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Optimal Steel Choice for Reducing the Cost of Spherical Pressure Vessels

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Abstract With the growing demand for strategically storing bulk liquids, the cost of the storage vessels gained excessive importance. This cost has great influence on the overall projects' cost. Hence, reducing the cost of a vessel is of prime importance. In this sense, the choice of steel and relative properties, specifically its allowable stress, used in the construction of a spherical pressure vessels plays an important role in reducing the price of the vessel. Moreover the Man-hours required to construct the vessel, especially the one related to the linear meters of weld, affects also the overall cost. In this paper, parametric studies with respect to the steel's allowable stress and linear meters of weld are performed. Different shell diameters are taken into consideration and the analysis is performed according to ASME VIII – Division 2_Standards and the "technical calculation and estimator's man-hour manual".

Keywords plate thickness, Man-hour rate, steel, linear meters of weld

1. Introduction

The demand for storing bulk liquids has extensively increased in the past decades. This is due to different reasons ranging from the exploration of new oil and gas fields going through strategic storage and not ending at fighting the scarcity of water. Therefore, various economic and political activities demand the storage of different types of liquids starting from water, to oil and gas, to edible oils. Each of these aforementioned liquids demands a different type of storage tank, like concrete tanks for water, cylindrical steel tanks for oil derivatives, spherical or bullet shaped pressure vessels for gas, stainless steel for edible oils, etc. Hence, the storage tanks are a major component in any storage project/facility and their cost has the highest effect on the overall project's cost. In this sense, reducing the price of storage tanks is of prime importance.

In our previous work [1], we focused on the cost optimization of cylindrical steel storage tanks where the effect of the allowable stresses for the design and hydrostatic test conditions was performed. In addition, the effect of Manpower was studied. The thickness of steel plates and the number of storage steel tanks needed for storing a specific volume was the main issue in [2]. Wankhede *et al.* [3] focused on the cost optimization of concrete water storage tanks mainly focusing on the impact of wall thickness, the depth of the floor slab and beam on the cost. Optimal size of steel storage tanks is also an important research topic [4, 5] along with spherical storage tanks [6, 7]. Various researchers also study the optimization of labor hours in constructing steel structures [8, 9].

In this paper, the effect of the steel's choice on the cost of a spherical tank is the addressed issue. Moreover, since the thickness of a spherical pressure vessel is inversely proportional to the steel's allowable stress, five different ascending values of the latter are considered. However, increasing the allowable stress would increase the steel's price but would also decrease the Man-hours (Mhr) required for welding since the thickness will be reduced. Hence, the total Man-hours required for welding the different components of the sphere's shell is also studied. Furthermore, it is commonly known that the steel's price is quasi-independent of the work place which is not case of the Man-hour rate. For this purpose, three different on-ground cases, each representing a different labor rate, are taken into account. It is also worth mentioning that two different sphere diameters are considered. After this introduction, the second section deals with the effect of the allowable stress on the thickness and thus on the total steel's price. The effects of the Linear Meters of Weld (LMW) and the Mhr rate on the cost are studied in section 3 where also on-ground cases are considered. Finally, conclusions of this study are drawn in the fourth section.

2. Effect of allowable stress

Contrary to cylindrical steel storage tanks where the thickness of steel plates depends of the above remaining height [1], the plates' thickness of spherical tanks is more or less uniform (neglecting the minor effect of hydrostatic pressure). This latter is given by [10]:

$$Th = \frac{D}{2}\left(\exp\left(\frac{0.5P}{S\times E}\right) - 1\right) \quad (1)$$

Where D is the sphere's diameter (in mm), P is the radial pressure fixed to 1.7 MPa in this work, E is the joint efficiency taken to be 1 and S is the steel's allowable stress. Furthermore, the mass of the spherical vessel can be written as:

$$M = \pi \,.\, D^2 .\, Th \,.\, \rho_{\text{steel}} \quad (2)$$

where, D is in meters and $\rho_{\text{steel}} = 7.85\ g/cm^3$. Equation (2) gives the mass in Kg which is then divided by 1000 to get it in Ton.

