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Technical-Economic Analysis of Industrial Buildings Using Non-Linear Lagrange Interpolation

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Abstract

Due to the notable increase of industrial buildings in Ecuador, it is necessary to carry out a technical-economic analysis to know the impact of the cost of materials on these structures. To do this, a sample of 40 buildings was prepared, establishing the relationship between clear span (L), frame height (H) and distance between frames (B), in order to determine a metric. For this study, the weight of the structure was established in kg/m². A mathematical model was applied using the results (Lagrange interpolation), a polynomial was obtained that describes the model of each group of buildings and its graphic representation, thus determining an approximation of the weight of the structures. The metrics that were found have a direct impact on the cost of the materials of the structures, these were obtained by multiplying them by the cost of the kg of steel. A verification was carried out with a sample of 6 buildings, in which we found the weight using the load and resistance factor design and later with a polynomial; obtaining an error: for buildings modulated at 5 m a mean of 0.03 % with a deviation of 0.03 and for buildings modulated at 6 m, a mean of 0.07 % with a deviation of 0.03. Keywords: 1.25Cr0.5Mo steel; posweld heat treatment; creep resistance.

Keywords: abacus; interpolation; Lagrange; industrial buildings; weights.

Análisis Técnico-Económico de Naves Industriales Mediante Interpolación No Lineal de Lagrange

Resumen

Debido al notable incremento de construcciones de naves industriales en Ecuador, es necesario realizar un análisis técnico-económico para conocer la incidencia del costo de materiales sobre ellas. Para ello, se elaboró una muestra de 40 naves, fijando relación entre luz libre (L), altura del pórtico (H) y distancia entre pórticos (B), con el propósito de determinar una métrica. Para este estudio se estableció el peso de la estructura en kg/m². Con los resultados se aplicó un modelo matemático (interpolación de Lagrange), se obtuvo un polinomio que describe el modelo de cada grupo de naves y su representación gráfica, por consiguiente, se determinó una aproximación del peso de estructuras. Las métricas que se hallaron tienen una repercusión directa en el costo de los materiales de las estructuras, estas se obtuvieron al multiplicarlas por el costo del kg de acero. Se realizó una comprobación con una muestra de 6 naves, en las se halló el peso utilizando el diseño por factores de carga y resistencia y luego con el polinomio; obteniéndose un error: para naves moduladas a 5 m una media de 0,03 % con una desviación de 0,03 y para naves moduladas a 6 m, una media de 0,07 % con una desviación de 0,03.

Palabras clave: ábacos; interpolación; Lagrange; naves industriales; pesos.

Introduction

Industrial buildings are those that allow not only the storage of supplies, but are also used as production centers, car washes, offices, shopping centers, industries, etc. (Hernández, 2015), which enable the satisfaction of humans in various spheres of society. An industrial building is a unit for industrial use that houses the production and/or storage of industrial goods, together with the workers, the machines that generate them, the internal transportation, the exit and entry of goods, among others (Arnal *et al.*, 2014).

The design of industrial buildings in Ecuador is based on the Ecuadorian Construction Standard (NEC, 2014), which is based on regulations such as: ASCE (2017), AISC (2016) and AISI (2016), which are dedicated to studying the characteristics and forms of behavior of steel and the development of standards for the structural calculation that governs steel design, thus developing the limit state method and the load and resistance factor design (LRFD) (NEC, 2014; AISC, 2016; AISI 2016; ASCE, 2017; Cano y Imanpour, 2020).

In civil engineering, and more specifically in the construction field, it is essential to have a well-structured budget for the correct implementation of a structure. We know that it is not always possible to have work quantities without first carrying out a seismic resistant analysis and design of a building, such is the case of industrial buildings (Guerrero, 2019). Consequently, this research proposed to carry out a structural analysis and design of a group of industrial buildings that have particular characteristics in terms of length, height and spacing between frames. Based on this analysis, the weights over m² of each building were obtained as a reference, which in turn were used to apply a non-linear Lagrange interpolation, which led to the determination of an equation with its respective graphic representation (abaci). With these results, it was possible to determine in a fairly approximate way the weight per m² of industrial buildings different from those that were taken at the beginning of the research, so that later, using these results, we would be able to get the cost of the material for each structure.

Experimental

The main objective of this research was to carry out a technical analysis of a group of industrial buildings, in order to find the costs of steel material using a non-linear Lagrange interpolation, which is represented through abaci.

