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Feature-Based Approach for a Process Supply System Design

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***Abstract*—The authors are motivated to investigate an effective method for achieving the knowledge-driven design in order to address the efficiency drawback in common CAD applications. In this paper, a systematic method, to embed in-depth engineering knowledge and to realize smart design changes in an advanced feature-based design, is proposed. To proof the feasibility and the effectiveness of the proposed method, a process fuel and water supply system has been designed comprehensively in the conceptual design stage. The findings of this research work are presented with some critical discussions at the end of this paper. The authors believe that this approach is easy to be implemented and useful to improve the knowledge reusability and engineering design productivity.**

Keywords—computer-aided design; knowledge modeling; unified feature-based design; pressure vessel; parametric modeling

I. INTRODUCTION

Computer-aided design (CAD) tools have been widely used in engineering; but the problem that how effectively the modern CAD tools are used to deal with the challenges of engineering complexity and knowledge embedment has been puzzling many companies. A company's engineering department very often finds that it is repeating some similar design modeling effort and yet the engineering models are not able to be reused. Although there had been temptations for using a previous project design for a new one, but the integrity of engineering model becomes unknown to too tedious to check. Such concerns are particularly strong in the system conceptual design stage. Hence, a systematic feature based method, to embed in-depth engineering knowledge and to realize smart design changes in an advanced feature-based design, is proposed.

To proof the effectiveness of the proposed method, a convincing case study is necessary. Via an in-depth project, a pilot but useful software system has been developed to create an efficient and reusable oil and water supply design so that industrial contractors can enhance their practices by adopting the proposed approach. The reason to study such a system to proof the concept is due to the ever increasing demand for electricity across the globe that has lead to a rapid rise in power plant construction and expansion. The fuel and water system design in power plants is essential in engineering design as it has major technical, operational, and economic impacts. Piping layout and equipment design is constantly changing with the advancement in the design, manufacturing, installation and construction of the plant due to various unseen factors. Hence it becomes important that the design details are updated in a mechanical model according to the changes in process and instrumentation diagrams (PIDs) or the layout design with minimum efforts. This is where advanced feature-based design modeling can play an effective and important role. Although the majority of power plants which are being set up are either based on coal or natural gas technology, a diesel fuel power plant is studied due to its suitable engineering scale and the limitation of the research resources. The authors believe that the proven method can be equally applied to larger scale projects.

This paper highlights the advanced design features that have been identified via a real world research project, illustrates the representation of them in a future feature modeling and development effort, and demonstrates the design feature implementation mechanisms based on parametric modeling. The advantages and drawbacks of this proposed feature-based method is discussed.

II. LITERATURE REVIEW

Traditionally, the feature concept was used for manufacturing. For example, machining features are traditionally defined as volumes of material removed in machining operations [1]. However, since features can represent engineering semantic patterns effectively, hence, there have been many researchers proposing the expansion of the concept and the related modeling schemes such that feature-based knowledge representation and implementation methods can be more coherently and consistently developed. A thorough review related to new feature types and their research state of art has been available in [2]. One attempt was to make various types of features to be more unified under a common scheme such that associative nature of advanced features [3] [4], such as cooling channels in plastic injection mould, can be modeled and supported for productivity enhancement software tools with certain information management automation [5]. Such evolvement of feature definition has made advanced feature application broaden and more convenient.

To design a process supply system with the advanced feature-based approach, there has been some challenges. First of all, the definitions of features in such design projects are non-standard and have never been explicitly identified. For example, the piping layout in a diesel fuel supply sub-system could be similar to the definition of cooling channels in mould design [5]. Such features related to conceptual design are even more difficult because of the

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abstract nature and further detailing in the down-stream [6] [7]. Second, the design cycle involves multiple processes including flow analysis, pressure vessel design and geometry design simulation. Design changes occur repetitively throughout the design cycles. The effective mechanisms to implement, validate and consistently achieve the downstream updates of changes are essential for knowledge driven design approach [2] [8]. Hence, in-depth case studies to identify, verify and prototype advanced features are imperative to beef up the support for the unification and diversification of feature-based knowledge engineering approach.