As stated in the introduction, a parametric study is performed. In this study two diameters are chosen (15m – 19.3m) along with five different steel allowable stresses. Table 1 shows the chosen types of steel with their respective price per ton (in usd). Surely the prices depend on the availability, market rates and shipping but these parameters are going to be neglected in this study since their effect is not important as the price itself.

Table 1: Allowable stresses and notation of steel

Allowable stress	Notation in remainder parts of paper	Price per ton (usd)
115.14	*S1*	650.00
126.17	*S2*	675.00
160.65	*S3*	815.00
172.37	*S4*	875.00
184.09	*S5*	950.00

As it can be seen in eq. (1), the allowable stress is inversely proportional to the plates thickness hence to the vessel's mass. In this sense, ascending the allowable stress would reduce the mass of the spherical vessel. Table 2 illustrates the effects of *S* on the thickness, mass and total steel price for the two different diameters. To note that the thickness is rounded up to the nearest unit.

Table 2: Effects of allowable stress on the thickness, mass and total price of steel

D (mm)	*S* (MPa)	*Th* (mm)	*M* (Ton)	Total steel Price (usd)
15000	115.14	56	310.74	201978.18
	126.17	51	282.99	191019.20
	160.65	40	221.95	180892.54
	172.37	38	210.86	**184499.30**
	184.09	35	194.21	**184499.30**
19300	115.14	72	661.41	429913.43
	126.17	66	606.29	409244.52
	160.65	52	477.68	394087.31
	172.37	48	440.94	**385819.75**
	184.09	45	413.38	392709.39

It can be shown, from table 2, that *S5* gives the smallest mass, which is logical, but that *S4* gives the lowest price in both cases. Also it can be seen that *S3* induces a total price less than that of *S5*. Nevertheless, a smaller plate thickness would lead to less Man-hours required for welding [11]. Hence, pursuing the effect of the thickness (thus the effect of allowable stress) on the needed Man-hours for welding is of prime importance.

3. Effect of the LMW

In [11], the rate of manual welding is given in Mhr/m for different plate thicknesses. On one hand, no direct relation is given between these two but on the other hand different rates are given for thicknesses varying discontinuously between 14 and 40 mm. Moreover, these rates vary according to the welded parts and to the direction of welding (vertical or horizontal) (see figure 1).

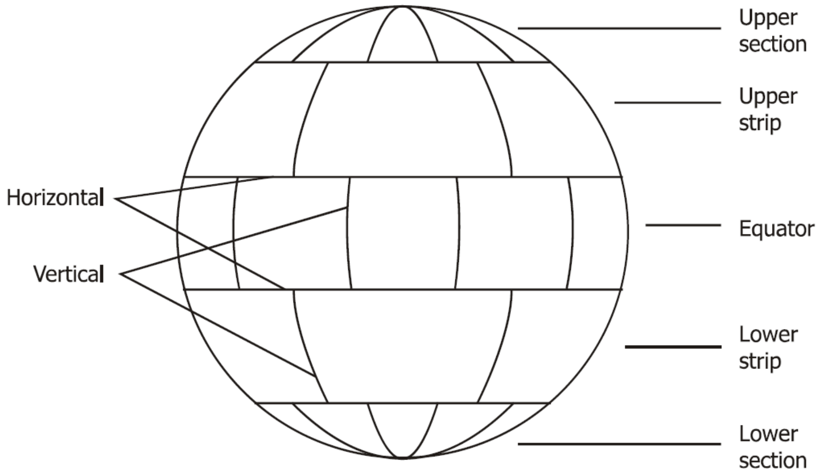

Figure 1: Different sections of a spherical vessel [11]

Looking back at table 2, it can be seen that most thicknesses are greater than 40 and so the rates for the values need to be extrapolated. Figure 2 plots the rate (in Mhr/m) against the thickness (in mm) for manual welding of vertical joints of the upper strip [11].

