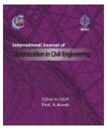
INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2020; 10(4):733-747



Technical Note

OPTIMAL DESIGN OF STEEL STRUCTURE OF STABLE FOR ADULT COWS WITH NATURAL VENTILATION SYSTEM USING META-HEURISTIC ALGORITHMS

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ABSTRACT

By incorporating structural engineering, animal husbandry, and veterinary, this interdisciplinary research accomplishes the following two main objectives: 1) design and optimization to reduce the weight of the steel structure skeleton of the stable with ECBO & CBO algorithms; 2) improving the performance of the natural ventilation system in the stable with some changes in the structure's geometric design.

In this study, each algorithm's performance will be investigated in the course of accomplishing the aforementioned objective. Furthermore, using stress ratios by algorithms in each member will be studied. Finally, using the algorithms, a stable steel structure with lower weight is designed.

In this paper, through changing and improving the structure's geometric design, a structure more compatible with the natural ventilation system's requirements is designed. These changes are as follows: 1) design of a taller stable structure; 2) larger design of the air inlets in the joint line between the upper part of the side walls and the lower part of the pitched roof.

Keywords: stable steel structure skeleton design; tapered members; optimization with ECBO & CBO Meta-heuristic algorithms; natural ventilation system of stable; adult cows.

Received: 12 August 2020; Accepted: 5 November 2020

1. INTRODUCTION

Along with advanced technologies currently in the service of animal husbandry and

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veterinary, a modern, standard stable structure can be useful to complete the growing cycle and meet the needs of livestock. With innovations in analysis, design, and optimization techniques [1], structural engineers have been able to find solutions far faster to solve problems and meet the requirements of construction. On this subject, the development of numerical techniques and meta-heuristic algorithms such as CBO [2] and ECBO [3] can be mentioned**.** Some researchers have even identified the most practical algorithm for designing structures through comparative approaches [4].

It should also be noted that some animal behavior patterns are characteristics of livestock health and well-being in the stable [5]. In some cases, due to the importance of housing and livestock welfare in the stables, if the above behavior patterns are not observed, the livestock center's activity will be prevented [6].

In this paper, a design of the steel structure of an adult cow stable with a natural ventilation system is introduced. Some changes have been made to the structure geometry to improve the natural ventilation system's performance. These changes include: 1) changes in the dimensions of the openings (inlet) for the inflow of wind into the structure; and 2) change in the height of the stable structure. The performance of CBO and ECBO algorithms will be analyzed against the performance of the original design of the structure which did not use the algorithms. Eventually, how to use the stress ratio by each algorithm in each steel member will be analyzed. The steel structure skeleton has been designed according to the AISC Regulations in SAP2000 [7] and using the Load and Resistance Factor Design (LRFD) method. The necessary constraints and restrictions in the design have been applied and observed.

Finally, two ideas have been suggested as future work for the design of stable with a natural ventilation system for adult cows, namely: A) A method of roof design for stable with an insulation approach to improve the function of the natural ventilation system, and B) design of air injection valves on the side walls near the cow’s bed.

2. PRELIMINARY INFORMATION REGARDING THE DESIGN OF STRUCTURES

In the design and construction of industrial structures, designers commonly use steel frames and tapered members with a pitched roof [8]. Structural designers usually use tapered members [9] to design steel members with gable frames. Following the optimal design rules, it is more likely to have a design closer to the optimal weight conditions [8]. As a result, the final design is expected to have an economic justification [10].

Depending on the owner's needs or the designer's reasons, the stable structure can be designed with one, two, or even multi-span [11] pitched roof frames**.** This structure can be constructed with single or double-pitched roofs, or even in some cases, with the double-layer barrel vaults [12] and designed by the elastic or plastic methods [13]. Although steel plates or shear walls for seismic resistance [14] are widely used in various structures, due to some of the inherent features of the stable structure, which will be introduced in this paper, these methods of design are not practical.

