engineering facilities; they found great applications in nuclear refineries and nuclear, chemical and power plants. Pressure vessels are designed to hold fluids (liquids or gases) at high pressure and are capable of withstanding various loading conditions. Pressure vessels can be classified as cylindrical or spherical according to their geometric configurations. They can also be classified into three categories according to their pressure retaining capacity, as described by Megyesy (2008): (1) atmospheric pressure vessels have a design pressure in the range of 0–2.5 psig (0–17.24 kPa) and are designed according to the application programming interface (API) 650 standard; (2) low-pressure vessels with the design pressures vary from 2.5 to 15 psig (17.24–103.422 kPa) and are designed in accordance with API 620 standard; and (3) high-pressure vessels with the design pressures vary from 15 to 3000 psig (i.e., 103.422 kPa to 20.684 MPa) and are designed in accordance with the American Society of Mechanical Engineers (ASME) section VIII, Division 1. From the shape design angle, a cylindrical pressure vessel can be horizontal or vertical. In Northern America, pressure vessel design has been highly regulated (Megyesy 2008).

In this work, engineering calculations are implemented as constraints in Excel worksheets. To give a basic concept of engineering calculations, the vessel thickness for a low-pressure cylindrical vessel can be studied. Other than the working pressure that is usually specific to the process involved with the vessel, fluid static head pressure must be considered as below:

$$\mathrm{PT} = P_{\mathrm{d}} + 0.433 * \mathrm{SG} * H, \tag{1}$$

where P_{T} is the total pressure (psi), P_{d} the pressure design (psi), SG the specific gravity of the fluid, and H is the height of the fluid (ft), Designing a cylindrical pressure vessel starts with its shell and hemispherical head thickness calculations. For shell thickness, first, the minimum thickness, T_{req}, is worked out as follows (Megyesy 2008):

$$T_{\mathrm{req}} = PR_i/(SE - 0.6P) + \mathrm{CA}, \tag{2}$$

where S is the maximum allowable stress value for the material (ASME, 2004), CA the corrosion allowance, E the joint efficient factor for a welded vessel, P the design pressure, and R_{i} is the inner radius of the cylindrical shell.

A nominal wall thickness (NWT) is determined according to the pressure, temperature and material from the handbook. Impact testing may be required for some materials in cold weather, e.g., as in Northern America. For example, if normalised SA 516 Grade 70 material (ASME 2004) is used, which has improved fracture toughness, according to ASME code (2004), the exempted temperature from impact testing is −55°F (−48.33°C). Referring to Table UCS-66, with a design pressure of 75 psi (518 kPa), the NWT can be found as 0.5 in. (12.7 mm). The thickness of the cylindrical shell, t, considering corrosion and mill tolerance allowance is calculated by

$$t = \mathrm{NWT} - \mathrm{CA} - (\mathrm{NWT} \times \mathrm{MTA}) \tag{3}$$

$$R_i = D_o/2 - t \tag{4}$$

in which MTA means mill allowance (MTA). For the above example parameters, MTA = 12.5%. To verify the thickness selected, the maximum pressure has to be calculated as follows (Megyesy 2008):

$$P_{\max} = SE_t/(R_i + 0.6t). \tag{5}$$

For a safe design, $T_{\mathrm{req}} < t$ and $P < P_{\max}$.

For calculating the thickness of hemispherical heads, t_{h}, the nominal wall thickness is calculated by a similar method. The minimum thickness at the design pressure is given as

$$T_{\mathrm{req}} = (PR_i)/(2SE - 0.2P) + \mathrm{CA}. \tag{6}$$

The maximum allowable pressure for the considered thickness is given as

$$P_{\max} = 2SE_t/(R_i + 0.2t). \tag{7}$$

It can be appreciated that such design engineering constraints are very specific and tedious to be manually evaluated. Stress calculations are required to include longitudinal bending stress, tangential shear stress, additional stress in the head and the circumferential stress at the horn of the saddle, in the case of a horizontal cylindrical vessel, as well as at the bottom of the shell (Megyesy 2008).

Other examples of such calculations include the capacity, weight, nozzle dimensions of the vessel, etc. An interesting design aspect other than the shell itself is the saddle (Megyesy 2008). Figure 1 gives a detailed dimension diagram for a saddle design. Although such pressure vessel saddle design is well known in the trade, for the benefit of the readers, a general description is given here.

The large diameter thin-walled pressure vessel is supported near the heads while the thick-walled pressure vessels are best supported at the point where the longitudinal bending stress becomes almost equal to the stress value at the mid span of the saddle. While designing the saddle supports in tension, the combined stress values due to longitudinal bending stress and stresses due to internal pressure should be kept below the allowable stress value of the material multiplied by the joint efficiency factor.

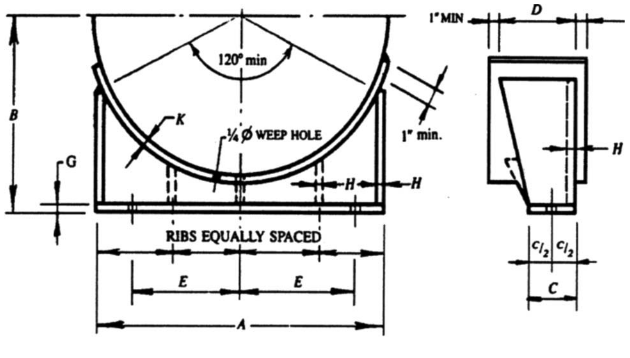


Figure 1. Saddle support detailed dimensions (Megyesy, 2008).

The tangential shear stress is calculated according to the spacing of the saddle from the corner of the vessel shell. For example, the tangential shear stress should be less than 0.8 times the allowable stress value of the material. The additional stress in the head, the circumferential stress at the horn of the saddle and the circumferential stress value at the bottom of the shell are also calculated and checked against the properties of the vessel material.

3.2. *Piping engineering design*

Hydraulic calculation and pipe size have to be determined as follows:

$$Q = AV, \tag{8}$$

$$A = \pi/4(d)^2, \tag{9}$$

where Q is the volume flow rate of fluid, V the velocity of the water, d the inner diameter of the pipe considering Schedule 40, and A is the cross-sectional area of the pipe.

Pipe flow Reynolds number calculation:

$$R_e = VD/v, \tag{10}$$

where R_e is the Reynolds number, V the mean velocity of flow in the pipe, D the diameter of the pipe, and v is the kinematic viscosity of the pipe.

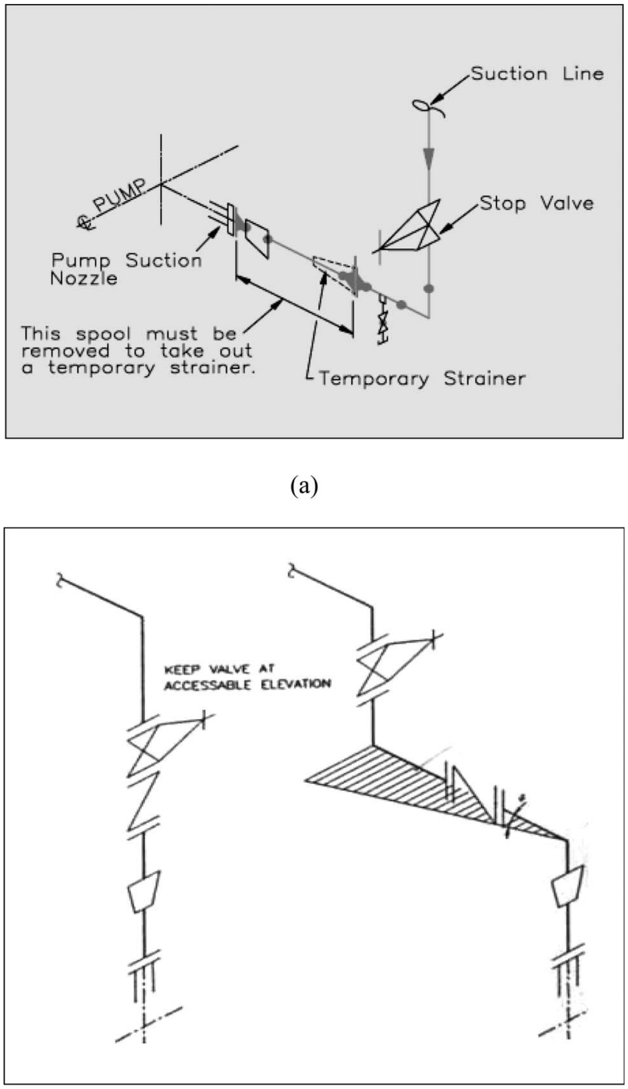
Proper piping layout design is an important portion of any plant as they constitute process flow channels. The most important criteria for the piping layout design are that they should meet all the design criteria as shown in the relevant PIDs. The piping should be done using the shortest route possible and with minimum number of fittings to save cost and reduce the frictional losses through the pipes and fittings. They should be neatly routed into groups, taking into consideration the ease of supporting arrangement and the movements of traffic. Another important criterion that should be considered while routing pipe is that there should be adequate clear working space around equipment, which requires frequent maintenance or servicing, and the safety of workers. All the valves, pressure, instrumentation gages and temperature indicators should be easily accessible, and they should be located in a position where they can be easily read. Wherever the piping needs to pass through roads, culverts should be used. It is also important that proper headroom clearance is provided for ease of movement of workers or traffic. The minimum headroom clearance is 2.2 m for man movement, and if the piping is passing above ground over roads, the minimum clearance is 6 m to allow smooth movement of traffic.