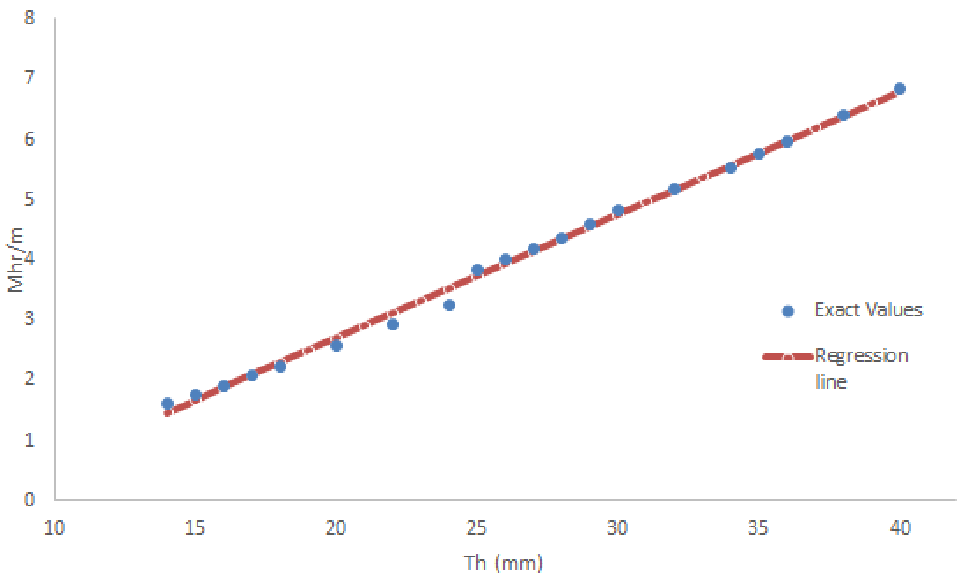

Figure 2: Scatter plot of values in [11] along with the regression line

The linear relation between the rate and the thickness is obvious and therefore, the linear least squares method [12] is used to extrapolate (or interpolate) the rate values that are not present in [11]. This method gives a regression line passing through the mean point and having the smallest y-distance with the given points. As seen in figure 2, the line represents a good approximation to the exact values and hence the linear least squares method can be used to find the Mhr rates of inexistent values in the tables of [11].

3.1. Case of the 19.3m-diameter

Figure 3 shows the design of the 19.3m spherical tank.

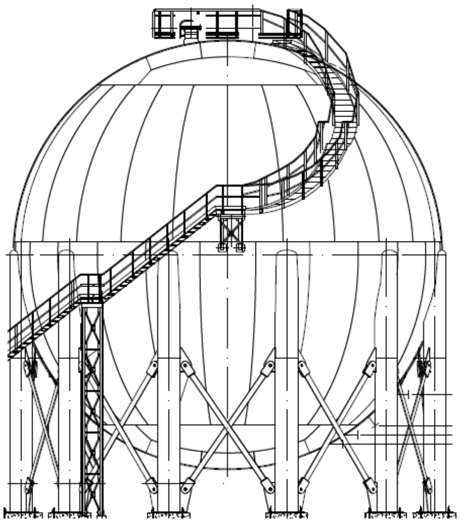

Figure 3: A 19.3m-diameter spherical pressure vessel

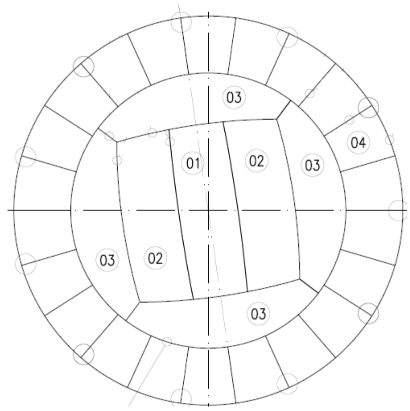

Figure 4: A top view of the lower and upper sections

It can be seen that this tank is composed of a lower and an upper section along with an upper and a lower strip without an equator section. The lower and upper sections were designed by the same manner. Figure 4 shows a top view of the design of these sections.

Furthermore, figure 5 shows the sketches of plates number 1, 2 and 3 that constitute the lower and upper sections. Also, the lengths of their sides are illustrated in this figure.