2.1 A brief introduction to the CBO optimization algorithm

The Colliding Bodies Optimization (CBO) algorithm is based on the collision of objects in one dimension and the physical laws governing the impact of collisions [2]. In summary, this algorithm has three unique features among the known algorithms in optimization methods, namely: 1) no internal parameters; 2) unlike many algorithms, this algorithm follows a simple method and concept to achieve the objective function, and 3) this algorithm does not require memory to store the best solution [Ibid]. In this algorithm, each particle represents a body with characteristics and physical properties such as mass, weight, velocity, and post-collision displacement [14]. Each particle has a weight assigned to it using the following formula [2]. In the following formula, fit (i) is the target function value of the impactor (i) and (n) the number of impactor objects.

$$m_k = \frac{\frac{1}{fit\,(k)}}{\sum_{i=1}^{n} \frac{1}{fit\,(i)}} \, ,k = 1,2,\dots,n \tag{1}$$

The initial position of the colliding objects is completely randomized [Ibid];

$$x_i^0 = x_{min} + rand\,(x_{max} + x_{min}), i = 1,2,\dots,n \tag{2}$$

In this algorithm, the colliding objects are divided into two groups: 1) fixed objects group and 2) variable objects group. Objects that are classified in the group of variable objects will hit objects that are classified in the fixed object group at a specified speed. After the collision, fixed objects are moved to a better position in the search space [Ibid]. The speed of the first object in the group of fixed objects is assumed to be zero. The second object in the variable body group has its speed determined by the following formula [Ibid]. In the following formula, (n) is the number of colliding particles.

$$v = 0,\ \ i = 1,2,\dots,\frac{n}{2} v_i = x_{i-\frac{n}{2}} - x_i \qquad i = \frac{n}{2} + 1, \frac{n}{2} + 2, \dots, n \tag{3}$$

The following formula determines the velocities of objects classified in the fixed and moving group after collision [Ibid]:

$$v_i' = \frac{\left(m_{i+\frac{n}{2}} + \varepsilon\, m_{i+\frac{n}{2}}\right) v_{i+\frac{n}{2}}}{m_i + m_{i+\frac{n}{2}}} \quad i = 1, 2, \dots, \frac{n}{2} \tag{4}$$

$$v_i' = \frac{\left(m_i - \varepsilon\, m_{i-\frac{n}{2}}\right) v_i}{m_i + m_{i-\frac{n}{2}}} \quad i = \frac{n}{2} + 1,\ \frac{n}{2} + 2, \dots, \frac{n}{2} \tag{5}$$

In the formula, (Ɛ) is called the compensation factor and is derived from the following formula. In this formula (iter) and ($iter_{max}$) are the current iteration number and the maximum number of total iterations in the optimization process, respectively [Ibid].

$$\varepsilon = 1 - \frac{iter}{iter_{max}} \tag{6}$$

The following formula determines the new position of each of the objects in the fixed and variable object group. In this formula, (x_{new}^{i}), (x_i) and (v_i) are a new position, the previous positions, and the velocity after the object (i) collision, respectively. Also, the rand is a random vector distributed evenly over intervals [1 and -1]. In this formula, the (o) signifies the element-by-element multiplication [Ibid].

$$x_i^{new} = x_i + rand \ o \ v_i' , \qquad i = 1, 2, \ldots, \frac{n}{2} \tag{7}$$

$$x_i^{new} = x_{i-\frac{n}{2}} + rand \ o \ v_i' , \qquad i = \frac{n}{2} + 1, \frac{n}{2} + 2, \ldots, n \tag{8}$$

2.2 A brief introduction to the ECBO optimization algorithm

The Enhanced Colliding Bodies Optimization (ECBO) algorithm is the enhanced format of the CBO algorithm, written by Professor Ali Kaveh et al. [3]. In summary, this algorithm has two different properties compared to the CBO algorithm: 1) this algorithm has the memory to store the best component of the objective function [15]; 2) to avoid local optimum traps, it is equipped with a tool called Pro [3]. This aspect appears in the following formula:

$$x^j = \begin{cases} random\ (L^i ,\ U^i), & rnd_j < pro \\ x^i , & otherwise, \end{cases} \quad j = 1, 2, \ldots, n \tag{9}$$