Special consideration should be given to make sure that there is no interference or clashes between the pipes or pipes with other equipment or structures. Further, there should be proper drainage and venting points at the lowest and the highest points, respectively. The drainage and venting location helps in filling, hydrostatic testing and also helps in removal of fluids before taking out the pipes for repairs or service. Among those many aspects of calculations required for piping design, hydraulic calculation and pipe size have to be determined.

Considering the required flow rate, a particular pipe size is chosen, and the resulting flow velocity is calculated. If the calculated velocity lies within the recommended range, the pipe size is selected. However, if the velocity falls out of the recommended range, then a new pipe size is selected for the system. Any calculated velocity that is higher than the recommended velocity may result in noise and erosion of pipe. Any size below the velocity will result in oversizing the pipe and increase in cost.

Once the pipe size is determined, it is necessary to find the Reynolds number of the flow. By finding the Reynolds number, it can be determined whether the flow is laminar or turbulent. Then, the friction factor is calculated followed by the total pressure drop in piping system along with all the fittings. For the minor losses, only the loss of pressure due to pipe fittings has been considered. The losses of pressure due to expansion, contraction, loss at pipe entrance and exit have been neglected.

Another typical piping design is for centrifugal pumps. The suction and discharge piping diagrams are shown in Figure 2(a) and 2(b). The height of the fluid in the pressurised tank is considered for the calculation of the pump-suction pressure. For design purpose, it is considered that the fluid level in the vessel doesn't fall below a specific level. If the level of fluid falls below a specific level, then the level switch is switched on and the pump will start to fill up the vessel.



(a)

(b)

Figure 2. Centrifugal pump piping design concepts. (a) Suction and (b) discharge piping.

The suction pressure is defined as the difference between the head pressure due to the fluid height minus the frictional pressure drop in the longest run of pump-section piping. For the calculation of the pump discharge pressure, the total frictional pressure drop in the longest run of piping is calculated. The total pump discharge pressure is calculated, taking into consideration 30% safety margin due to aging and variations in actual construction and installation and also considering the required pressure at the outlet. The net pumping pressure or delivery pressure is the difference between the discharge pressure and the suction pressure. An allowance of 20% is considered on the net pumping pressure. Once the net suction and the net pumping pressures are known, it can be used for the design of pump and motor for pump power and efficiency calculations. The motor is pre-selected, and it is compared with the pump shaft power. The pump motor power has to be greater than the pump shaft power.

Piping layout design constantly changes with the advancement in the installation and construction of the plant due to various expected or unexpected factors. Hence, it becomes important that the design details including PIDs are updated with minimum efforts. This is where parametric modelling plays an important role.

4. Research methodology

Parametric modelling, as an enabling mechanism for knowledge-based CAD modelling, is an effective technique being increasingly employed in industries. Parametric modelling supports parameters or expressions in the CAD environment and enables design-model dimensions to be changed by changing the values. Parametric modelling is the supporting mechanism for feature-based design approach. The parametric technique depends on well-defined mathematical relations in such a way that if one entity or parameter is altered, its impacts on all the other relative parameters can be updated automatically. A well-defined parametric modelling application can embed design knowledge into the design models in a generic manner and significantly increases the productivity of the design processes. The main advantage of parametric modelling is that there is no need for the remodelling of updated models based on the changes of input design parameters. This regeneration capability eventually leads to the savings of time, effort and cost. However, without an appropriate design scheme, simply using parametric modelling creates a lot of CAD modelling parameters such that their semantic meanings, relations and rules applied to them are tedious to manage, and engineers will be overwhelmed by the 'hidden' relations among parameters and dimensions if the design task becomes reasonably complex, or if the engineer is not familiar with or no longer remembers the meaning of different parameters and their embedded constraints.

To make better use of the parametric design mechanism, feature technology is required. This is because many engineers are dependent on CAD tools to deliver their design contents. A feature defines relations between different entities in a semantically explicit and coherent manner (Ma *et al.* 2008). Via features, design entities are calculated based on complex relationships and mathematical formulas according to typical engineering design patterns. With features, they can easily manipulate the design models with common engineering semantic patterns; and their design intent can be fully defined and managed throughout the iterative design cycles of revisions. Advanced feature-based approach basically entails flexible well-defined feature definitions, constraint management and effective service functions, where, usually, object-oriented software engineering methodology is used. In this research, a unified feature scheme is applied when initiating the process engineering design activities.

The definition of a unified feature has been given in Chen *et al.* (2006) and shown in Figure 3. The unified feature definition provides a generic feature format and granularity for different product development stages. The unified feature definition differentiates itself from other feature definitions by enabling associations among feature entities as well as among three information layers, such as knowledge bases, features and geometry. A system of object classes were introduced by Chen *et al.* (2006), where four feature properties are specified generically, i.e., attributes parameters, constraints and geometric references. Associations in the unified feature modelling scheme were classified into horizontal and vertical types. Horizontal ones represent feature associations via common topological entities. The associated features may belong to the same or different life-cycle stages. Vertical associations serve as the intermediate interfaces upward to the knowledge model and downward to the geometric model. Components or modules were assumed to be modular and replaceable parts of a system. Further, in the unified feature scheme, a product information model consists of sub-models that correspond to individual development stages. Each of them can be constructed with three layers: a knowledge-based semantic model, a geometric model and a feature model.

The proposed unified feature-based modelling scheme was intended to solve the well-known multi-view representation of features and feature relationship modelling problems by: (1) including the conceptual design, together with the functional requirements, into the multiple-view feature modelling process; (2) supporting non-geometric associations across different stages; and (3) assisting in the creation and maintenance of the associations between the canonical form of a feature and the boundary representation model, and between application features and the facts in the higher-level knowledge model. Such associations are necessary to maintain the geometric consistencies among feature models and to support knowledge-based reasoning processes, such as design intent validation. The framework of the unified feature is adopted in this article, which reports the continued effort. Two types of associations used in the unified feature modelling scheme, sharing and dependency, are implemented

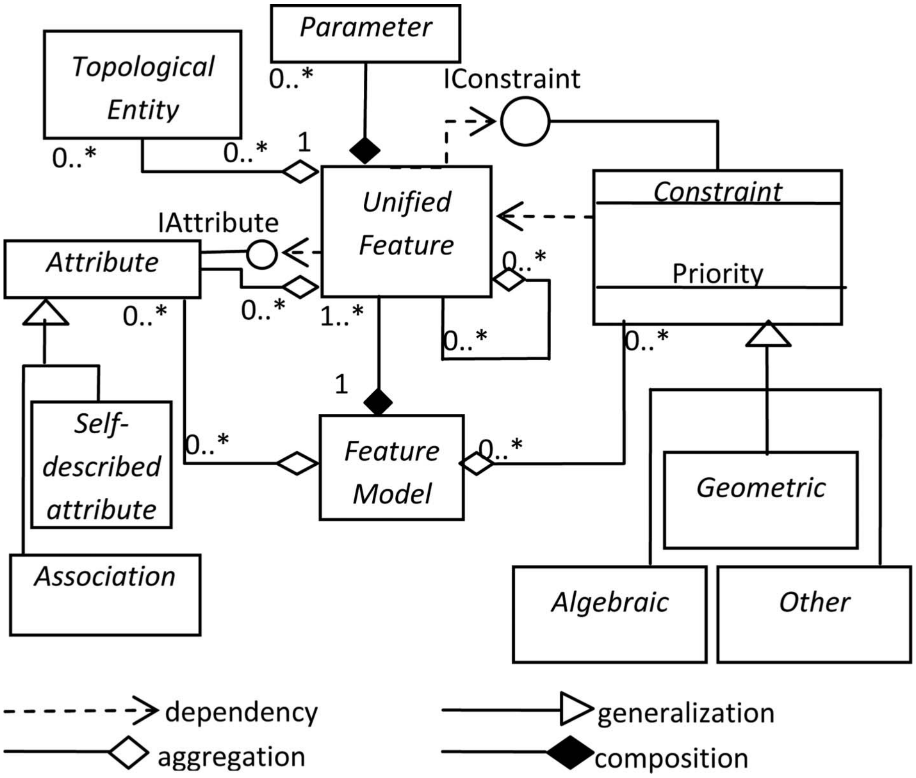


Figure 3. Semantic definition of a unified feature in UML format (Chen *et al.* 2006).

covering the integration of the conceptual and the detail design stages.