Pre-design of the structural elements of industrial buildings

One of the considerations that were used in this research was a pre-design of the structural elements that make up industrial buildings, with the aim of starting with data that will be approximate to the expected results in the behavior of a frame under gravitational stresses, which must meet the resistance requirements. Generally, reinforcements are placed in the areas with greater stresses to ensure the stability and safety of the structure. (Élez, 2016). In this specific way, the research had the following parameters as its starting point: column free height (H), clear span of the building (L), modulation between frames (B1 or B2), defined in Table 1 and illustrated in Figure 1. With this, the geometry of the structure was defined, obtaining 40 combinations of industrial buildings, which were analyzed and modeled.

Table 1. Variants and combinations of free column height, frame width and length of the industrial building.

Free column height (Hi) (m)				**Clear span (m)**	**Modulation (m)**	
H1	H2	H3	H4	L	B1	B2
6	7	8	9	15	5	6
6	7	8	9	20	5	6
6	7	8	9	25	5	6
6	7	8	9	30	5	6
6	7	8	9	35	5	6

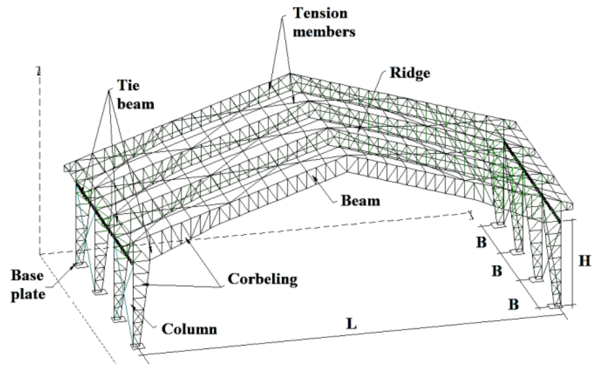

Figure 1. Geometry and variants of a metallic industrial building.

The industrial buildings formed by the structural profiling in accordance with ASTM A 1011 (2018) are: C-type channels, cold-formed G-type purlins, structural profiling (ASTM A36, 2018; A36M-08, 2018) such as: hot-formed L-type angles (ASTM A1011, 2018; A1011M-18a, 2018). This article, regarding the structural design, was carried out with the load and resistance factor design method called LRFD, which considers the resistance or failure condition, where the applied service loads are factored and the theoretical resistance of the material is reduced. The criterion that the factored load must satisfy must be less than or equal to the reduced resistance (Garibov y Bashirzade, 2020). This approach is based on two fundamental concepts: the limit state of resistance and the limit state of service. The first focuses on the safety or load-bearing capacity of structures and includes plastic, overturning, fatigue, fracture, and buckling resistances; while service limit states refer to the behavior of structures under normal service loads and have to do with aspects associated with use and occupation, such as excessive deflections, slips, vibrations and cracking (McCormac, 2013). The LRFD method (Garibov and Bashirzade, 2020; Crisafulli, 2018), recommends that service loads (Qi) are multiplied by certain load or safety factors (λi), which are almost always greater than 1.0; to obtain the “factored loads” used for the design of the structure. The magnitudes of the load factors vary, depending on the type of load combinations, as can be seen in Equations 1 to 6 (NEC, 2014):

$$U_1 = 1.4D + L \tag{1}$$

$$U_2 = 1.D + 1.6L + 0.5(L_r\ o\ S\ o\ R_r) \tag{2}$$

$$U_3 = 1.2D + 1.6L + 0.5(L_r o\ S\ o\ R_r) + 0.5(L\ o\ 0.8W) \tag{3}$$

$$U_4 = 1.2D + 1.3W + 0.5L + 0.5(L_r o\ S\ o\ R) \tag{4}$$

$$U_5 = 1.2D + 1.5E + 0.2S \tag{5}$$

$$U_6 = 0.9 - (1.3W\ o\ 1.5E) \tag{6}$$

Where: U_i: load combination, D: dead load, L: live load, L_r: roof live load, S: snow load, R_r: rain load, except flooding, W: wind load.

The structure is sized to have a sufficient ultimate design resistance able to resist the factored loads. This resistance is considered equal to the nominal theoretical resistance (Rn) of the structure member, multiplied by a resistance factor Ø which is normally less than 1.0 (Hernández, 2015), according to:

$$\sum \lambda_i Q_i \leq \emptyset R_n \tag{7}$$

The design resistance of each structural component is greater than or equal to the required determined resistance, according to the LRFD load combinations, according to:

$$R_u \leq \emptyset R_n \tag{8}$$

Where: R_u: resistance required by the LRFD method, R_n: nominal resistance given by the material, Ø: resistance factor, $ØR_n$: design resistance.