2.3 Ventilation

Ventilation means supplying fresh air in the stable. The following two simple processes usually play a pivotal role in a variety of stable ventilation methods: air exchange and air distribution [16]. The use of three types of ventilation systems is common in most stables by focusing on these processes: 1) mechanical ventilation systems; this system performs air conditioning of stable by consuming energy [17]. 2) Natural ventilation systems; in this method, the ventilation system does not need electricity or other energies for indoor air conditioning [18]. It is noteworthy that this type of ventilation is very economical, as up to 60% energy savings have been observed. This system usually uses two of the following parameters to move air inside the stable to perform ventilation. These two factors are the Stack effect [17] and the Chimney effect [18]; 3) hybrid ventilation systems; this system is a combination of natural and mechanical ventilation systems [17].

2.4 Reasons for using ventilation in stables

Achieving the highest level of livestock production in stables and providing an environment away from stressful situations (low oxygen levels, unfavorable temperature, and high humidity) seem essential [5]. The index used to evaluate the above parameters in the stables is the THI (Temperature Humidity Index) [17]. One of the reasons for heat, humidity, and other adverse environmental conditions may be lack of proper ventilation in the stable. In some cases, this inappropriate environment can provide conditions for the spread of some diseases, such as BRD (Bovine Respiratory Disease) [Ibid]. If a ventilation system with a good standard is used [17], the required airflow in the stable will be provided. The use of ventilation, notably natural ventilation, which will operate without energy consumption, is likely beneficial to the animal husbandry.

2.5 Advantages and disadvantages of natural ventilation

Natural ventilation in cold climates performs better than in hot climates. Mechanical ventilation systems can be used when natural ventilation is not working correctly. Usually, using these two systems, Cross or Tunnel [17] flow is created in the stable. One of the operators used in this situation is mechanical and individual air conditioning, usually located on the ridge of the roof for the air outlet, it is known as a Cupola fan [Ibid]. Some of the geometrical and physical properties of the structure that influence the performance of the natural ventilation system are as follows: 1) appropriate approximation for ceiling slope of the stable [Ibid]; 2) suitable dimensions and locations for airflow inlet and outlet [19]; 3) height of structure [20]; and 4) appropriate direction of the stable structure according to the direction of prevailing winds in the region. If the stable structure's design does not meet the natural ventilation requirements [16], the efficiency of the natural ventilation, i.e., air entering, moving, and exiting from the stable, will be reduced.

2.6 How natural ventilation works in stable

As mentioned, the Stack Effect [17] and the Chimney Effect [18] are two key parameters affecting natural ventilation. With the help of the above parameters and the Bernoulli principle, necessary conditions will exist for moving the warm layers residing near the bed upwards. However, these two phenomena alone are not enough in the warm seasons to perform natural ventilation in stables. One way to solve this problem in these conditions is to ventilate the hot, humid, and dense layers of air in the stable with the help of wind flow into the structure. It will be possible through the air entry openings embedded in the upper part of the structure's side walls. The characteristics mentioned in the following section will be examined as influential factors in the accumulation and buoyancy of air layers [Ibid].

2.7 Structural requirements for optimal operation of the natural ventilation system

The stable design's geometric features will be discussed, all providing the conditions for a natural ventilation system to encourage unfavorable and static air layers to flow and exchange with the outside air.

2.7.1 Insulation

Proper insulation improves the Stack Effect’s performance, and this is the predominant aspect in cold climates for natural ventilation [17]. Some engineering design methods, such as airflow-containing ducts, can be used for insulation. In this method, the ducts are embedded across the inside surface of the pitched roof [21]. With proper insulation, it can maintain ambient humidity below 80% and take a practical step against condensation and dew point [17]. Note that humidity higher than 80% causes livestock stress [19].

2.7.2 Dimensions of the openings on top of the side walls for the inflow of wind into the structure

To utilize the full capacity of the natural ventilation system, it is necessary to use the proper dimensions of the openings for the inflow of wind into the stable. One of the best places to design the openings to enter the airflow to the stable is through openings that are in the joint line on the top of the side walls and lower edges of the pitched roof. The openings on the ridge of the roof allow airflow to go out of the stable. The inlet of airflows designed in stable side walls with an angle of 90 degrees to the prevailing winds creates the highest amount of airflow inside the structure compared to other directions [Ibid].