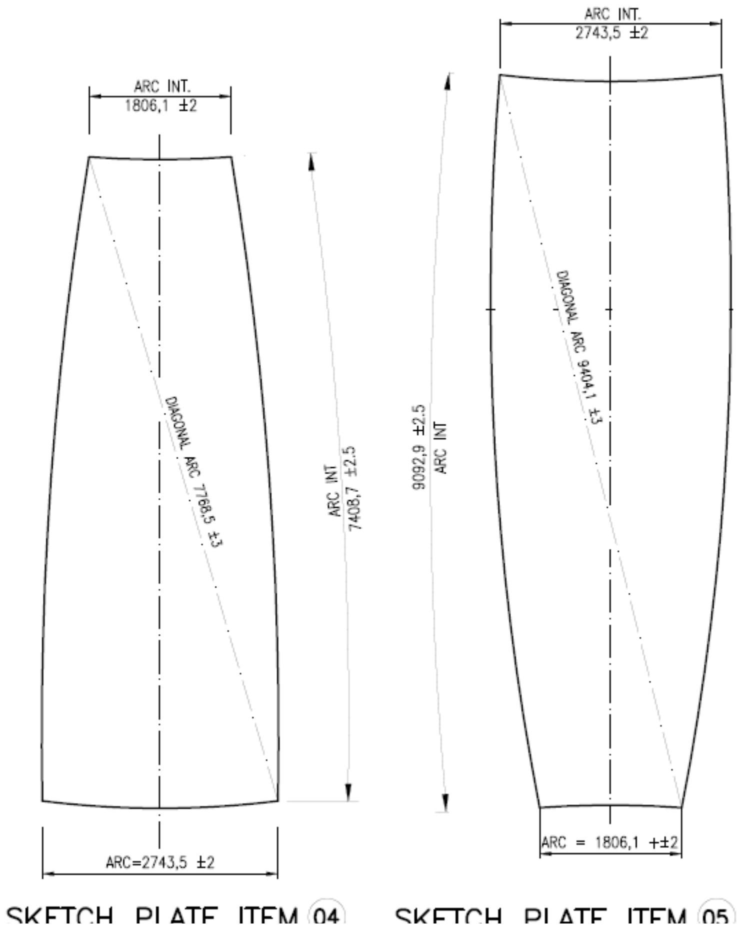

Figure 5: Sketches of plates number 1, 2 and 3 constituting the upper and lower sections

Moreover, sketches of plates number 4 and 5 that form the upper and lower strips respectively are shown in figure 6 along with the lengths of their sides.

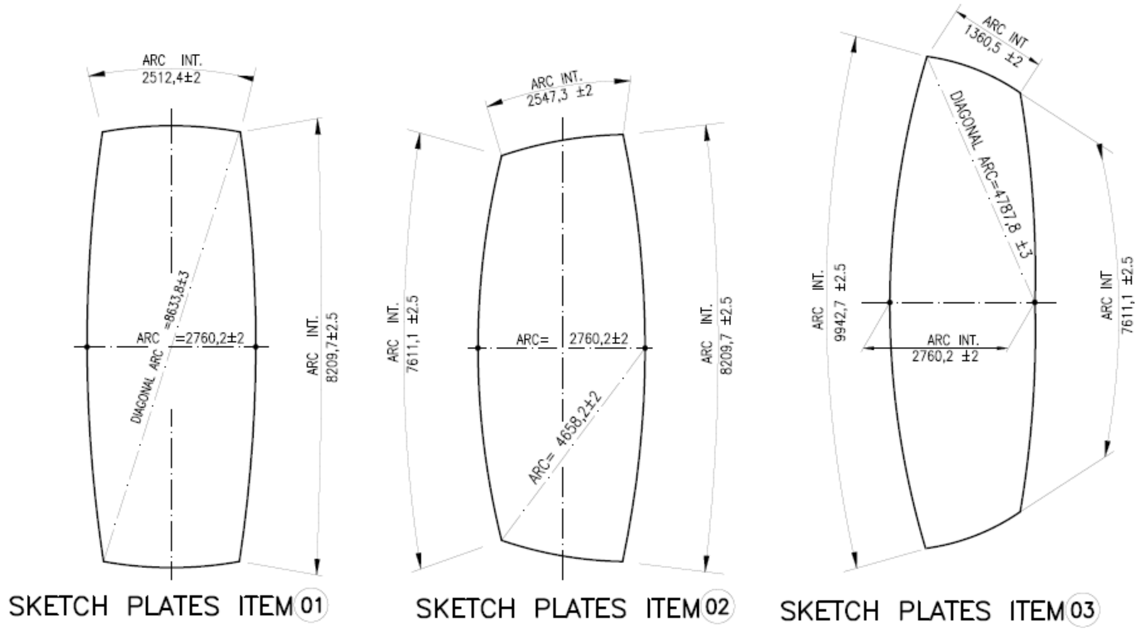

Figure 6: Sketches of plates number 4 and 5 constituting the upper and lower strips