In this particular research work, basically, the design intent can be expressed as a set of common, flexible, and well-defined unified features, where the engineering conceptual patterns, e.g., the pipeline layout, a piece of equipment or a key design code to be associated and checked in the context of a process supply system, are represented generically as objects with a set of geometric and topologic entities, associated driving parameters, constraints and attributes. Unified features can be used to define engineering patterns at different semantic detail levels, and a set of lower-level features can be used to define higher-level features. Figure 3 uses unified modelling language (UML) representation, which has a standardised software modelling method for illustrating class property data and process definitions and their relations in object-oriented programming methodology (Jacobson *et al.* 1998).

This work is not about coding unified features via software. Rather, it is a verification and application of the proposed concept of unified feature through a typical and yet real example. The research tries to answer two questions. The first is how unified feature properties can correspond to a real application, and the second is how the definition of the unified feature can be generic enough for those similar projects like the case studied here so that the unified feature-based engineering approach can serve as an effective engineering information management method. Engineering change propagation is a common concern among the research community, and some initial thoughts have been described by Chen *et al.* (2008).

5. System development

5.1. *Architecture*

From an informatics point of view, this research work was also aimed to create an efficient and reusable process engineering design system model for similar industrial applications. Figure 4 shows the system design of the proposed method. The user can be the process engineer or an engineering designer. Figure 5 shows the research project implementation processes and the tools used.

The Microsoft Excel module takes care of engineering design calculations according to the design codes mentioned (ASME 2004). In this work, to begin with, a process engineer (a user) needs to interactively input the basic process parameters and select the common process elements via an user interface of Excel software template. This interfacing spreadsheet is implemented as the top-design conceptual feature tabbed as 'Input' sheet in Excel.

In this Excel module, engineering codes are implemented using the built-in checking formulas. Following the top-level input feature, different aspects of the engineering design rules are created in different 'sheets'. System-level constraints are listed in a 'Formula' sheet, which can be viewed as the constraint list of the top conceptual design feature. Other sheets implemented include 'Flow Calculation', 'Pressure Loss Calculations', 'Stress Verification for Saddle', 'Area Reinforcement', 'Dike Wall Calculation', 'Pipe Wall Thickness Calculations', etc. Among those engineering aspect sheets, interconnections are built via cell references. In addition, those calculated output parameters are readily listed in an interfacing 'spreadsheet',

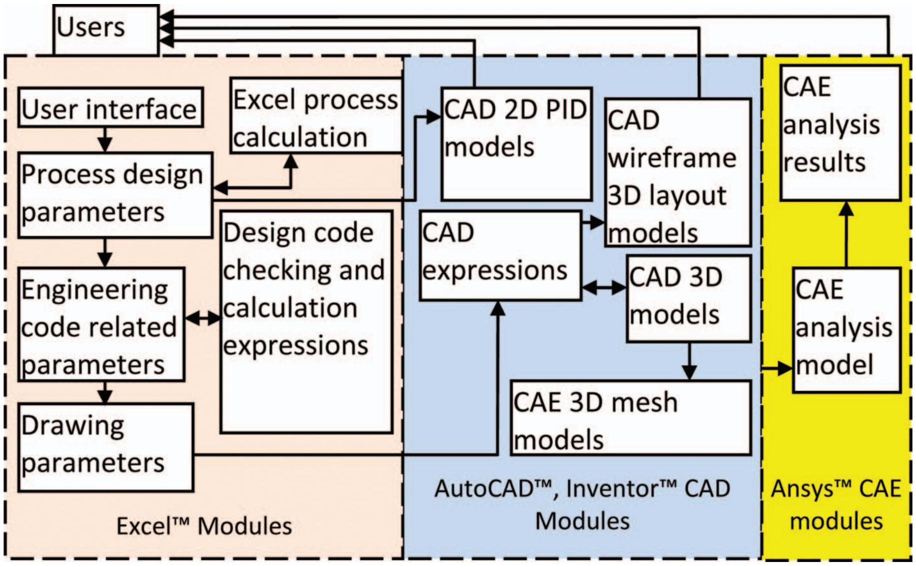


Figure 4. System design for the proposed method.

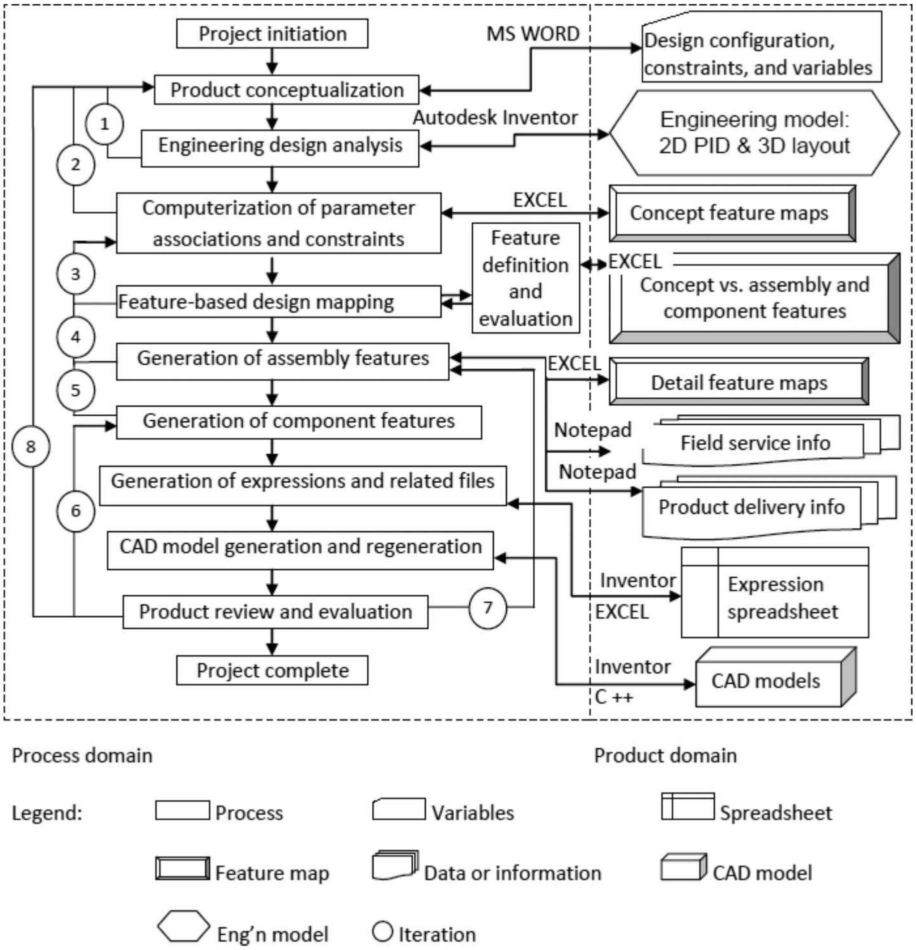


Figure 5. Design processes and the implementation tools.

named as ‘Model Attachment’ tab. They are directly integrated with the CAD module for creating 2D/3D design models.

The CAD module using Autodesk Inventor creates 2D PID, 3D equipment design and piping layout models. First, process parameter attributes are used to create process design blocks and, eventually, these blocks are then used for 2D PID generation. As a major input for the detailed design of pressure vessels and piping layout, this generated 2D PID captures the process engineer’s design inputs and intention. Once the PID is verified, those specified key pressure vessels are developed in the CAD module by interacting with the Excel module. This is due to the nature of such process engineering design cycles. Such cycles need progressive evaluation of the changes throughout the design process at different stages and involve different devices. Once these key devices, such as all the pressure vessels are designed, a 3D spatial layout design is created with the references to the existing buildings, obstacles and spaces available. This stage is necessary for the mechanical designers to reflect the plant-routing constraints and paths for the piping systems. After satisfying all the initial spatial requirements, the 3D piping layout is designed by taking care of those aspects as described in Section 2.2.

The computer aided engineering (CAE) module takes the geometry output from the CAD tool and using ANSYS software tool to verify the stress distribution with the finite element analysis technique. As indicated before, equipment design, such as pressure vessels and piping layout, constantly changes with the advancement in stages of design, manufacturing, installation and construction. For the flexibility to accommodate the frequent changes and to propagate the checking process iterations, advanced feature-based design modelling approach is adapted (Ma *et al.* 2008). Take piping design as an example, there are three major differences between the feature-based piping design and the traditional approach. (1) Piping circuits are parametrically designed with the built-in characteristics of the conceptual patterns, such as the connectivity of circuits, calculation of pressure drops and sizing of the pipes, as well as their associative changes similar to the case of cooling channels, as reported in Ma and Tong (2004). (2) Changes of the piping parameters are organised according to the features; their integrity of properties and the satisfaction of constraints are checked upon the updating command. (3) Higher-lever design concepts are conveniently associated to these user-defined features via rules, constraint-solving algorithms and logics, such that when the conditions of a design concept is changed, the relevant features are automatically checked, validated and updated.