In this research, the analysis and design of the structural elements was carried out using computer packages, which were subjected to load combinations for each group of industrial buildings modulated at every 5 and 6 m, each of them with a column height that varied between 6 and 9 m and a clear span of 15 to 35 m, based on the Ecuadorian construction standard (NEC, 2014).

The parameters that intervene in the calculation of the seismic loading percentage, which will constitute the basal shear applied to each industrial building, are tabulated in Table 2.

Table 2. Parameters that intervene in the calculation of the basal shear of industrial buildings.

Parameter	**Variable**	**Value**
Seismic zone	V	-
Zone acceleration factor	Z	0.4
Soil type	D	-
F_a site factor	F_a	1.20
F_d site factor	F_d	1.19
Inelastic behavior factor of the soil	F_s	1.28
Factor associated with the geographic location of the project	r	1
Spectral amplification ratio	η	2.48
Acceleration at $T = T_o$	$S_a[g]$	1.19
Limit period at $T = T_o$	$T_o[s]$	0.127
Limit period at $T = T_c$	$T_c[s]$	0.698
Limit period at $T = T_L$	$T_L[s]$	2.856
C_t Coefficient	C_t	0.073
Period calculation Coefficient	α	0.75
Total element height	$h_n[m]$	-
Theoretical period method 1	$T_1[s]$	0.441
Theoretical period method 2	$T_2[s]$	0.57
Seismic force reduction factor	R	3.00

The live load (CV) had a value equal to the hail load which, according to the NEC SE CG (2014) standard, by default, has a specific hail weight value equal to 1 T/m³ on lower slopes at 15% and a minimum load of 0.5 kN/m². In this case, we considered the accumulation of hail in a short time and a hail layer thickness of 10 cm in height and a specific weight of 0.75 T/m is assumed.[3]; obtaining a load of 75 kg / m^2, that used in all models: The dead load (CM) we used was 5.0 kg/m^2 for the facilities and 4.0 kg / m^2 for the roof, having a constant value for the entire set of industrial buildings of CM = 9 kg/m^2 and e CV = 75 kg/m^2, and are represented in Figure 2 (Redroban, 2015).

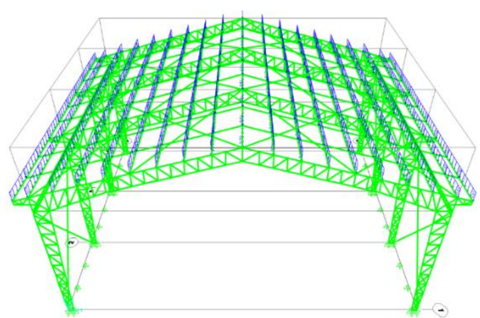

Figure 2. Live load and dead load of industrial buildings.

The graphical representation in Figures 3 and 4 of the wind load, corresponding to windward W1, W2 and leeward W3 and W4, with modulations between frames at every 5 and 6 m, respectively (Hernández, 2015).

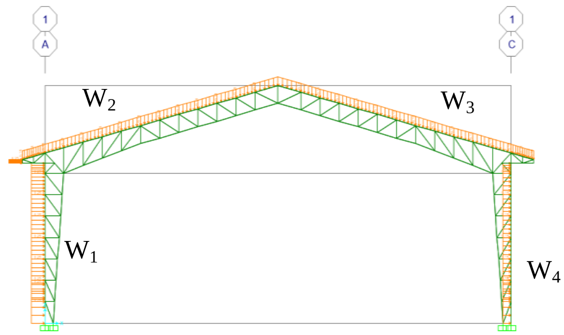

Figure 3. Wind load of industrial buildings. W1: windward column, W2: windward beam, W3: leeward beam, W4: leeward column.