Afterwards, the length of the joints used in welding is found for each plate. According to their position on the vessel, this length is either halved (since welding two adjacent plates require only one side) or kept or not taken into consideration (when considered in other plates). Finally, the result is multiplied by their respective quantities to get the LMW of each plate. Table 3 details these results.

Table 3: The LMW needed for each section of the 19.3m-diameter sphere

		D = 19.3 m			
Item	**Use in welding**	**Perimeter (mm)**	**Joint length (mm)**	**Quantity**	**LMW (m)**
1	Upper and Lower section	21450	21450	2	21.45
2	Upper and Lower section	20921	20921	4	41.842
3	Upper and Lower section	20282	10337	8	41.348
	Vertical Upper strip		7410		81.51
4	Upper strip with upper section	19373	1808	22	39.776
	Upper strip with lower strip		2745		60.39
	Vertical Lower strip		9095		200.09
5	Lower strip with lower section	22743	1808	22	39.776
	Lower strip with upper strip		2745		0

Moreover, for each thickness found in table 2 and for each section and direction of welding, the rate of welding in Mhr is found by interpolating (or extrapolating) from the values of [11] using the least squares method as explained at the beginning of section 3. Table 4 details these values for the 19.3m spherical vessel.

Table 4: The rates for each section and each thickness of the 19.3m sphere

		D=19.3m			
***Th* (mm)**	**Use in welding**	**LMW (m)**	**Rate (Mhr/m)**	**Rate of Section (Mhr)**	**Rate of sphere (Mhr)**
	Upper and Lower section	21.45	8.45	181.32	
	Upper and Lower section	41.84	8.45	353.70	
	Upper and Lower section	41.35	8.45	349.53	
	Vertical Upper strip	81.51	13.38	1090.95	
72	Upper strip with upper section	39.78	19.76	785.83	7431.21
	Upper strip with lower strip	60.39	19.98	1206.39	
	Vertical Lower strip	200.09	14.06	2814.13	

	Lower strip with lower section	39.78	16.33	649.36	
	Lower strip with upper strip	0.00	0.00	0.00	
	Upper and Lower section	21.45	7.72	165.69	
	Upper and Lower section	41.84	7.72	323.20	
	Upper and Lower section	41.35	7.72	319.38	
	Vertical Upper strip	81.51	12.15	990.49	
66	Upper strip with upper section	39.78	17.94	713.49	6751.71
	Upper strip with lower strip	60.39	18.13	1094.83	
	Vertical Lower strip	200.09	12.77	2555.05	
	Lower strip with lower section	39.78	14.82	589.58	
	Lower strip with upper strip	0.00	0.00	0.00	
	Upper and Lower section	21.45	6.02	129.20	
	Upper and Lower section	41.84	6.02	252.03	
	Upper and Lower section	41.35	6.02	249.05	
	Vertical Upper strip	81.51	9.28	756.10	
52	Upper strip with upper section	39.78	13.69	544.70	5166.22
	Upper strip with lower strip	60.39	13.82	834.51	
	Vertical Lower strip	200.09	9.75	1950.54	
	Lower strip with lower section	39.78	11.32	450.09	
	Lower strip with upper strip	0.00	0.00	0.00	
	Upper and Lower section	21.45	5.54	118.78	
	Upper and Lower section	41.84	5.54	231.69	
	Upper and Lower section	41.35	5.54	228.96	
	Vertical Upper strip	81.51	8.45	689.13	
48	Upper strip with upper section	39.78	12.48	496.48	4713.22
	Upper strip with lower strip	60.39	12.59	760.13	
	Vertical Lower strip	200.09	8.89	1777.82	
	Lower strip with lower section	39.78	10.31	410.23	
	Lower strip with upper strip	0.00	0.00	0.00	
	Upper and Lower section	21.45	5.17	110.96	
	Upper and Lower section	41.84	5.17	216.44	
	Upper and Lower section	41.35	5.17	213.88	
	Vertical Upper strip	81.51	7.84	638.91	
45	Upper strip with upper section	39.78	11.57	460.31	4373.47
	Upper strip with lower	60.39	11.66	704.35	

strip			
Vertical Lower strip	200.09	8.24	1648.28
Lower strip with lower section	39.78	9.56	380.34
Lower strip with upper strip	0.00	0.00	0.00