5.2. *Constraint implementation*

Design codes involved are modelled as sets of constraints in an MS Excel module with embedded analytical calculations. The main design codes and standards implemented are:

- ASME Section VIII, Division 1: *Boiler & pressure vessel design code*
- API 650: *Storage tank design*
- ASME B 31.1: *Power piping code*
- ASME B 16.10: *Face-to-face dimensions of valves*
- ASME B 16.34: *Valves – flanged, threaded and welding end*
- ASME B 16.9: *Butt-welded fittings*
- ASME B 16.5: *Pipe flange and flange fittings*
- ASME B 36.10: *Welded and seamless wrought steel pipe*.

5.3. *Constraint and change management*

It can be appreciated that MS Excel, as a very popular tool to manage parameters, has the 'formula implementation' function that can handle embedded dependencies and equation constraints. The updating mechanisms are capable to propagate changes automatically within the Excel environment. This feature has been fully used by this research work to mange those engineering changes and carry out iterative rule checking. Further, the new updates of related design parameters can be automatically reflected in Inventor design models due to the automated updating interface between Inventor and Excel under the technology of parametric feature-based design. One advantage for feature-based modelling is the parametric change management that can be mapped to semantic engineering characteristics of design patterns. Instead of changing individual parameters, a set of them are changed at a time. By managing changes in groups corresponding to feature patterns, the consistency of those design patterns, i.e., features, can be better managed in keeping their integrity than updating parameters one by one. If all the parameters are updated one by one, updating conflicts could arise from the incompatible intermediate values. This is the merit point of this proposed design approach and the pilot system.

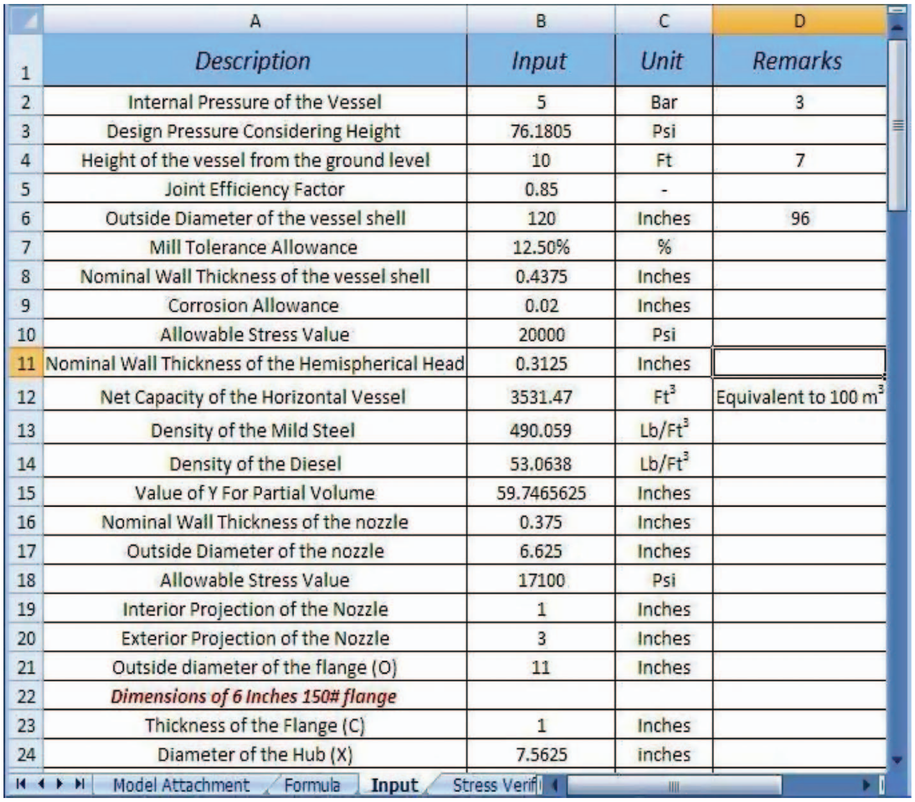
In process supply system design, an interesting observation can be made from the common practice of process engineering projects. Unlike other commercial product development, industrial process development is heavily coded and regulated according to some national standards. That is why Section 5.2 is included. The regulations warrant safe design procedure and constraints but also eliminate the possible variations of design candidates. Such regulations cover design requirements, processes and parameter evaluation. Hence, there is not much flexibility in the field. However, because of the prescribed details of pressure vessels and piping, the proposed method can consistently model the constraints and generation of features according to the codes and parameters where a unified feature approach is adequately applicable in a general way.

6. Case study

The aim of this case study is to create an efficient and reusable design system for a medium-size electrical plant so that industrial contractors can enhance their practices by adopting this pilot approach. The reason to study such a power plant supply system case to prove the concept is due to the ever-increasing demand for electricity across the globe that has led to a rapid rise in power plant construction and expansion. A diesel fuel power plant is studied due to its suitable engineering scale and the practical limitation of the available research resources. The authors believe that the proven method can be equally applied to larger-scale projects.

Typically, there are three aspects considered for a power plant supply system, i.e., diesel fuel, portable water and fire water sub-systems. The fuel and water system design in power plants is essential in engineering design as it has major technical, operational and economic impacts. In addition to the diesel fuel subsystem that is obviously necessary to provide constant energy, the portable water and fire water system is meant to supply water to the boiler, generator and the incinerator plant building, respectively. In the incineration building, the solid waste and liquid organic wastes are treated.

In all the subsystems, centrifugal pumps are used to maintain the required pressure. In the fire water system, jockey pump is also used if the pressure drops due to any sort of leakage, or during emergency, the pressure will keep on dropping. To maintain the required discharge pressure, the jockey pump will



	A	B	C	D
1	*Description*	*Input*	*Unit*	*Remarks*
2	Internal Pressure of the Vessel	5	Bar	3
3	Design Pressure Considering Height	76.1805	Psi	
4	Height of the vessel from the ground level	10	Ft	7
5	Joint Efficiency Factor	0.85	-	
6	Outside Diameter of the vessel shell	120	Inches	96
7	Mill Tolerance Allowance	12.50%	%	
8	Nominal Wall Thickness of the vessel shell	0.4375	Inches	
9	Corrosion Allowance	0.02	Inches	
10	Allowable Stress Value	20000	Psi	
11	Nominal Wall Thickness of the Hemispherical Head	0.3125	Inches	
12	Net Capacity of the Horizontal Vessel	3531.47	Ft^3	Equivalent to 100 m^3
13	Density of the Mild Steel	490.059	Lb/Ft^3	
14	Density of the Diesel	53.0638	Lb/Ft^3	
15	Value of Y For Partial Volume	59.7465625	Inches	
16	Nominal Wall Thickness of the nozzle	0.375	Inches	
17	Outside Diameter of the nozzle	6.625	Inches	
18	Allowable Stress Value	17100	Psi	
19	Interior Projection of the Nozzle	1	Inches	
20	Exterior Projection of the Nozzle	3	Inches	
21	Outside diameter of the flange (O)	11	Inches	
22	***Dimensions of 6 Inches 150# flange***			
23	Thickness of the Flange (C)	1	Inches	
24	Diameter of the Hub (X)	7.5625	inches	

Figure 6. Partial input page implemented with Excel.