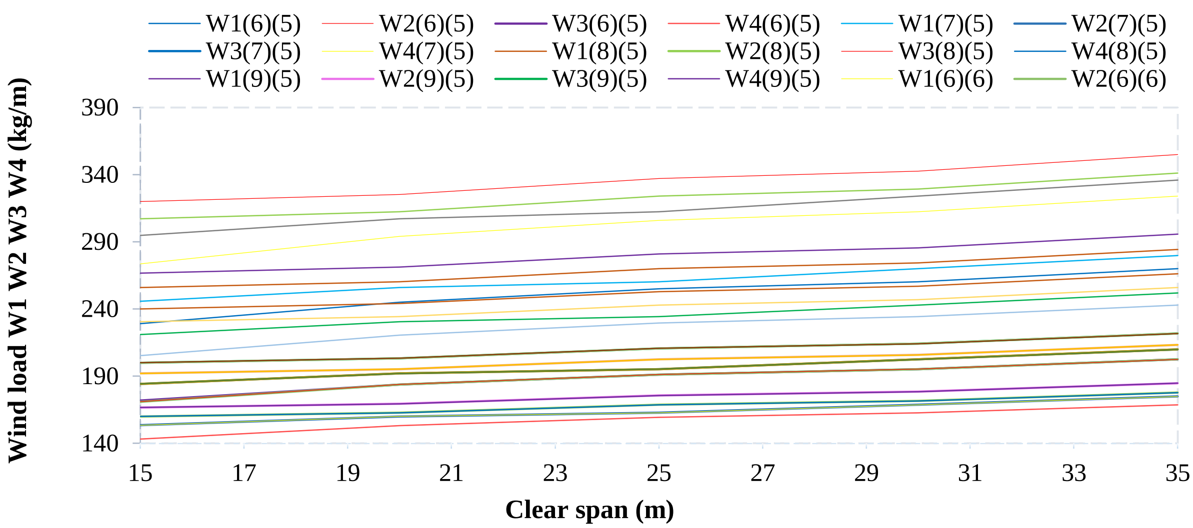

Figure 4. Summary of wind loads (W1, W2, W3 and W4) for industrial buildings with modulation between frames B = 5 and 6 m (windward).

Design of the structural elements of industrial buildings

For these designs, we verified that they met the controls stipulated both in the ASCE (2017), SEI 7-16 (2017) and the NEC (2014) standards. The optimization of the structures is the next step to continue with the objective of guaranteeing the service and resistance conditions. For this, we used the computational tool for the modeling and analysis of the industrial buildings, to determine the total weight of all the sections that make up the industrial shed structure, in a systematic way (ASCE, 2017). In this way, the forces and other maximum requirements needed were obtained, both for columns and beams, in order to carry out a design of the elements subject to compression, verifying that the limit states of local buckling and global buckling were met. Similarly, a design was made for members subject to bending, which were analyzed for the effects of creep and torsional lateral buckling, according to the steel construction manual (SAP 2000, 2016; AISC, 2016).

Once the analysis was carried out, the structural elements were designed, where the demand-capacity ratio was verified, which involves the compression capacity with the ability to resist bending moments, and should not be greater than 1.0 (Cuichan, 2016).

In this research, most of the elements were found between 0 and 95% of their capacity, that is, they were working in a very acceptable way, since in metallic structures it should be ensured that they work at their maximum capacity, leveraging on their large advantages (Acero, 2011). In order to check the stresses of the structural elements of the set of industrial buildings, a manual check was carried out with the computer package, choosing the elements with the highest demand/capacity ratio, both in columns and in beams, and these are tabulated in Tables 3 and 4.

Table 3. Demand/capacity ratio in columns and beams with modulation between frames H = 9 m, L = 25 m and B = 5 m.

Column				Beam			
Members	**Profile (mm)**	**D/C_S**	**D/C_M**	**Members**	**Profile (mm)**	**D/C_S**	**D/C_M**
PE	C150x5x4	0.849	0.838	PE	C150x5x3	0.647	0.639
PI	C150x5x4	0.775	0.770	PI	C150x5x3	0.702	0.693
CD	L40x4x4	0.906	0.893	CD	L40x4x5	0.796	0.786
CH	L40x4x4	0.782	0.779	CH	L40x4x4	0.090	0.120

PE: outer profile, PI: inner profile, CD: diagonal lattice, CH: horizontal lattice, D/C_S: demand index for the capacity obtained by software, D/C_M: demand index for the capacity obtained manually.

Table 4. Demand/capacity ratio in columns and beams with modulation between frames H = 9 m, L = 25 m and B = 6 m.

Column				Beam			
Members	**Profile (mm)**	**D/C_S**	**D/C_M**	**Members**	**Profile (mm)**	**D/C_S**	**D/C_M**
PE	C150x5x4	0.914	0.908	CE	C150x5x3	0.898	0.885
PI	C150x5x4	0.825	0.815	CI	C150x5x3	0.817	0.804
CD	L40x4x4	0.522	0.547	CD	L40x4x3	0.866	0.859
CH	L40x4x4	0.862	0.856	CH	L40x4x3	0.506	0.493

PE: outer profile, PI: inner profile, CD: diagonal lattice, CH: horizontal lattice, D/C_S: demand index for the capacity obtained by software, D/C_M: demand index for capacity obtained manually.