III. METHODOLOGY

Parametric modeling, as an enabling mechanism for knowledge base engineering modeling, is one of the new and smart modeling techniques being employed in industries. Parametric modeling can be understood as a CAD modeling method which supports expressions in the CAD environment and enables design model dimensions used to be changed by changing the expression values. Parametric modeling is the supporting mechanism for feature-based design (references) approach. Parametric techniques depend 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 modeling application can embed design knowledge into the design models in a generic manner, and significantly increases the productivity of design processes. The main advantage of parametric modeling is that there is no need for the generation of new models based on the changes of input design parameters, which eventually leads to the savings of time, effort and cost. However, without an appropriate design scheme, simply using parametric modeling creates a lot of CAD modeling 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 or no longer familiar to the hidden parameters and their embedded constraints.

In order to make better use of the parametric design mechanism such that, many engineers, who in these days are dependent on CAD tools to deliver their design contents, can easily operate the design steps with their common engineering semantic patterns and their design intent can be fully defined and managed throughout iterative design cycles of revisions, feature technology is required. A feature defines relations between different entities in a semantically explicit and coherent manner. A review on the development of feature technology and the new paradigm of concurrent and collaborative engineering has been available [2]. Via features, design entities are calculated based on complex relationships and mathematical formulas according to typical engineering design patterns. 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 the reported research project, a unified feature concept is applied when initiating the engineering activities.

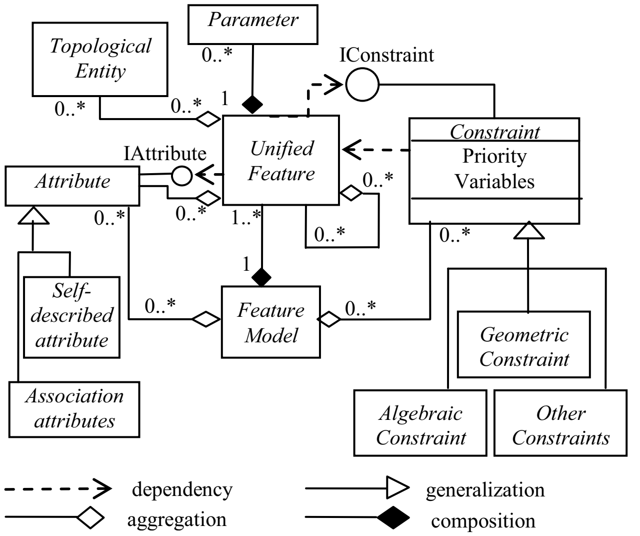


Figure 1. Semantic definition of unified feature in UML format [9].

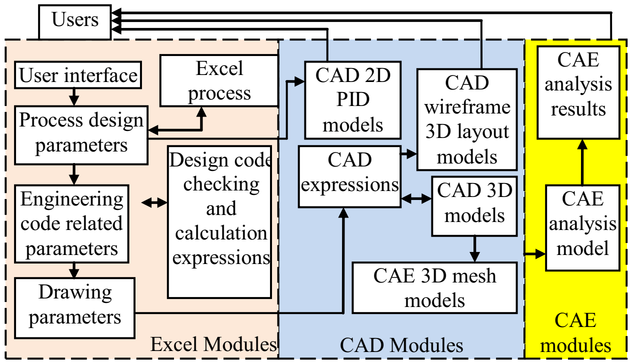


Figure 2. System design for the proposed method.

The definition of a unified feature has been given in [9] and shown in Figure 1. Basically, the design intent can be expressed as a set of common, flexible, and well-defined data structures, i.e. unified features, where the engineering conceptual patterns, e.g. the pipeline layout, a piece of equipment, or a key design code to be checked in the context of a process supply system, are represented generically in a set of geometric or topologic entities, associated driving parameters, constraints, and attributes. Unified features can be used to define the engineering patterns at different semantic detail levels, and a set of lower level unified-features can be used to define a higher level feature. UML (Unified Modeling Language) representation is standardized software modeling design method for illustrating class property data and process definitions and their relations in object-oriented programming methodology [10].

This work is not about the coding aspect to achieve unified feature modeling via software. Rather, it is a verification and application of the proposed concept of unified feature through a real example. The research tries to answer two questions. The first is how unified feature properties can be corresponding to a real application, and the second is if the definition of the unified feature can be generic enough for those similar projects so that the engineering approach with it can serve as an effective engineering information management method.