In addition to the positive effect of openings on side walls and the ridge in the stable ventilation, the floating property of the air layers is important to the natural ventilation system's performance. These factors and the Chimney effect direct the warm air accumulated around the livestock to ascend to the top and the air exit through the ridge of the roof. It is recommended that the dimensions of the openings on the ridge design to be 5 cm for every 3 m width [17]. However, some sources have suggested that the sum of eaves & ridge openings for the natural ventilation system in the winter is about 2.5 cm for every 3 m width [22]. It should also be noted that the minimum size of openings should not be less than 15 cm [17].

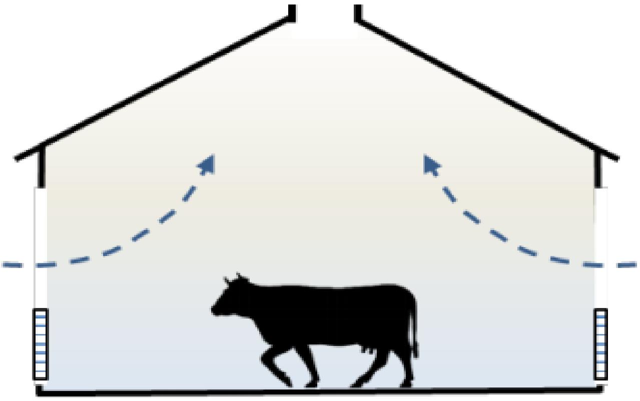


Figure 1. Natural ventilation. Airflow enters through the side walls openings and exit through the ridge [19]

Some other texts stated that it is better to design the size of the openings of the lower edge of the sloping roof (eaves) on both sides of the structure in total equal to the size of the openings on the Ridge [Ibid]. Also, in winter, to avoid a severe cold in the stable, with wind speeds of about 16 km / h (10 mph), it is advisable to reduce the mentioned dimensions to about 10 cm (4 inches) [22]. In addition to the above numbers, the following formula can be used to calculate this structural property to design a set of natural ventilation openings. (A), (Q), and (V) are openings level (sq.in.), ventilation rate (cfm) and wind speed (mph), respectively [Ibid].

$$A = \frac{(4.7\,Q)}{V} \tag{10}$$

2.7.3 Height of stable structure

Designers should note that, for a better functioning natural ventilation system, a high rise structure is far better than a low rise structure [16]. Some researchers have pointed out the height of the structural walls, about 5 meters to be sufficient [17]. There are also some practical suggestions by Jens and et al. [22]. A study shows that when the height of Holstein cattle stable rises from 5 to 8 meters, the temperature will decrease by about 4°C [20]. Overall, by combining these theories, it can be concluded that it is better to use a high rise structure as a stable for adult cows because the natural ventilation system works better in these conditions.

3. METHODS AND MATERIALS IN OPTIMAL DESIGN OF STABLE STEEL STRUCTURE

3.1 Objective function

In this paper, the weight of the steel structure as an object function was determined for CBO [2] & ECBO [3] algorithms. The codes of algorithms are written in MATLAB software. In the tapered members [9], the average cross-sectional area was taken into account. The following formula defines the objective function in the optimization process, (NOE) is the number of members, (ρ) is the density of steel, (L_i) is the length, and (A_i) is the cross-section of each member [3].

$$Cost_{ini} = \sum_{i=1}^{NOE} \rho l_i \; A_i \tag{11}$$

3.2 Variables

As mentioned in table (2), all steel sections with (I) shape used in this design have the same flange thicknesses. Also, all columns are designed with the same shape and size, and the upper parts of the columns have a larger cross-sectional area than the lower parts of these members. The beams consist of three parts, as depicted in Fig. 2; the top and bottom of the beams are designed to have a larger cross-sectional area than the middle sections.

3.3 Loading

After modeling this structure in SAP2000 software [7], the structural skeleton is designed according to AISC360 / IBC2006 regulations and LRFD (Load and Resistance Factor Design) method [Ibid]. In the optimization process of this structure, no new steel section, outside the initial bank (main bank) that the initial designer (original designer) used in the design of this structure as variables, entered the optimization process [23].