Polynomial interpolation

The Lagrange high order interpolation method (Pacheco *et al*., 2012). The numerical analysis that defines the Lagrange interpolation polynomial, corresponding to the n+1 given values, as the degree polynomial function at the most n that takes different numerical values on the n+l $\{x_o, x_1, ..., x_n.\}$, the n+l given values $\{y_o, y_1, ..., y_n\}$. An interpolating polynomial is obtained as a formal expression $f(x) = a_o + a_1x + a_2x^2 + ... + a_o.x^n$ (Sandoval, 2019).
By assuming known values at n+1 points $x_0, x_1, \dots, x_n$ (dependent values) and $f_0, f_1, ..., f_n$ (independent values) of a function; a $P_n(x)$ polynomial was constructed with a degree less than or equal to n, as shown in Equation 9, according to (Sandoval, 2019).

$$P_n(x) = f_i, i = 0,1, \dots, n \tag{9}$$

The $P_n(x)$ polynomial thus constructed is called an interpolating polynomial or an interpolation polynomial. One possible way to solve the problem was to propose the following degree n polynomial, indicated in Equation 10:

$$P_n(x) = a_0 + a_1x + a_1x^2 + \dots + a_nx^n \tag{10}$$

With undetermined coefficients a_i, i = 0, 1,…, n , and impose that Equation 10 verifies Equation 9. This means that obtaining the interpolating polynomial is equivalent to solving the system of linear equations given in Equation 11:

$$a_0 + a_1x_1 + \dots + a_nx_1{}^n = f_1. \tag{11}$$

Lagrange polynomial

In this research we used the Lagrange interpolation polynomial, since it allows us to generate a function that passes through all the points, thus facilitating modeling and obtaining fairly reliable approximations. Given the set of points $(x_0.f_0).(x_1.f_1)\ldots .(x_n.f_n)$, we consider the polynomial, using Equations 12 to 14 (Suárez, 2012).

$$f_n(x) = \sum_{i=0}^{n} f(x_i) L_i(x) \tag{12}$$

Where $L_i(x)$:

$$L_i(x) = \prod_{\substack{j=0 \\ j\neq i}}^{n} \frac{x - x_j}{x_i - x_j} \tag{13}$$

The second-degree Lagrange polynomial is:

$$f_1(x) = \frac{(x-x_1)(x-x_2)}{(x_0-x_1)(x_0-x_2)} f(x_0) + \frac{(x-x_0)(x-x_2)}{(x_1-x_0)(x_1-x_2)} f(x_1) + \frac{(x-x_0)(x-x_1)}{(x_2-x_0)(x_2-x_1)} f(x_2) \tag{14}$$

In this case $f_n(x)$ is the "y" interpolated and the "x" is the x to interpolate. The more data in the table, the higher degree polynomial can be used. In this section, the polynomial obtained was of the fourth degree. For this research, the $f(x_i)$ value corresponds to the weights of each industrial building modulated every 5 and 6 m, while the Li (x) value is the Lagrange polynomial, which depends on the clear span of the frame, which varies from 15 to 35 m.

Results and Discussion

The cost of the materials of an industrial building when preparing a referential budget for a specific project is one of the important factors that influences the feasibility and award to develop the project for the company that budgets an offer (Guerrero, 2019). The determination of this parameter was obtained in a direct way, that is, the weight of an industrial building in kg/m² indicated in Figures 5 and 6, multiplied by its area. In this research the area ranged between 225 and 525 m² for frames modulated every 5 m, and from 270 to 630 m² for frames modulated every 6 m. With these values, the weight of material that is related to the properties of the elements that was considered in the design was obtained.

Based on the requirements and complying with the ASCE (2017), SEI 7-16 (2017), NEC SE AC (2014) and NEC SE DS (2014) standards, this section presents the results of kg/m² achieved by industrial buildings as shown in Table 5. Likewise, the numerical analysis is indicated by the Lagrange polynomial, with which the equations that govern each group of buildings with modulations at 5 and 6 m were determined.

Interpolation result using the Lagrange polynomial

Once the weights in Table 5 were known and applying the programming language, the equations were formed based on the Lagrange polynomial for the 5 and 6 m modulations of industrial buildings, with spans that vary every 5 m and ranging from 15 up to 35 m respectively, as indicated in Figures 5 and 6.

Table 5. Total weights per square meter obtained for buildings with modulations at 5 and 6 m.