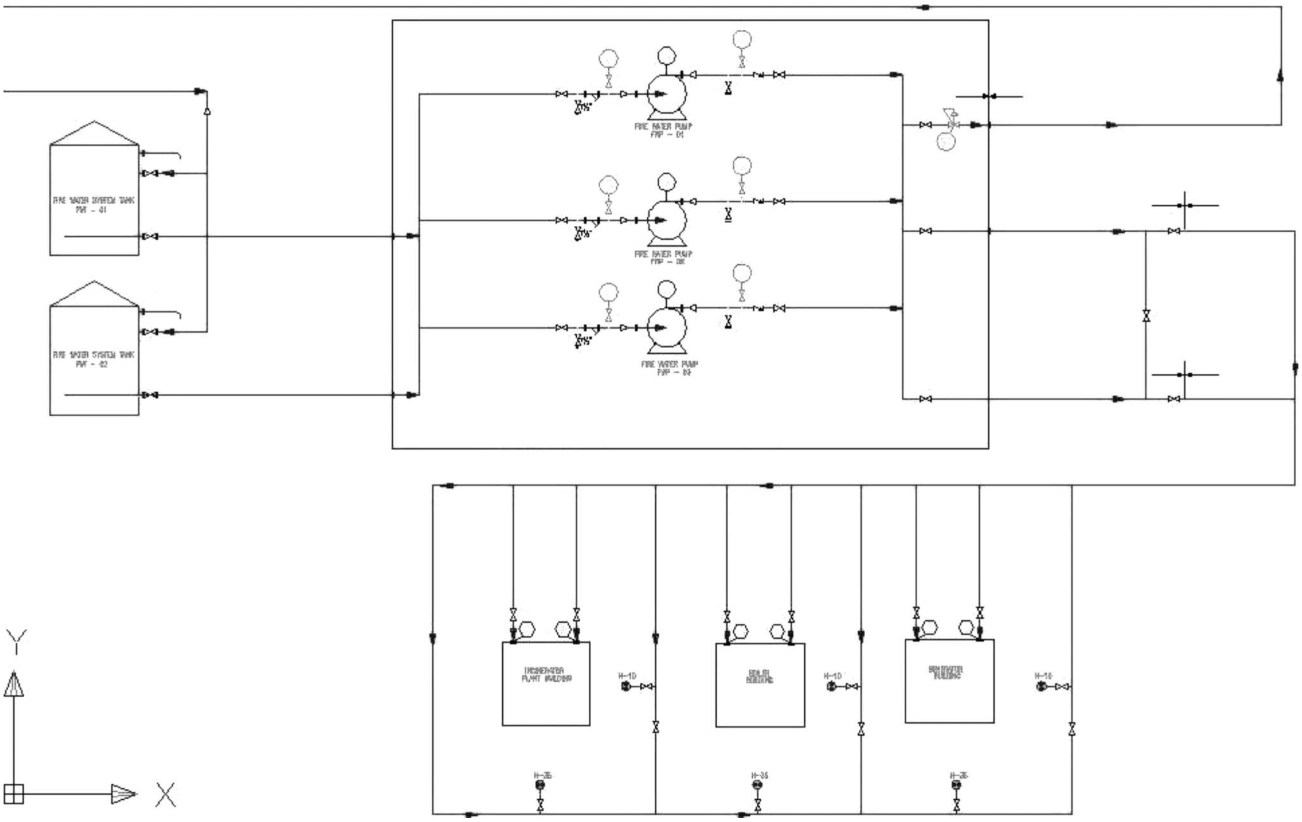
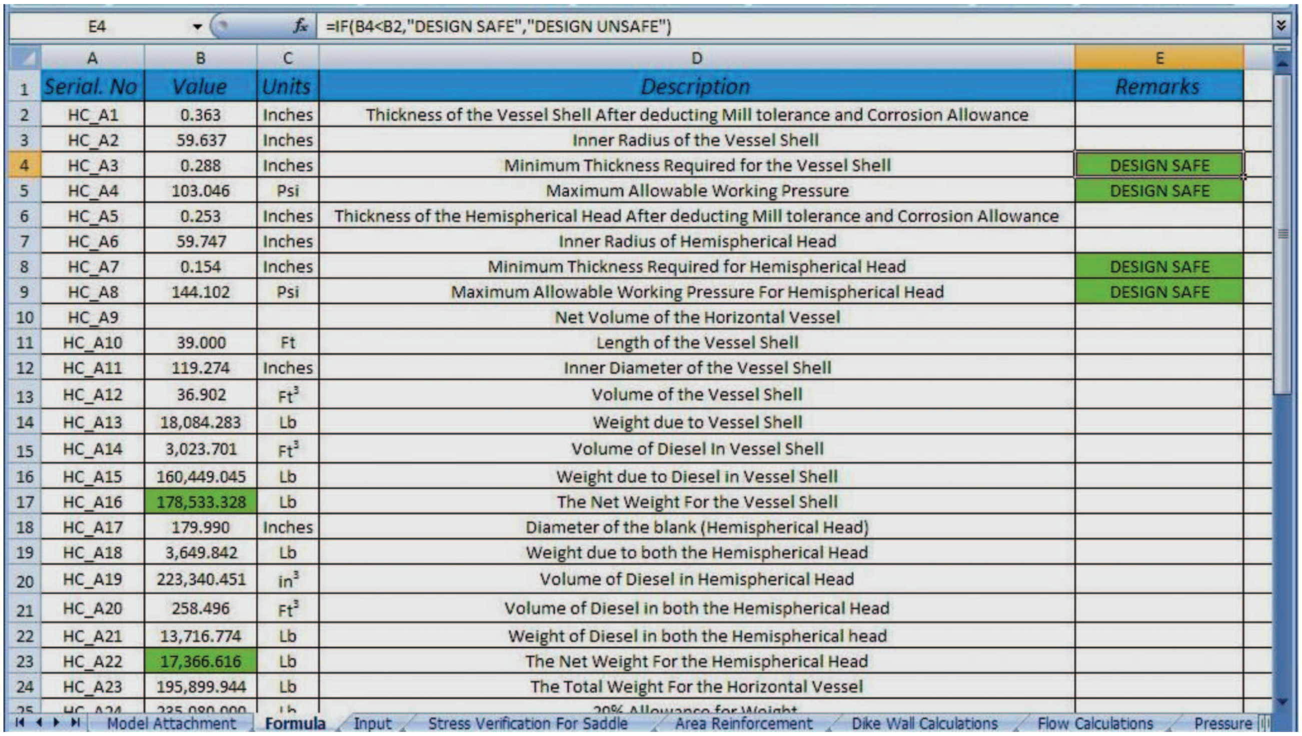


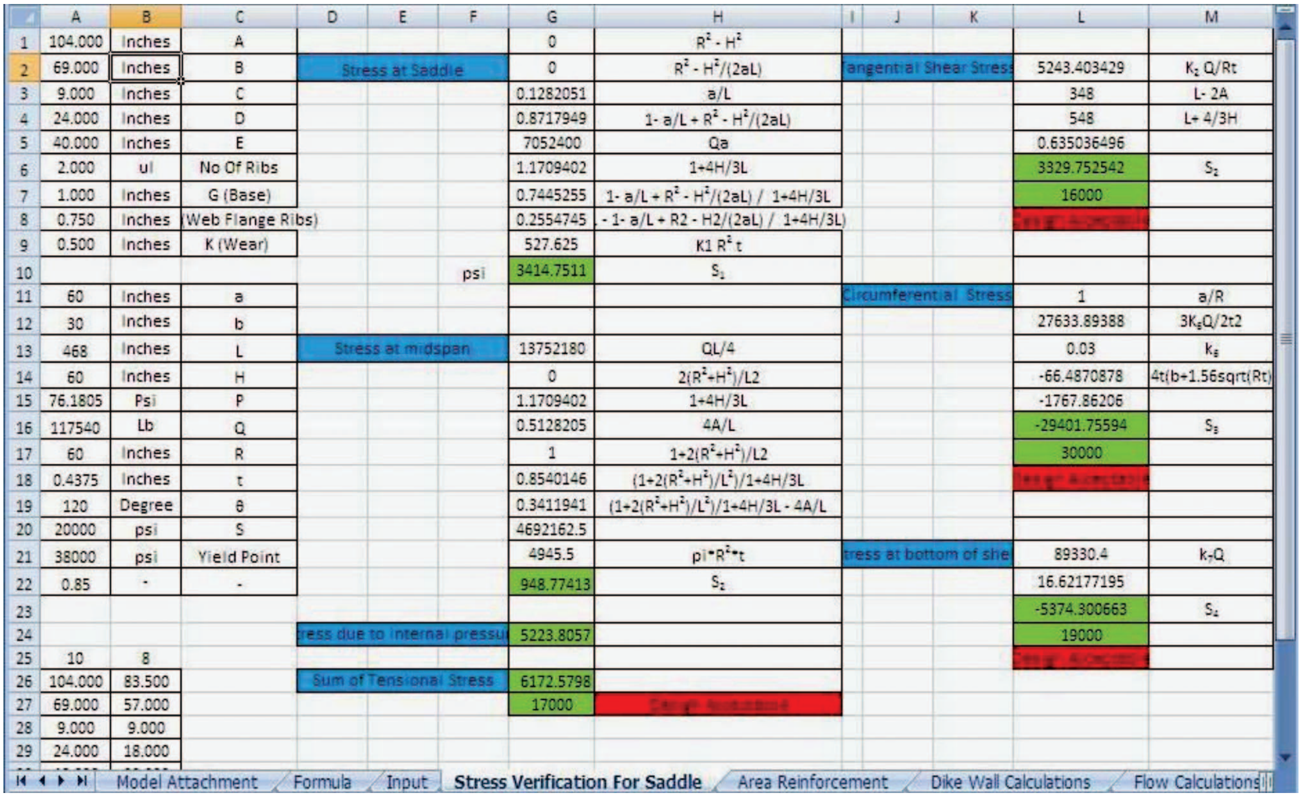
Figure 7. PID diagram for the fire water supply sub-system.