IV. SYSTEM ARCHITECTURE

From application point of view, the project was also aimed to create an efficient and reusable supply system design models for some common industrial applications, such as a power plant, by developing a feature-based CAD parametric design model. Typically, there are three sub-systems are considered for a power plant supply system, i.e. diesel fuel, portable water, and fire water. Figure 2 shows the system design of the proposed method.

V. ENGINEERING DESIGN PROCESS FLOW

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. Figure 3 shows a partial screen snap of the input page.

	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 3. Partial input page implemented with Excel.

Then, the detailed attributes to generate a 2D a process and instrument diagrams (PID) for each sub-system is then automatically created in a page. Based on his input, the 2D PID diagram is parametrically generated in the CAD system. Figure 4 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 and the piping layout and pressure vessel designs attributes were created semi-automatically via necessary interactions between the user (now, it could be a mechanical designer) and the template pages of the modeling system.

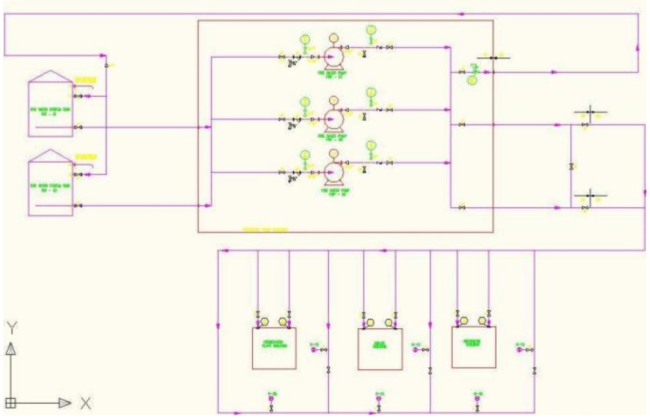


Figure 4. PID diagram for the fire water supply sub-system.

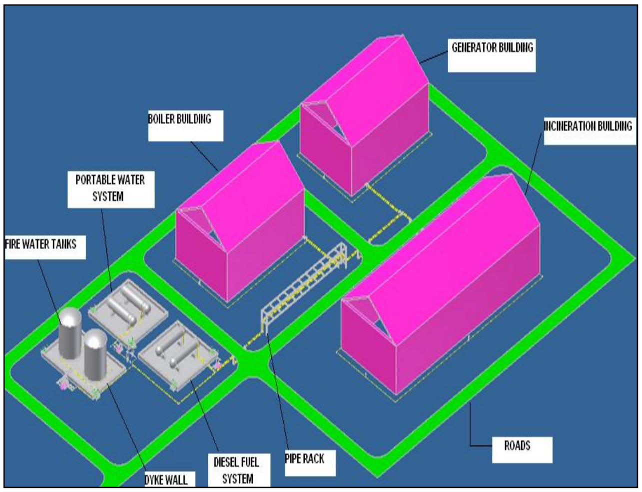


Figure 5. Fully generated conceptual 3D design in the CAD system.

Note that professional code regulations have been fully considered at this stage by validate 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 in order to validate the pressure vessel conceptual design feature. Analytical calculation was implemented in the Excel model.

Following the above design attribute generation step, Autodesk Inventor was used for the development of the 3D models and the driving parameters are controlled by Excel spread sheet templates. Figure 5 shows a fully generated conceptual design for the system. Figure 6 and 7 show the fire water supply system model in more detail. Because of the built-in software integration capability, this system design (see Figure 2) supports that any changes can be implemented into the 3D mechanical models with minimum efforts via parametric modeling. Internal relations for each design block, such a pressure vessel design dimensions, are implemented into related formulas of Excel.

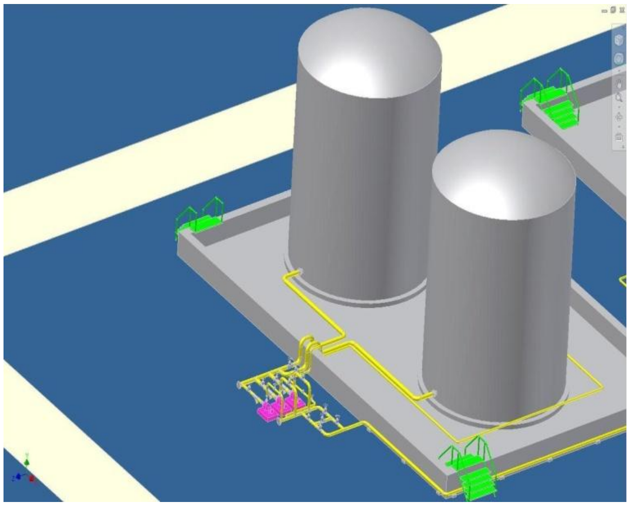


Figure 6. Fire water storage tanks and piping layout.