It can be seen that the total rate of welding (in Mhr) is proportional to the thickness of the plates. But recall that the smallest thickness corresponded to the most expensive steel. Will the difference in Mhr compensate for the price of steel?

3.2. Case of the 15m-diameter

A 15m-diameter sphere, can be constructed by an upper section and a lower section along with an equator section. The number of needed plates for each section and the corresponding joints and LMW are summarized in table 5.

Table 5: The LMW needed for each section of the 15m-diameter sphere

		D = 15 m		
Item	**Use in welding**	**Joint length (mm)**	**Quantity**	**LMW (m)**
1	Lower and Upper Section	16400	2	32.8
2	Lower and Upper Section	15700	4	62.8
3	Lower and Upper Section	4400	4	17.6
	Lower Section to Equator Horizontal	37700	1	37.7
4	Vertical equator	9650	16	154.4
	Equator to Upper Section Horizontal	37700	1	37.7

Furthermore, for each thickness found in table 2 and for each section and direction of welding, the rate of welding in Mhr is found by interpolating (or extrapolating) from the values of [11] using the least squares method. Table 6 details these values for the 15m spherical vessel.

Table 6: The rates for each section and each thickness of the 15m sphere

		D = 15 m			
***Th* (mm)**	**Use in welding**	**LMW (m)**	**Rate (Mhr/m)**	**Rate of Section (Mhr)**	**Rate of sphere (Mhr)**
	Lower and Upper Section	32.8	6.51	213.51	
	Lower and Upper Section	62.8	6.51	408.78	
56	Lower and Upper Section	17.60	6.51	114.56	3495.03
	Lower Section to Equator Horizontal	37.7	12.32	464.37	
	Vertical equator	154.4	11.22	1731.82	
	Equator to Upper Section Horizontal	37.70	14.9067	561.98	
	Lower and Upper Section	32.8	5.90	193.58	
	Lower and Upper Section	62.8	5.90	370.63	
51	Lower and Upper Section	17.60	5.90	103.87	3145.79
	Lower Section to Equator Horizontal	37.7	11.07	417.15	
	Vertical equator	154.4	10.08	1555.71	
	Equator to Upper Section Horizontal	37.70	13.3912	504.85	
	Lower and Upper Section	32.8	4.57	149.74	
	Lower and Upper Section	62.8	4.57	286.70	

40	Lower and Upper Section	17.60	4.57	80.35	2377.46
	Lower Section to Equator				
	Horizontal	37.7	8.31	313.27	
	Vertical equator	154.4	7.57	1168.25	
	Equator to Upper Section				
	Horizontal	37.70	10.0571	379.15	
	Lower and Upper Section	32.8	4.32	141.77	
	Lower and Upper Section	62.8	4.32	271.44	
38	Lower and Upper Section	17.60	4.32	76.07	2237.77
	Lower Section to Equator				
	Horizontal	37.7	7.81	294.38	
	Vertical equator	154.4	7.11	1097.80	
	Equator to Upper Section				
	Horizontal	37.70	9.4509	356.30	
	Lower and Upper Section	32.8	5.16	169.25	
	Lower and Upper Section	62.8	5.16	324.05	
35	Lower and Upper Section	17.60	5.16	90.82	2164.31
	Lower Section to Equator				
	Horizontal	37.7	7.06	266.05	
	Vertical equator	154.4	6.43	992.13	
	Equator to Upper Section				
	Horizontal	37.70	8.5416	322.01832	

It can be seen, from tables 4 and 6 that the total Mhr rate of the sphere is proportional to the thickness of its plates which is logical. This means that the most expensive steel (*S5*) leading to the thinnest plates also gives the least Man-hours required. Surely, the rate depends on the location of construction, hence three on-ground cases are considered.