=IF(B4<B2,"DESIGN SAFE","DESIGN UNSAFE")

	A	B	C	D	E
1	*Serial. No*	*Value*	*Units*	*Description*	*Remarks*
2	HC_A1	0.363	Inches	Thickness of the Vessel Shell After deducting Mill tolerance and Corrosion Allowance	
3	HC_A2	59.637	Inches	Inner Radius of the Vessel Shell	
4	HC_A3	0.288	Inches	Minimum Thickness Required for the Vessel Shell	DESIGN SAFE
5	HC_A4	103.046	Psi	Maximum Allowable Working Pressure	DESIGN SAFE
6	HC_A5	0.253	Inches	Thickness of the Hemispherical Head After deducting Mill tolerance and Corrosion Allowance	
7	HC_A6	59.747	Inches	Inner Radius of Hemispherical Head	
8	HC_A7	0.154	Inches	Minimum Thickness Required for Hemispherical Head	DESIGN SAFE
9	HC_A8	144.102	Psi	Maximum Allowable Working Pressure For Hemispherical Head	DESIGN SAFE
10	HC_A9			Net Volume of the Horizontal Vessel	
11	HC_A10	39.000	Ft	Length of the Vessel Shell	
12	HC_A11	119.274	Inches	Inner Diameter of the Vessel Shell	
13	HC_A12	36.902	Ft^3	Volume of the Vessel Shell	
14	HC_A13	18,084.283	Lb	Weight due to Vessel Shell	
15	HC_A14	3,023.701	Ft^3	Volume of Diesel In Vessel Shell	
16	HC_A15	160,449.045	Lb	Weight due to Diesel in Vessel Shell	
17	HC_A16	178,533.328	Lb	The Net Weight For the Vessel Shell	
18	HC_A17	179.990	Inches	Diameter of the blank (Hemispherical Head)	
19	HC_A18	3,649.842	Lb	Weight due to both the Hemispherical Head	
20	HC_A19	223,340.451	in^3	Volume of Diesel in Hemispherical Head	
21	HC_A20	258.496	Ft^3	Volume of Diesel in both the Hemispherical Head	
22	HC_A21	13,716.774	Lb	Weight of Diesel in both the Hemispherical head	
23	HC_A22	17,366.616	Lb	The Net Weight For the Hemispherical Head	
24	HC_A23	195,899.944	Lb	The Total Weight For the Horizontal Vessel	
25	HC_A24	235,080.000	Lb	20% Allowance for Weight	

Figure 8. Constraints implemented for pressure vessel design module.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	104.000	Inches	A				0	$R^2 - H^2$					
2	69.000	Inches	B	Stress at Saddle			0	$R^2 - H^2/(2aL)$		angential Shear Stress		5243.403429	K_2 Q/Rt
3	9.000	Inches	C				0.1282051	a/L				348	L- 2A
4	24.000	Inches	D				0.8717949	$1- a/L + R^2 - H^2/(2aL)$				548	L+ 4/3H
5	40.000	Inches	E				7052400	Qa				0.635036496	
6	2.000	ul	No Of Ribs				1.1709402	1+4H/3L				3329.752542	S_2
7	1.000	Inches	G (Base)				0.7445255	$1- a/L + R^2 - H^2/(2aL)$ / 1+4H/3L				16000	
8	0.750	Inches	(Web Flange Ribs)				0.2554745	- 1- a/L + R2 - H2/(2aL) / 1+4H/3L)				[illegible]	
9	0.500	Inches	K (Wear)				527.625	K1 R^2 t					
10						psi	3414.7511	S_1					
11	60	Inches	a							Circumferential Stress		1	a/R
12	30	Inches	b									27633.89388	$3K_6Q/2t2$
13	468	Inches	L	Stress at midspan			13752180	QL/4				0.03	k_6
14	60	Inches	H				0	$2(R^2+H^2)/L2$				-66.4870878	4t(b+1.56sqrt(Rt)
15	76.1805	Psi	P				1.1709402	1+4H/3L				-1767.86206	
16	117540	Lb	Q				0.5128205	4A/L				-29401.75594	S_3
17	60	Inches	R				1	$1+2(R^2+H^2)/L2$				30000	
18	0.4375	Inches	t				0.8540146	$(1+2(R^2+H^2)/L^2)/1+4H/3L$				[illegible]	
19	120	Degree	θ				0.3411941	$(1+2(R^2+H^2)/L^2)/1+4H/3L - 4A/L$					
20	20000	psi	S				4692162.5						
21	38000	psi	Yield Point				4945.5	$pi*R^2*t$		tress at bottom of she		89330.4	k_7Q
22	0.85	-	-				948.77413	S_2				16.62177195	
23												-5374.300663	S_4
24				ress due to internal pressu			5223.8057					19000	
25	10	8										[illegible]	
26	104.000	83.500		Sum of Tensional Stress			6172.5798						
27	69.000	57.000					17000	[illegible]					
28	9.000	9.000											
29	24.000	18.000											

Figure 9. Constraints implemented for the saddle of a horizontal storage tank.

come into play. Jockey pumps are attached in such a way that they come into act when drastic pressure drop takes place. Once the pressure reaches the minimum required pressure, it is automatically switched off.

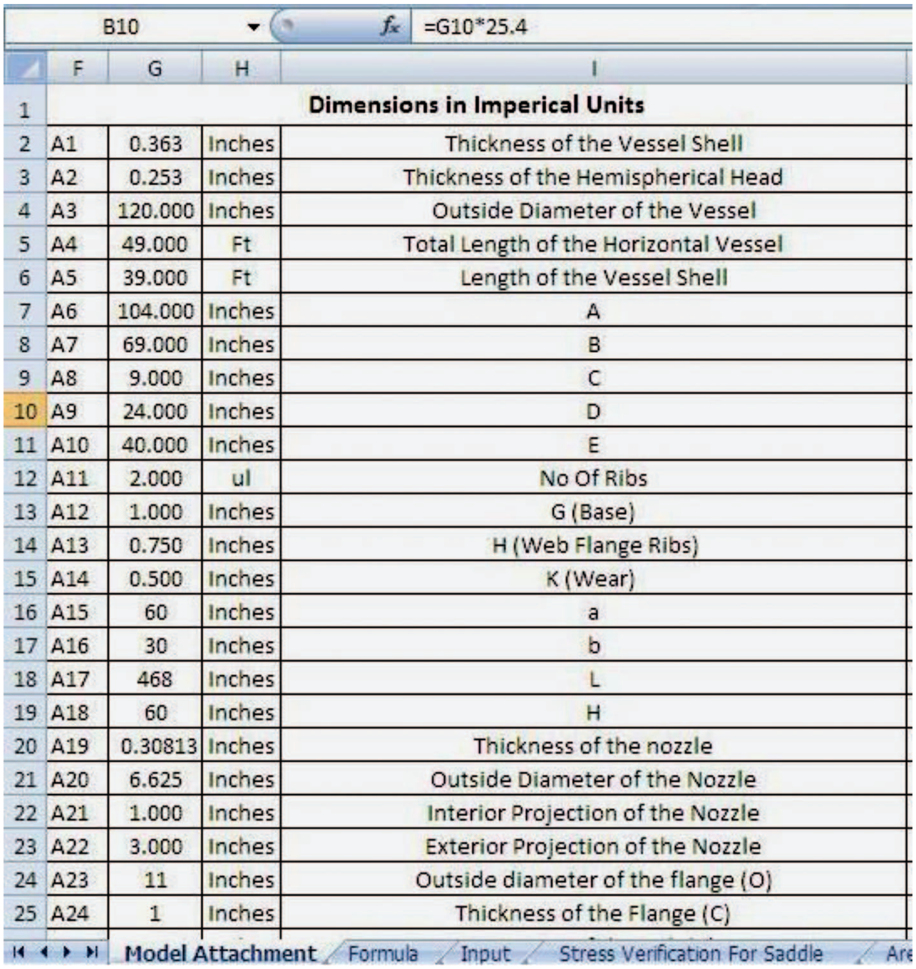
6.1. Process model creation and code-checking mechanism

To begin with the case study, as described earlier, the process engineer has to define the basic process parameters, such as the internal pressure and capacity of a pressure vessel. Figure 6 shows a partial screen snap of the input page.

Then the above-detailed attributes are used to generate a 2D PID for each sub-system automatically created in a CAD page. Note that these 2D PIDs are parametrically generated by using API functions of the CAD system based on the process engineer's input. Figure 7 shows the PID for the fire water supply sub-system. Similarly, the PIDs for portable water and fire water systems are also created parametrically. Such PIDs are in fact a form of conceptual process design features. They have to be validated by basic process calculation formulas, which are in turn a set of constraints to be satisfied in the implementation of a feature-based system in the future.

Next, those attributes of the newly created PIDs is used as the design inputs for pressure vessel and the piping layout design. Pressure vessels were designed first, and design attributes were created semi-automatically via necessary interactions between the user (now, it could be a mechanical designer) and the template pages of the modelling system.

In the Excel calculation implementation for constraints, a modular design approach is used. In addition to the major pressure vessel design code-checking module, the following modules are implemented as well: flow calculation, pressure loss calculations, pipe wall thickness calculation, fire water tank, nozzle reinforcement calculation, dike wall calculation, area reinforcement and stress verification for saddles. It was found that it was convenient to



B10 =G10*25.4

	F	G	H	I
1	**Dimensions in Imperical Units**			
2	A1	0.363	Inches	Thickness of the Vessel Shell
3	A2	0.253	Inches	Thickness of the Hemispherical Head
4	A3	120.000	Inches	Outside Diameter of the Vessel
5	A4	49.000	Ft	Total Length of the Horizontal Vessel
6	A5	39.000	Ft	Length of the Vessel Shell
7	A6	104.000	Inches	A
8	A7	69.000	Inches	B
9	A8	9.000	Inches	C
10	A9	24.000	Inches	D
11	A10	40.000	Inches	E
12	A11	2.000	ul	No Of Ribs
13	A12	1.000	Inches	G (Base)
14	A13	0.750	Inches	H (Web Flange Ribs)
15	A14	0.500	Inches	K (Wear)
16	A15	60	Inches	a
17	A16	30	Inches	b
18	A17	468	Inches	L
19	A18	60	Inches	H
20	A19	0.30813	Inches	Thickness of the nozzle
21	A20	6.625	Inches	Outside Diameter of the Nozzle
22	A21	1.000	Inches	Interior Projection of the Nozzle
23	A22	3.000	Inches	Exterior Projection of the Nozzle
24	A23	11	Inches	Outside diameter of the flange (O)
25	A24	1	Inches	Thickness of the Flange (C)

Figure 10. Partial list of attributes related to CAD model features.