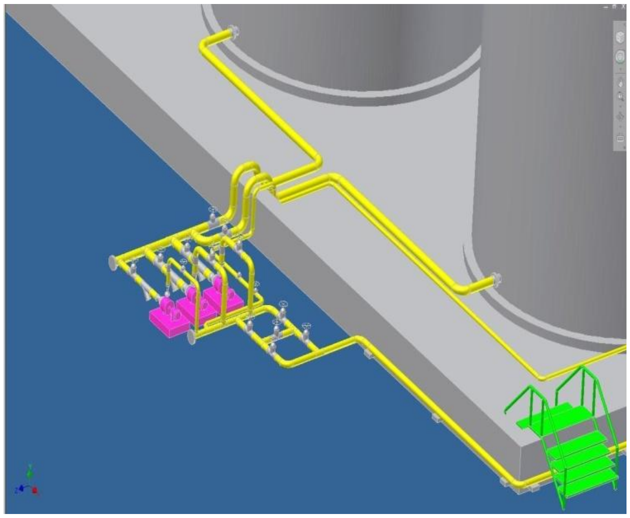


Figure 7. A closer view of the fire water supply sub-system.

Finally, all the analytical calculation done was further validated with 3D finite element models which are created based on the mesh output generated from the aforementioned parametric CAD modeling step and structural analysis was then carried out. Figure 8 shows the stress analysis results for the diesel fuel storage tank with the consideration of the saddles' effect.

VI. CONSTRAINT IMPLEMENTATION

Design codes involved are modeled as a set of constraints. The three sub systems are essential for the operation of a power plant. Other than the diesel fuel sub-system that is obviously necessary to provide constant energy whereas 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 plant building the solid waste and liquid organic wastes are treated. In all the systems, centrifugal pumps are used to maintain the required pressure of systems. In the fire water system jockey pump is also used so that if the pressure drops due to any sort of leakage, or in emergency the pressure will keep on dropping.

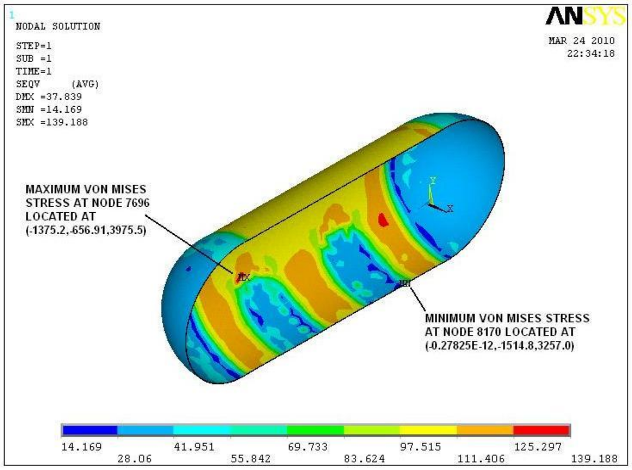


Figure 8. Maximum and minimum Von Mises stress values.

In order to maintain the required discharge pressure the jockey pump will 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 up to the minimum required pressure it is automatically switched off.