4. On-ground cases and results

As stated above, three on-ground cases are taken into consideration. These locations, which are Sudan, Jordan and Cyprus, represent low, middle and high income rates respectively. In Sudan, the hourly rate of are welder is considered to be around 5.4 usd, whereas in Jordan it is taken about 11.65 usd and 14.78 usd in Cyprus. These hourly welding rates yield the final results illustrated in tables 7 and 8 for the 19.3m and 15m spheres respectively.

Table 7: The total cost of the steel + welding cost of a 19.3m sphere for all five types of steel in the three on-ground cases.

		D = 19.3 m		
Cost of a Mhr (usd)	**Th (mm)**	**Total Man-hours Required**	**Total welding cost (usd)**	**Steel + Welding cost (usd)**
	72	7431.21	40128.52	470041.96
Sudan	66	6751.71	36459.24	445703.76
5.4	52	5166.22	27897.59	421984.90
	48	4713.22	25451.40	**411271.15**
	45	4373.47	23616.76	416326.14
	72	7431.21	86573.57	516487.01
Jordan	66	6751.71	78657.44	487901.96
11.65	52	5166.22	60186.46	454273.77
	48	4713.22	54909.04	**440728.78**
	45	4373.47	50950.97	443660.36

	72	7431.21	109833.25	539746.69
Cyprus	66	6751.71	99790.29	509034.81
14.78	52	5166.22	76356.73	470444.04
	48	4713.22	69661.42	**455481.17**
	45	4373.47	64639.94	457349.33

Table 8: The total cost of the steel + welding cost of a 15m sphere for all five types of steel in the three on-ground cases.

D = 15 m				
Cost of a Mhr (usd)	**Th (mm)**	**Total Man-hours Required**	**Total welding cost (usd)**	**Steel + Welding cost (usd)**
	56	3495.03	18873.15	220851.33
Sudan	51	3145.79	16987.26	208006.46
5.4	40	2377.46	12838.30	**193730.84**
	38	2237.77	12083.95	196583.24
	35	2164.31	11687.29	196186.59
	56	3495.03	40717.08	242695.25
Jordan	51	3145.79	36648.44	227667.64
11.65	40	2377.46	27697.45	**208589.99**
	38	2237.77	26070.00	210569.29
	35	2164.31	25214.25	209713.55
	56	3495.03	51656.51	201978.18
Cyprus	51	3145.79	46494.76	191019.20
14.78	40	2377.46	35138.91	**180892.54**
	38	2237.77	33074.21	188872.77
	35	2164.31	31988.55	184499.30

It can be concluded that, for the 19.3m spherical vessel, even after adding the welding cost, *S4*is the most cost effective choice of steel in all three cases. Nevertheless, it can be noticed that, in all three cases, using *S5* became less expensive than using *S3* and that difference between using *S4* and *S5* is not great. Hence, in the case of a 19.3m tank, representing large vessels, using *S4* or *S5* is recommended depending on the market prices and their availability.

As for the 15m-diameter spherical tank, it can be seen that using the *S3* type of steel leads to the cheapest overall cost in the three on-ground cases. Also, it is noticed that in Sudan and Jordan the difference between *S4* and *S5* is very small. Nevertheless, according to the requirements for Post Weld Heat Treatment (PWHT) of pressure parts in [10], and considering the material being studied, PWHT will be mandatory for the spheres that have plates thickness over 38mm. This is the case of all 5 types of steel for the 19.3m spheres and for *S1, S2,* and *S3* for the 15m spheres. Accordingly, table 9 gives the estimated costs for performing this activity onthe15m-diamtere tank.