Table 1. Calculated saddle stresses for verification.

A	104	Inches	Longitudinal bending stress	
B	69	Inches	Stress at saddle (S_1) (psi)	3201.654
C	9	Inches	Stress at mid span (S_1) (psi)	269.846
D	24	Inches	Stress due to internal pressure (psi)	5148.093
E	40	Inches	Sum of tensional stress (psi)	4878.246
No. of ribs	2		Allowable stress value (psi)	17000
G (base)	1	Inches	*Design safe*	
H (web flange ribs)	0.75	Inches	Tangential shear stress	
K (wear)	0.5	Inches	Stress in shell (S_2) (psi)	753.5764
a	60	Inches	Allowable stress value (psi)	16000
b	30	Inches	*Design safe*	
L	204	Inches	Circumferential stress	
H	60	Inches	At horn of saddle (S_4) (psi)	14286.5
P	75.07635	psi	Allowable stress value (psi)	30000
Q	57113.5	lb_f	*Design safe*	
R	60	Inches	Stress at bottom of shell (psi)	2611.41
t	0.4375	Inches	Allowable stress value (psi)	19000
θ	120	Degree	*Design safe*	
S	20,000	psi		
Yield point	38,000	psi		
Joint efficiency factor	0.85	–		

Note: Unit conversion – 1 inch = 0.0254 m; 1 ft = 0.3048 m; 1 psi = 6895 Pa; 1 lb_f = 4.4482 N.

cluster calculations according to the rules corresponding to the related regulation sources and their calculation sections. In such a way, code verification and validation are made easier to be conducted either automatically or manually by the designers.

Figure 8 shows a partial code-checking template in Excel for a pressure vessel design. Figure 9 shows the partial implementation of constraints used for saddle design stress verification.

6.2. *Process model and 3D pressure vessel model integration*

To automatically interface with the CAD models created in the CAD software, a dedicated page of model-related attributes, corresponding to those driving CAD model parameters, is developed as shown in Figure 10. The interface page is constructed according to the parametric modelling requirement of an Autodesk Inventor form so that the integration between Excel and Inventor can be fully supported and parametric modelling is then readily achieved.

Following the above design attributes generated, the 3D parametric CAD models were created to interface with these attributes exactly, and these driving parameters are controlled by Excel spread sheet templates. This implies that any change can be propagated into the 3D mechanical models with minimum efforts via parametric modelling.

As an example to show the design parameters used for pressure vessel design, Table 1 lists those parameters for saddle stress verification following the design code described in Section 2.2. Table 2 shows two sets of parameter values. The first set was used to create the given horizontal vessel while the other was assigned to the CAD model demonstrating parametric

Table 2. Feature-based change management testing parameters and values.

Parameters	Original	Changed
Internal pressure of vessel (bar)	5	3
Height of the vessel from ground level (ft)	10	7
Outside diameter of the vessel shell (inches)	120	96
Distance between horizontal vessel (m)	7.5	7
Net capacity of the vessel (m^3)	100	50
Saddle dimensions		
A (inches)	104	83.5
B (inches)	69	57
C (inches)	9	9
D (inches)	24	18
E (inches)	40	32
No. of ribs	2	1
G (base) (inches)	1	1
H (web flange ribs) (inches)	0.75	0.5
K (wear) (inches)	0.5	0.375
Fire water tank height of each course (m)	2.625	2
Diameter of the tank (m)	8.53	8
Pressure vessel nozzle nominal wall thickness of nozzle (inches)	0.375	0.5
Exterior projection (inches)	3	2
Interior projection (inches)	1	0
Fillet size (inches)	0.5	0.3

Note: Unit conversion – 1 inch = 0.0254 m; 1 ft = 0.3048 m; 1 bar = 10^5 Pa.

and feature-based updating capability. Figure 11(a) and 11(b) shows change effect on the horizontal water tank before and after the change update. For the pressure vessel shown in Figure 11(a), there is only one rib in the middle of the support; also, there is no reinforcement pad shown; but for the pressure vessel shown in Figure 11(b), there are two ribs and also, as per the nozzle reinforcement calculations, the reinforcement pad is updated automatically around the nozzle connection. Therefore, because of the built-in software integration capability, this system design (see Figures 4 and 5) supports any expected change that can be implemented into the 3D mechanical models with minimum effort via parametric modelling. Internal associative relations for each design block, such as pressure vessel design dimensions, are integrated with those implemented constraint formulas of Excel.

So far, analytical calculation was addressed to calculate the design parameters of pressure vessels. Such analytical calculations done were further

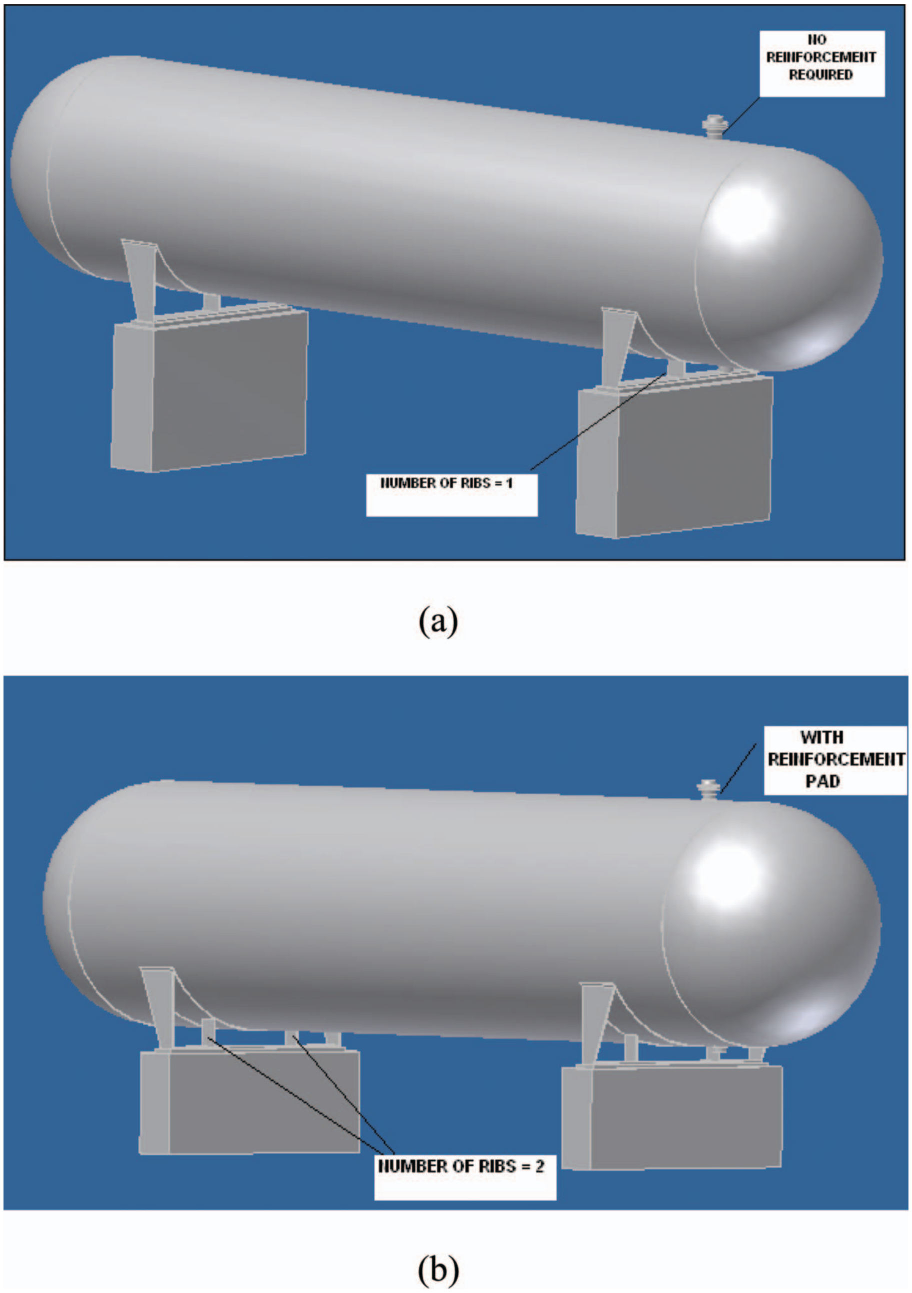


Figure 11. Pressure vessel model using (a) original and (b) new parameter values.

validated with 3D finite element analysis, where the CAE models were created based on the mesh output generated from the aforementioned parametric CAD models. Structural analysis was then carried out. Figure 12 shows the stress analysis results for the diesel fuel storage tank with the consideration of the saddles' effect. A new method to achieve the integration of CAD and CAE using a common data model has been reported recently in another separate contribution (Gujarathi and Ma 2011).