Clear span (m)	**Column height (m)**	**Weight (kg/m^2) modulated at 5 m**	**Weight (kg/m^2) modulated at 6 m**	**Clear span (m)**	**Column height (m)**	**Weight (kg/m^2) modulated at 5 m**	**Weight (kg/m^2) modulated at 6 m**
15	6	17.42	18.62	15	8	21.01	21.63
20	6	18.12	19.26	20	8	21.64	22.11
25	6	19.41	20.18	25	8	22.48	22.96
30	6	20.84	21.64	30	8	23.79	24.37
35	6	22.65	23.09	35	8	25.49	25.92
15	7	19.67	20.38	15	9	22.60	23.24
20	7	20.37	20.99	20	9	22.94	23.74
25	7	21.39	21.82	25	9	23.70	24.37
30	7	22.62	23.30	30	9	24.84	25.49
35	7	24.35	25.03	35	9	26.21	26.96

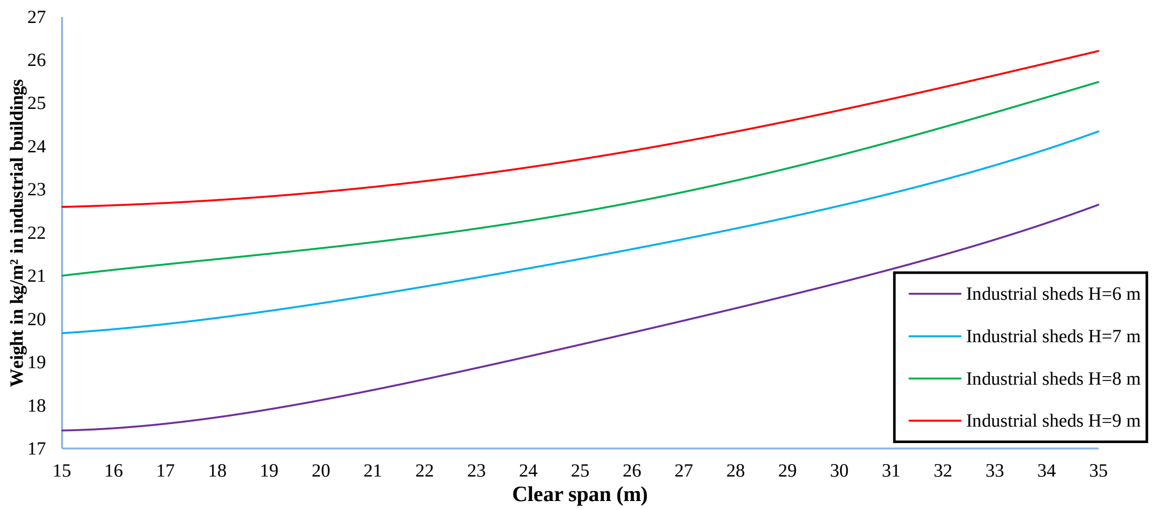

Figure 5. Interpolation curves (abacus) for industrial sheds with 5 m modulations.

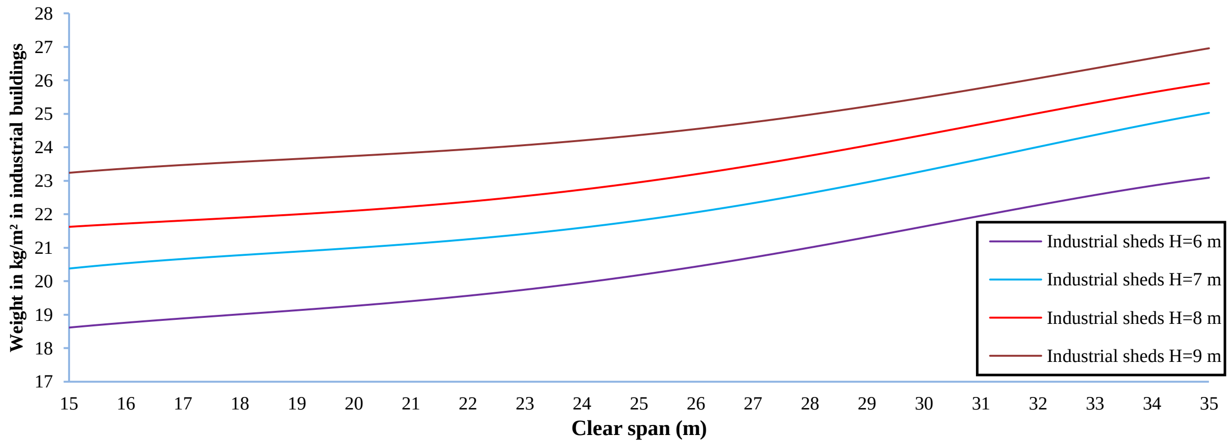

Figure 6. Interpolation curves (abacus) for industrial sheds with 6 m modulations.