4. DISCUSSION

4.1 Design and specifications of the stable structure

In this project, the beams and columns sections were designed in a non-prismatic method. Also, double angle sections are used for the braces. As shown in Table (1) and Fig. 3, this structure is composed of consecutive frames, and each frame is 6 m apart and eventually extends the length of the structure to approximately 48 m. Each frame has four columns, two shorter outer columns, and two taller inner columns.

Table 1: Geometric parameters

Dimensions of the hall	48 * 37 m^2	Half-floor live load	500 kg / m^2
Number of frames	8	Crane load	5000 kg
Frame spacing	6 m	Roof slope	15%
Structural specifications in the longitudinal direction	Simple frame and brace	Height of external and internal columns	6.5 & 10 m
Structure specifications in the width direction	Moment steel frame	The height of the sloping roof to the floor	11.87 m
Connecting the column foot to the foundation	Hinged support	Width of span	25 m
Light ceiling weight 30 kg / m^2	30 kg / m^2	Height of Half-floor with heavy ceiling	3.2 m
Heavy roof weight	550 kg / m^2	--------	----

In this structure, two light walls were added to the basic design of the structure to meet the natural ventilation system's needs. These two lightweight walls do not have a significant impact on the behavior of the structure. According the footnote of (3), a lightweight wall was designed in parallel with the length of the structure in the first stage. This wall connected all nine inner long columns of the left half of the structure to each other. In the second step, the same method applies to the nine internal columns of the right half of the structure. The space provided for the placement and maintenance of adult cows in this stable is the distance between two rows of inner taller columns, as shown in Fig. 3. As a result, a space around 25 x 48 m will be available to take care of cows. If these two lightweight walls were not designed on both sides of the structure, some of the natural ventilation system requirements would not have been met, the airflow in the space would have been disrupted, and the cows would have settled on either side of the structure, below the concrete roofs, suffering from poor air circulation.

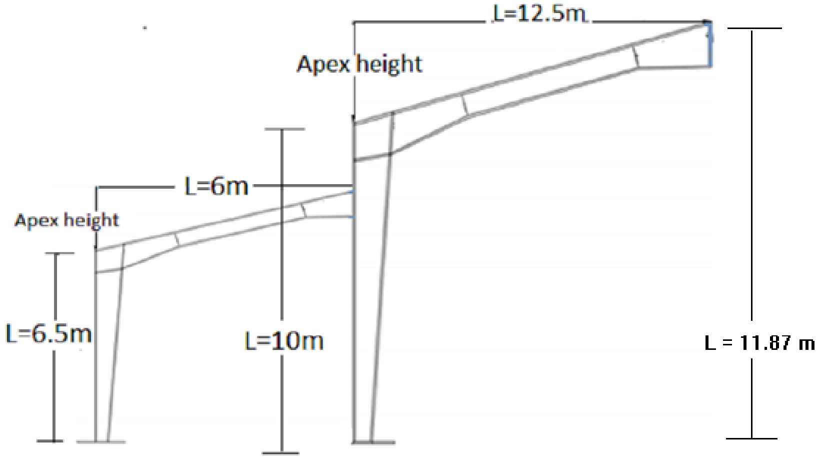
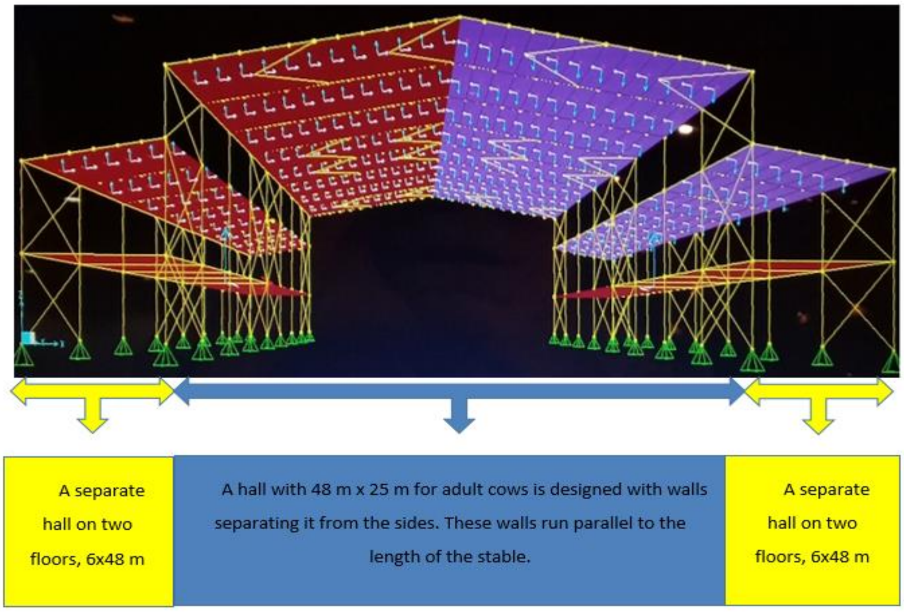