6.3. *Process model and 3D piping model integration*

The piping layout design in the form of 3D wireframe spatial diagram can be automatically generated using APIs or via necessary interactions with the users of

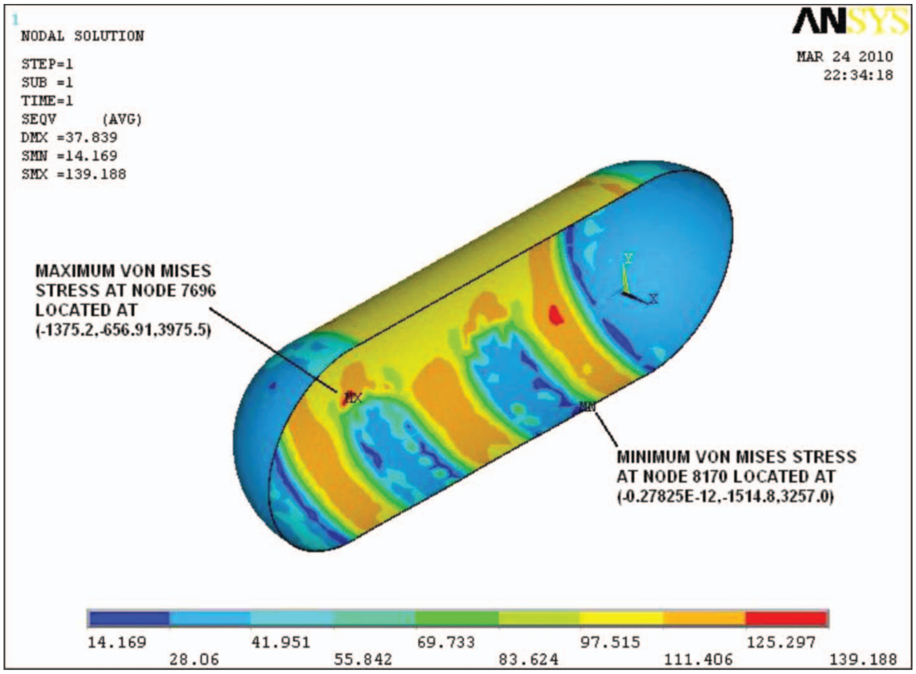


Figure 12. Maximum and minimum Von Mises stress values.

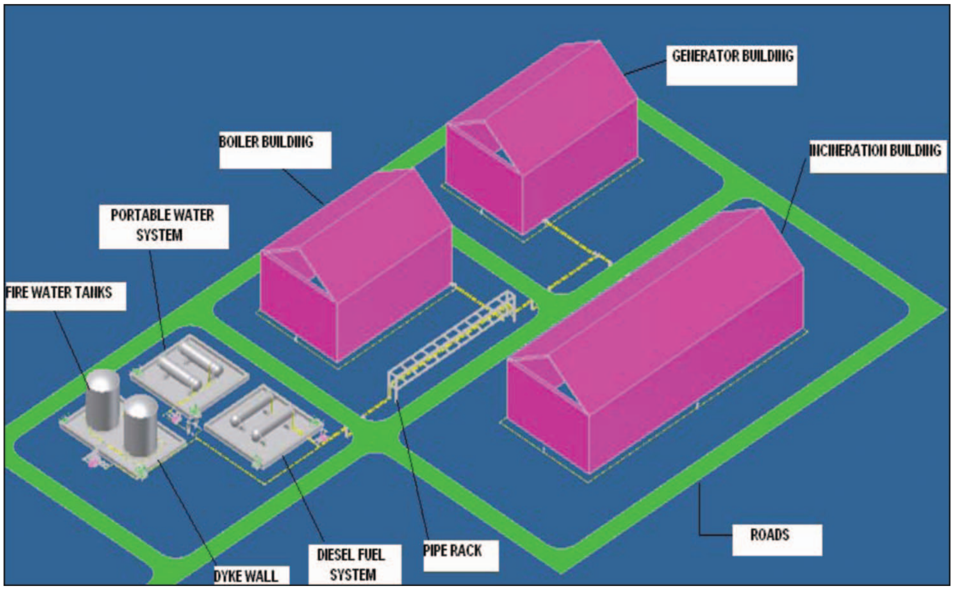


Figure 13. Fully generated conceptual 3D design in the CAD system.

the design tool. A compromise of a semi-automatic approach is more acceptable to companies. In this method, those well-established design patterns are parametrically captured and modelled into templates while certain options of the detail design can be customised by the user by selecting the relevant parameters or logic variables. Hence, this method provides the necessary rigor of design constraints and expected variations. Figure 13 shows a fully generated conceptual design for the system. Figure 14 show the fire water supply system model in more detail.

7. Conclusions

This article reports a new application method of the unified feature, as reviewed by Ma *et al.* (2008), and supports the application of advanced conceptual design features in real industrial engineering, i.e., a process supply system consisting of diesel fuel, portable water and fire water sub-systems. Under the guiding principles of the unified feature, the implementation was carried out in a schematic manner but mainly enabled by parametric modelling between CAD and Excel interactions.

Comparing with the existing practice (Megyesy 2008), the proposed method offers the systematic organisation and evaluation of engineering design intent via advanced feature technology – multiple view representation and association of features at different stages/aspects of design engineering. Furthermore, automated generation and change propagation via programs make the engineering iterations more efficient and consistent. Since the current practice of engineering also involves system modelling and documentation anyway, the effort required by the proposed method is nothing more than a disciplined design coding and documentation effort, so the additional effort involved is not significantly more than the current practice; but the value added by adopting the new method is quite obvious. Therefore, the authors believe that the proposed method has the potential industrial application prospect. However, the authors can foresee the limitations of this approach in the industrial applications: (1) demanding engineers of higher software engineering capability; (2) the industrial design practice has to be well defined in stages, computer model deliverables and clearly specified with a industrial codes or standards; and (3) certain constraint modelling can be too tedious to be completely built into the implementation system.

Although more software coding needs to be done, but due to the resources constraint, only a prototype system has been developed to test the application effectiveness. It has been clear that the unified feature has been useful for the identification and organisation of engineering design patterns in this traditional but highly regulated application domain. More research on the development of a reusable design software toolkit is expected as future work.

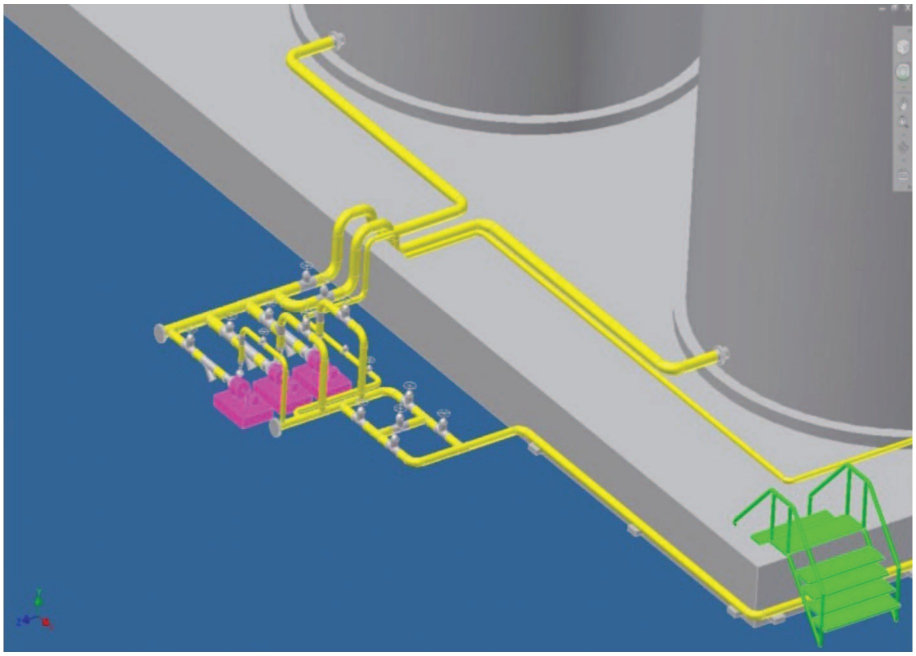


Figure 14. A closer view of the fire water supply sub-system.

Note that professional code regulations have been fully considered by validating the design inputs via a set of built-in code checking templates specially tailored according to design rules. In this case, regulation codes, such as ASME pressure vessel design codes under Section VIII, have been implemented. Such codes can be understood as design constraints and they have to be satisfied for the detailed design parameters to validate the pressure vessel conceptual design features.

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