Table 9: Estimated cost of the PWHT for the 15m-diameter sphere

Surface Area (m^2)		706.50
Insulation Installation (Mhr/m^2)	0.94 [11]	664.11
Insulation Removal (Mhr/m^2)	0.94/3	221.37
Insulation Price Rate (Mhr/m^2)	10.00	7065.00
	Sudan 5.4	4781.59
Mhr Rate (usd)	Jordan 11.65	10315.84
	Cyprus 14.78	13087.39
Equipment Rental for 6 Days (usd)		17500.00
LPG Gas for Burners (usd)		3500.00
	Sudan	32846.59
Total Estimate Cost of PWHT (usd)	Jordan	38380.84
	Cyprus	41152.39

The above consideration is a vital element in determining the selection of material as it has a significant time and cost impact. And since in the 15m case, using *S3*will require performing PWHT and using *S4* or *S5* does not require this type of operation (since the thickness of the plates are less or equal to 38mm) then adding its cost to the steel and welding costs makes the choice of *S3*much more expensive than *S4* and *S5*. Therefore, *S4* and *S5* are also the recommended steel choices when constructing medium-sized spherical vessels also.

Moreover, this study is performed for only one tank which is rarely the case in a construction site. Hence, when the cost reduction is multiplied by the effective number on constructed tanks, it would imply major cost optimization.

5. Conclusion

This paper dealt with the effect of the allowable stress and the LMW on the overall cost of spherical pressure vessels. A medium and a large sized vessels were considered along with five different types of steel denoted from *S1* to *S5* in an ascending order of stress and price. Regarding the steel cost, *S4*and *S5* yielded the less expensive cost in the medium-sized case and *S4* was the least expensive is the large-sized case. Looking at the LWM, surely *S5* had the smallest number of Man-hours needed to weld the plates since it gives the smallest thickness.

Furthermore, three on-ground cases representing low, middle and high income rates were considered. For the 19.3m vessel, the lesser cost of welding of *S5* did not compensate for its difference with the steel cost of *S4* which remained the most cost effective choice of steel but with a small difference with *S5*. As for the 15m sphere, *S3* yielded the smallest "steel + welding" price in all three cases but since the thickness of its plates exceed 38mm (which is not the case for *S4* and *S5*), PWHT is needed. This type of treatment costs much more than the difference between *S3* and *S4* or *S5*which means that *S4* and *S5* remain the recommended choices for medium sized spherical vessels.

References

[1]. Hitti, K., Feghali, S., & Tahhan, A. (2017). Cost reduction of cylindrical steel oil storage tanks. *The International Journal of Engineering and Science*, 6(12):18-24.

[2]. Roncetti, L. (2011). Structural and economical optimization of welded steel storage tanks. *21st Brazilian Congress of Mechanical Engineering, Natal, RN, Brazil*.

[3]. Wankhede, S., Salunke, P. J., & Gore, N. G. (2015). Cost Optimization of Elevated Circular Water Storage Tank. *The International Journal of Engineering and Science*, 4(4):28-31.

[4]. Abdi, B., Mozafari, H., Ayob, A., & Kohandel, R. (2012). Optimum Size of a Ground-based Cylindrical Liquid Storage Tank under Stability and Strength Constraints using Imperialist Competitive Algorithm. *Applied Mechanics and Materials*, 110-116:3415-3421.

[5]. Shi, G. (2012). Cost Optimal Selection of Storage Tanks in LPG Vaporization Station. *Natural Resources*, 3:164-169.

[6]. Arabzadeh, V., Niaki, S.T.A., & Arabzadeh, V. (2017). Construction cost estimation of spherical storage tanks: artificial neural networks and hybrid regression—GA algorithms. *Journal of Industrial Engineering International*: 1-10.

[7]. Cheng, B., Huang, J.X., & Shan, Y. (2015). The Economic Design and Analysis for Mixed Model Spherical Tank Shell Angle Partition. *Procedia Engineering*, 130:41-47.

[8]. Sarma, K. C., & Adeli, H. (2000). Cost optimization of steel structures. *Engineering optimization*, 32(6):777-802.

[9]. Klanšek, U., & Kravanja, S. (2006). Cost estimation, optimization and competitiveness of different composite floor systems—Part 1: Self-manufacturing cost estimation of composite and steel structures. *Journal of Constructional Steel Research*, 62(5):434-448.

[10]. ASME. (2007). *ASME Boiler and Pressure Vessel Code, Section VIII, Division 2.*New York.

[11]. Bulic, M. (2003). *Technical calculation and estimator's man-hour manual*, Zagreb.

[12]. Hornbeck, R. W. (1975). *Numerical Methods*. Quantum Publishers Inc., New York