Figure 2. Semi-structural geometric parameters



A separate hall on two floors, 6x48 m

A hall with 48 m x 25 m for adult cows is designed with walls separating it from the sides. These walls run parallel to the length of the stable.

A separate hall on two floors, 6x48 m

Figure 3. The structural model simulated in SAP2000 software

On the other hand, as noted in the footnote of Fig. 3, this structure has three separate halls in total. Two smaller salons on either side of the structure. These two halls, with dimensions of 6 x 48 m, provide two separate salons from the livestock breeding hall for cattle breeders. This part of the structure is designed on two floors; the first floor is separated from the second one by a concrete roof. These two halls (located on both sides of the structure) can be used to store fodders, equipment, office spaces, and workers' accommodation. Between these two smaller salons, a larger salon has been designed as a stable in the middle of the structure to keep adult cows (between the two taller internal columns). The dimensions of this larger salon are 25 x 48 m.

4.2 Design of a taller stable structure to improve the function of the natural ventilation system

As mentioned earlier, when the height of the structure increases from 5 to 8 m, the temperature will decrease by about 4°C [20]. It has been demonstrated that, along with other requirements, to improve the function of the natural ventilation system, a high-rise structure for a stable is much better than a low-rise structure [16]. According to the above requirements, a stable structure with a height of 11.87 m has been designed and proposed to improve the natural ventilation system.

4.3 Changes in the design of openings' dimensions for more inflow of wind into the stable

To use the natural ventilation systems full capacity, it is necessary to use the appropriate dimensions for the openings in the side walls to allow airflow to enter the stable. As we saw in Section 2, the numbers mentioned in various sources for the dimensions of openings are quite different. We have inferred that the joint between the highest part of the side walls and the lower part of the sloping roof is the best place to design these air inlets in this structure with the natural ventilation system.

Thus, in the proposed structure, as it has a roof with a staircase shape, it is possible to design and install windows throughout the structure to allow more airflow to enter the stable. As shown in Fig. 2, the height of the inner columns is taller than the outer columns. These internal columns have a height of 10 meters. On top of the interior columns around 8.5 to 10 m, windows with 1.5x48m dimensions are designed to let air in. With this type of design, airflow into the stable will be facilitated, and an improved performance of the natural ventilation system is seen.

4.4 Optimal design of the stable steel structure

The steel structure with the geometrical properties given in Fig. 2 has been modeled in SAP2000 [7]. The CBO [2] & ECBO [3] algorithms have also been implemented in Matlab software. The design is optimized using the algorithms to reduce the weight of the steel structure. After reaching the final result, the weight difference of the optimized structures is shown. How stress ratio is applied to each steel member by each algorithm as well as a structure design without the use of meta-heuristic algorithms are also compared.

4.4.1 Optimization of weight and how to use stress ratio in members

In the optimization process, the number of algorithm populations is set to 30, and the Pro parameter is used to escape local optimizations by ECBO to 0.3, and memory to 4. In this structure, all beams and columns are designed with tapered member shapes [9]. The only members that do not follow this method of design are the braces. At the end of the optimization process, in the reduction of the overall steel weight of the steel structure skeleton by 7.65% with ECBO, and by 5.27% with CBO.