Figures 7 and 8 show the reference costs for each group of industrial buildings, according to 5 and 6 m modulations, respectively. The reference price for hot rolled steel coils reached US $99 per metric ton in 2019. According to estimates for the year 2022, this figure would decrease slightly to around 463 US dollars (Díaz, 2021; Investing, 2021).

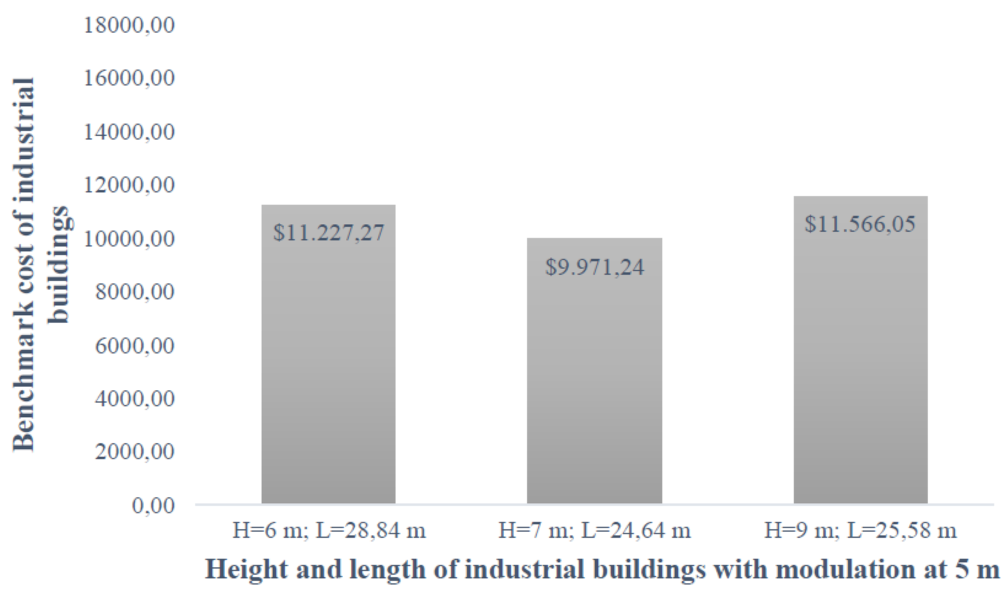

Figure 7. Benchmark cost graph of industrial buildings modulated at 5 m (Investing, 2021).

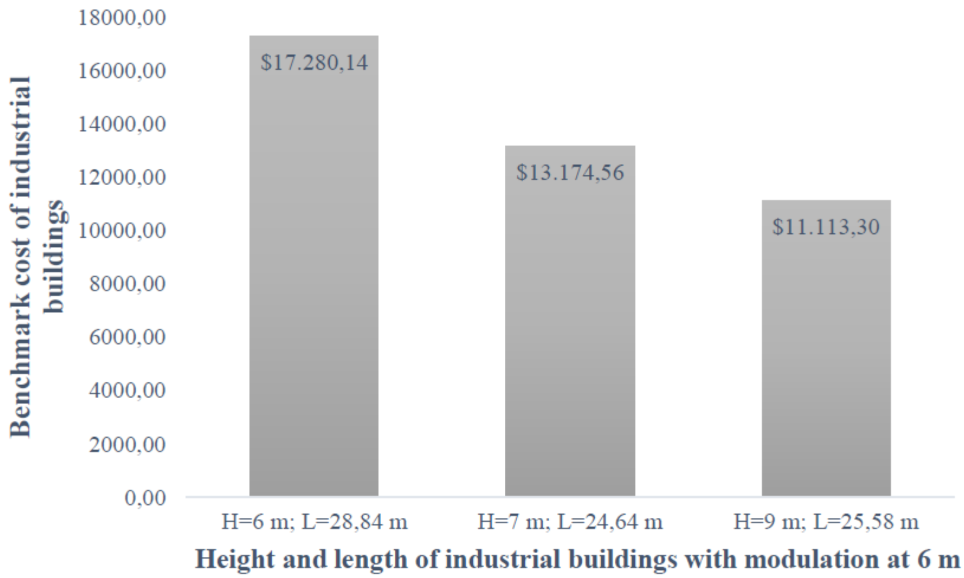

Figure 8. Benchmark cost graph of industrial buildings modulated at 6 m (Investing, 2021).