The main design codes and standards implemented are:

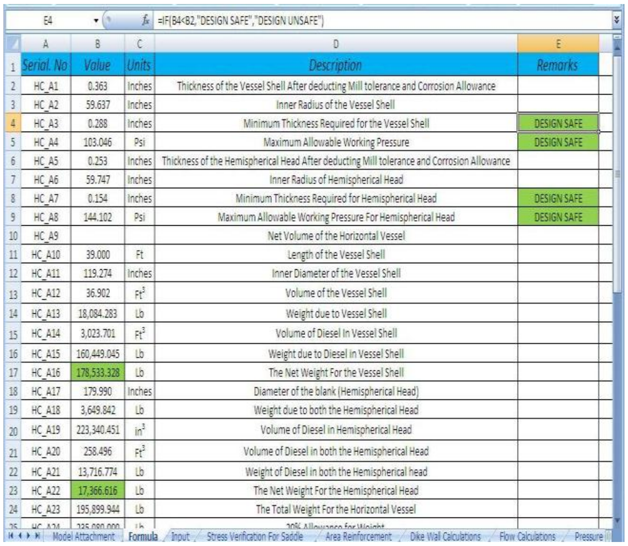
- ASME Section VIII, Division 1 - Boiler & Pressure Vessel Design Code.
- API 650 – Storage Tank Design.
- ASME B 31.1 - Power Piping Code.
- ASME B 16.10 – Face to Face dimensions of Valves.
- ASME B 16.34 – Valves – Flanged, Threaded and Welding End.

- 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.

In the Excel calculation, modular approach is used. For the project, in additional 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 quite convenient to cluster calculations according to the rules corresponding to the relater 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 9 shows a partial code checking template in Excel for the pressure vessel design. Figure 10 shows the partial implementation of constraints used for saddle design stress verification.

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 11. The interface page is constructed according to the parametric modeling requirement of Autodesk Inventor form so that the integration between Excel and Inventor can be fully supported and parametric modeling is then readily achieved.



E4 =IF(B4<B2,"DESIGN SAFE","DESIGN UNSAFE")

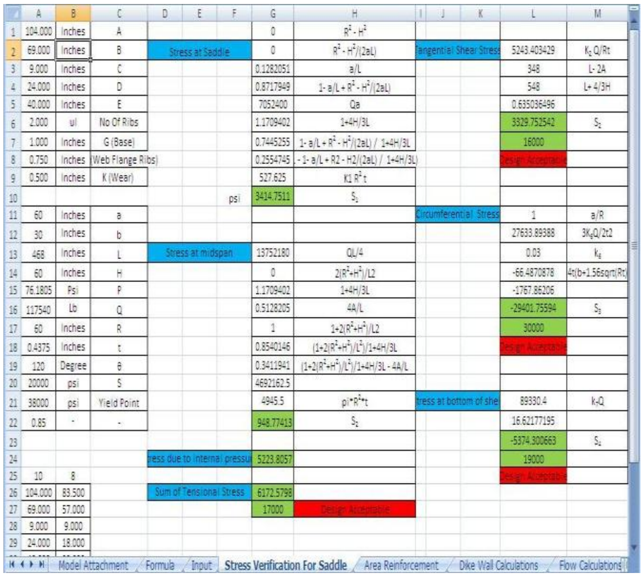
	A	B	C	D	E
1	Serial. No	Value	Units	Description	Remarks
2	HC_A1	0.363	Inches	Thickness of the Vessel Shell After deducting Mill tolerance and Corrosion Allowance	
3	HC_A2	59.637	Inches	Inner Radius of the Vessel Shell	
4	HC_A3	0.288	Inches	Minimum Thickness Required for the Vessel Shell	DESIGN SAFE
5	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	

Figure 9. Constraints implemented for pressure vessel design module.

VII. CHANGE MANAGEMENT

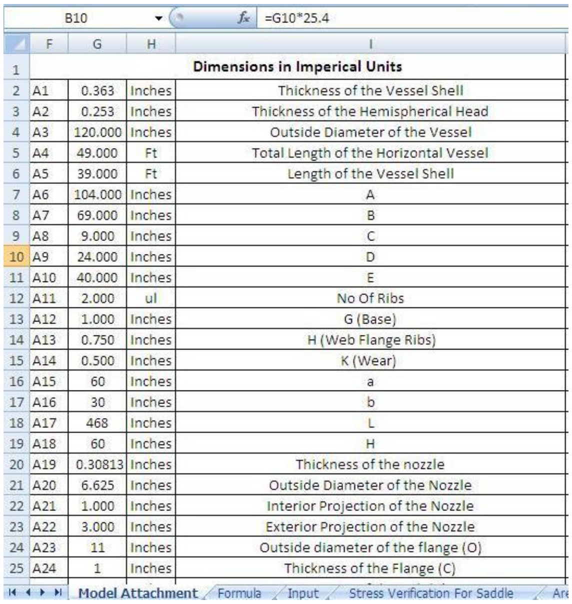
One advantage for feature-based modeling is the parametric change management. Instead of changing individual parameters, a set of them are change at a time. By managing changes in groups, the consistency can be well kept than updating parameters one-by-one because there could be a lot of intermediate updating conflicts arise from the in compatible values of a feature pattern.