Table 2: Feasible range of variables bands (cm)

Variables	Dimensions of I / Wide Flange						Dimensions of Double Angel			
Outside hight	0.4	0.3	0.25	0.7	0.6	0.5	Outside depth	0.06	0.08	0.1
Flange width	0.35	0.3	0.25	0.35	0.3	0.25	Outside width	0.13	0.17	0.21
Flange thickness	0.02	0.02	0.02	0.02	0.02	0.02	Thickness	6.000E-03	8.000E-03	0.01
Web thickness	0.015	0.01	0.01	0.015	0.01	0.01	Back to back	0.01	0.01	0.01

Table 3: Optimized weight of the structure by ECBO & CBO algorithms and the initial design

Sections	HI* (kgf)	ECBO (kgf)	CBO (kgf)
Beam sections	172491.1	172448.71	172448.71
Brace sections	24721.1	18816.14	24721.1
Column sections	50698.44	37684.71	37684.71
Total weight of the Structure	247910.64	228949.57	234854.52

***HI** = Design of the Structure with **H**uman **I**ntelligence, but Without the Help of the Algorithms.

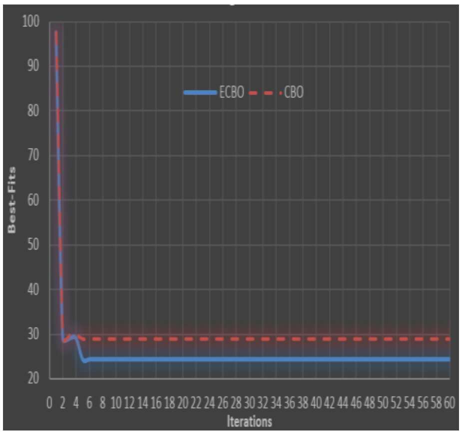


Figure 4. Convergence curves for the optimal design

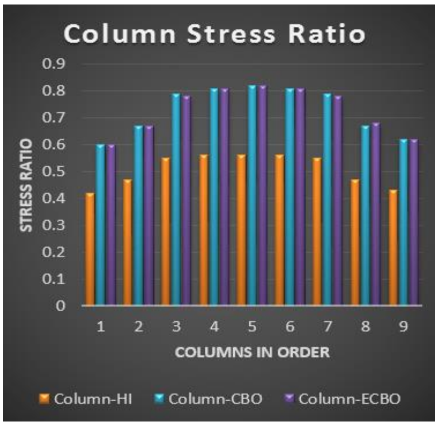


Figure 5. Comparison of stress ratios in columns

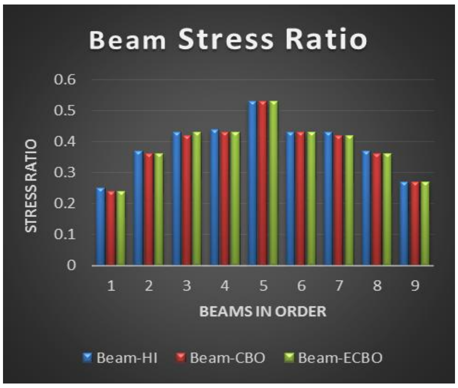


Figure 6. Comparison of stress ratios in beams

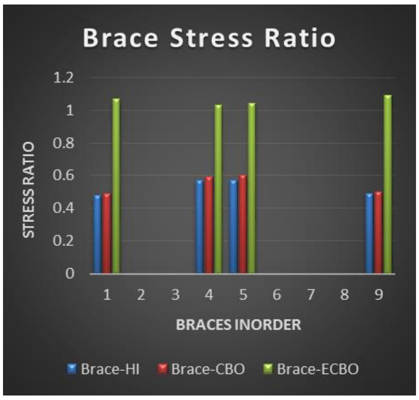


Figure 7. Comparison of stress ratios in braces

4.5 Two suggestions as to future work for the design of the stable structure with a natural ventilation system

4.5.1 A method for stable roof design

The idea behind this design method comes from R806.3 Residential Structural Design International Law of humans [21]. This type of design is used for roof insulation of residential structures. This design system can also be used to insulate the stable for adult cows with a natural ventilation system. To achieve this design, the roof deck could be designed with two membranes (two shells). This two-layer ceiling membrane extends from the lower edge of the eaves to the ridge. This insulation system works well against moisture and the effect of temperature convection between inside and outside the stable.