Determination of the normalized percent error

In order to establish the real value, it is sometimes difficult to have the true value, for such cases, one option is to normalize the error, using the best possible approximation of the true value. For this study, the normalized percent error is calculated with the expression given in Equation 15:

$$\varepsilon_t = normalized\ percent\ error \qquad (15)$$

$$E_t = true\ value - approximation$$

$$\varepsilon_t = \frac{E_t}{true\ value} x\ 100\ \%$$

In order to validate the results obtained in the abaci of Figures 5 and 6; regarding the computational tool, when obtaining the weight in kg/m² of the industrial building, we assumed that the true value is the one obtained from the program and the approximation value is the value that was determined by the Lagrange polynomial. For verification purposes, 6 additional industrial buildings were evaluated with intermediate values that do not exist in Table 5, consequently, the results presented in Tables 6 and 7 were obtained.

Table 6. Total weights per square meter for intermediate values obtained for industrial sheds with a modulation of B = 5 m.

B (m)	**H (m)**	**L (m)**	**Weight with software (kg/m²)**	**Weight with equation (kg/m²)**	**(%) Error**	**Weight (kg)**	**Cost ($)**
5	6	28.84	20.49	20.50	0.05	8868.30	11227.27
5	7	24.64	21.31	21.31	0.00	7876.18	9971.24
5	9	25.58	23.80	23.81	0.04	9135.90	11566.05
			Mean		0.03		
			Deviation		0.03		

L: clear span, H: frame height, B: distance between frames.

Table 7. Total weights per square meter for intermediate values obtained for industrial sheds with a modulation of B = 6 m.

B (m)	H (m)	L (m)	Weight with software (kg/m²)	Weight with equation (kg/m²)	(%) Error	Weight (kg)	Cost ($)
6	6	33.42	22.71	22.69	0.09	13649.40	17280.14
6	7	26.16	22.08	22.10	0.09	10406.45	13174.56
6	8	21.83	22.33	22.34	0.04	8778.28	11113.30
			Mean		0.07		
			Deviation		0.03		

L: clear span, H: frame height, B: distance between frames.

Determination of the proportionality of the H, L and B parameters Vs. Weight

In order to establish the level of proportionality that exists between the aforementioned parameters (H, L and B) with respect to the weight per square meter of the group of buildings, a radial graph was obtained, which shows that there is a proportionality from L = 15 m to L = 35 m, which is evidenced in Figure 9.

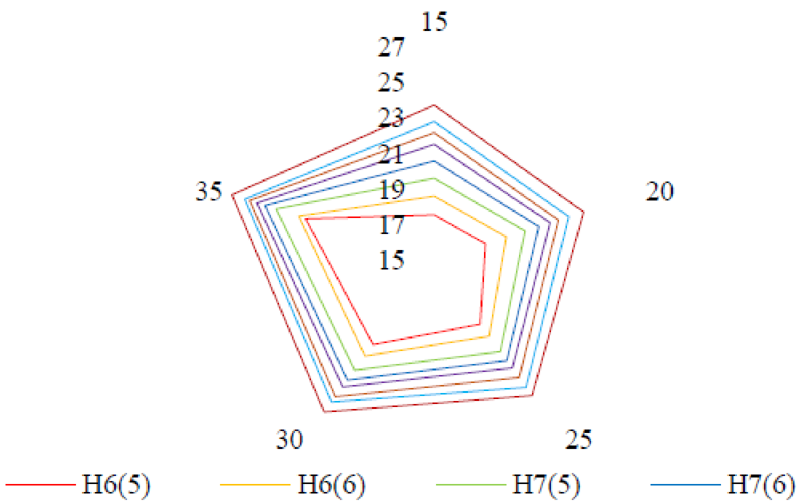

Figure 9. Radial graph of column free height Vs. weight per square meter.

Conclusions

When carrying out a structural analysis and design using a computer package for a set of industrial buildings with different parameters for length, height and spacing of frames, we obtained the values corresponding to the index between the weight and area of the structures, and when comparing them with the values obtained from the Lagrange polynomial, a fairly low mean error was found. Therefore, we can conclude that the interpolation indicated in this research, with the parameters described above, can simply be used to directly find the cost of the steel material in industrial buildings.

Regarding the cost of the industrial buildings, the corresponding value of the cost of steel should be taken into account, depending only on the area in which the project will be implemented; consequently, the preparation of a budget will be much more agile than carrying out a previous structural analysis and later find the costs.

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