Table 1 shows a set of parameters with the current and new values to be assigned. Figures 12(a) and (b) shows change effect on the horizontal water tank before and after the change update. For the pressure vessel shown in Figure 12(a) there is only one rib in the middle of the support and also there is no reinforcement pad shown, but for the pressure vessel shown in Figure 12(b) there are two ribs and also as per the nozzle reinforcement calculations the reinforcement pad is updated automatically around the nozzle connection.



	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)				Design Acceptable	
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	$(1+2(R^2+H^2)/L^2)/1+4H/3L$				Design Acceptable	
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				tress due to internal pressu			5223.8057					19000	
25	10	8										Design Acceptable	
26	104.000	83.500		Sum of Tensional Stress			6172.5798						
27	69.000	57.000					17000	Design Acceptable					
28	9.000	9.000											
29	24.000	18.000											

Figure 10. Constraints implemented for the saddle of a horizontal storage tank.



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 11. Partial list of attributes related to CAD model features.

VIII. CONCLUSIONS

This paper reports a new application case of the unified feature definition [2] and supports the effectiveness of applying 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 unified feature, the implementation was carried out in a schematic manner but mainly enabled by parametric modeling between CAD and Excel interactions. Although the software coding has not been done due to the resources constraint, however, it has been clear that the unified feature definition has been useful for the identification and organization of engineering design patterns in this traditional but well regulated application domain. More research on the development of a reusable design software toolkit is expected as the future work.

ACKNOWLEDGMENTS

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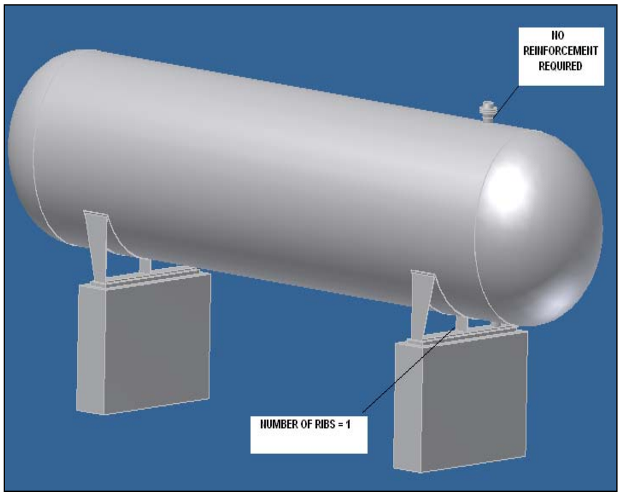
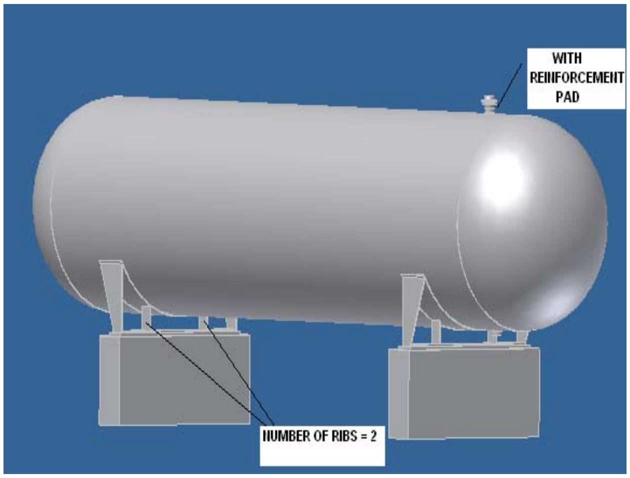
TABLE 1
FEATURE-BASED CHANGE MANAGEMENT TESTING PARAMETERS AND VALUES

Parameter	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 (ul)	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



(a) Pressure Vessel model using original parameter values



(b) Pressure Vessel model using new parameter values

Figure 12. Partial list of attributes related to CAD model features.

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