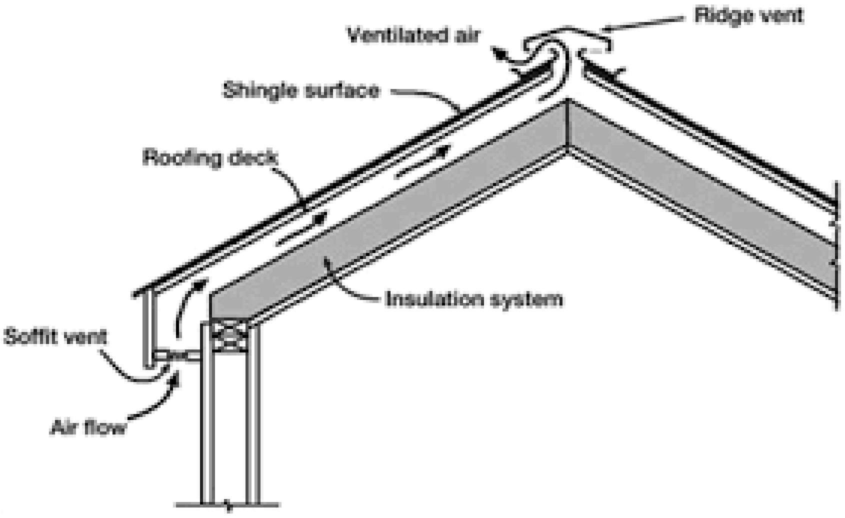


Figure 8. Double-layers roof ventilation system [24]

4.5.2 Air injector valves

The accumulation of harmful gasses and hot air near the bed of cows kept in a stall is one of the challenges for natural ventilation systems. Stall or Individual box is a space, part of a stable, where only one cow is enclosed. In the stables with individual boxes, the number of cows kept is usually equal to the number of boxes. These sections are usually separated from other parts of the stables by walls of about 1 or 2 meters high. The walls surrounding the stall cause poor ventilation of this part of the stable. Given the experience of designing residential structures for humans, extending this design to stables with natural ventilation systems seems possible and desirable. 30 to 40 cm is an appropriate distance between the valves on the side walls to the animal’s bed. These valves will inject air and, as a result, apply positive pressure to each stall. The static layers of air enclosed in the stall will then be pressured to climb and exit through the ridge (openings) on the roof.

Figure 9. Air injection valves on side walls in residential houses. It can be incorporated in the design of stables with natural ventilation systems

5. CONCLUSIONS

By consolidating civil engineering (structure), veterinary, and animal husbandry, the design of a stable steel structure, compatible with the natural ventilation system, was proposed. The design is optimized in terms of weight with meta-heuristic algorithms. As a result, achieving the objectives defined in this article, design, construction, and use as a stable will be more economical compared to what is possible alternatively.

In this paper, the performance of ECBO & CBO algorithms, used to minimize the weight of steel used in the design of a stable structural skeleton, are also investigated. based the numerical results, using the algorithms for the design resulted in the reduction of the overall steel weight of the steel structure skeleton by 7.65% with ECBO, and by 5.27% using CBO.

Furthermore, in terms of applying the maximum stress ratio in the tapered members (beams and columns), both algorithms performed well and better than the original structural designer. However, in the design of the braces, which were made of double angle sections, the results were quite different. The ECBO algorithm increased the stress ratio to the maximum at about 1. Still, the CBO algorithm and the initial structural designer cautiously cut the stress ratio at about 0.6, and both of them completed their design around this number.

Changes have also been made in the stable structure's geometric design to improve the natural ventilation system's performance, including: 1) the structural height was increased to 11.87m; 2) the dimensions of airflow inlets (openings) at the intersection of the upper part of the side walls and the lower part of the pitched roof have been increased to allow for more airflow.

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