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Evaluation of Structural Systems for Industrial Dairy Farming Facilities

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Abstract: ***This paper presents the assessment of conventional structural systems used for industrial dairy farming focusing on the cost and energy consumption. Various structural forms for industrial dairy farming were investigated considering dozen of structural models and materials. Eleven different structural systems were compared in terms of cost and energy consumption. Steel girders, steel columns, glued-laminated timber, reinforced concrete (RC) columns and steel trusses were used in this research as the structural components and materials. The SAP2000 software was used for the analysis of the modeled structures. The obtained results of the analyses demonstrated that the use of RC members or prefabricated concrete components is economically advantageous, while the use of glued-laminated timber was the least economical alternative. The highest cost was observed for a structural model fabricated with a conventional Gable steel frame and the lowest cost was observed for a structural model made of a 2-span twin mono-pitch Portal frames constructed with prefabricated RC beams and columns. However, the lowest energy consumption was observed for a structural model constructed with a single-span twin mono-pitch Portal frames constructed with RC columns and glued-laminated timber beams and the highest energy consumption was observed for the structural model fabricated with a conventional Gable steel frame, which had the highest cost.***

Keywords: ***Industrial Dairy Farming, Structural Analysis, Barn Design, Steel, Reinforced Concrete, Timber, Energy Consumption, Economy.***

I. INTRODUCTION

High investment costs may delay the rejuvenation of small-scale dairy farms [1, 2]. The designed-basic components of primary structures within a layout plan have been determined to be the dairy barn, milking shed, delivery room/infirmary, feed storage, and administrative building [3]. The functions separately undertaken by these buildings and the related plan are critical for the efficient operation of a structural system [4]. Barns that satisfy the needs of dairy cattle are important in industrial dairy farming [5, 6]. Studies have reported that interior barns are more economical than exterior ones [7]. During winter, interior barns are preferable for more efficient milk production ([8, 9]). The results of structural system analyses, which give the resultant paths of dairy barns' physical structures and functions, vary according to climatic conditions, geophysics and geological conditions, earthquakes, and management philosophy variations [10, 11]. When the aforementioned variables are kept constant, the structural systems and the materials employed in these systems become the dominant factors influencing the analysis results. Different structural system alternatives and their details result in different manufacturing costs ([12, 13]. Agricultural structures are mostly single-story structures that are produced for investment and are profit-oriented. In the livestock farming industry, facilities should be designed in order to fulfill animals' needs and optimize profit [8, 9, 10, 11]. Nowadays, industrial dairy farming facilities have become completely computer-controlled systems as a result of changing conditions such as improvements in the equipment used in the facilities, the importance of animal health, and the biological structure of raw milk ([14, 15, 16]. The yield gained from the animals is directly affected by the modernity of the facilities [1, 2, 17]. This effect on efficiency is the result of both the correct planning of the barns and the level of technology used. In industrial dairy farming facilities, in order to improve the animals' health and increase the efficiency, the physical structure, functionality, and comfort of the barns should be taken under consideration when designing the facility [18]. The majority of the aforementioned facilities are utilized for indoor feeding, while some provide the opportunity for departures at specific times of a year [19, 20, 21]. Additionally, geological and climatic characteristics are factors that should be considered in the selection of the structures and materials [5, 7, 13, 22]. Naess and Stokstad [2] investigated the effect of the arrangement of the facilities and materials used in construction costs. Their research approached cost management of the facilities from two different sides: new construction with the latest technologies and technological enhancement of an existing facility. According to the investigation, facilities with automatic milking systems had lower costs compared to facilities with traditional milking systems. The construction of a building with dimensions of 25 m × 40 m (1000 m^2) required a change in the wall height of between 3 m and 5 m, and a roof pitch change of between 20° and 30°, corresponding to 3.1% of the total cost of the facility. The research concluded that modernization is an advantage for small farms, but may result in greater costs for larger farms [2].Uzal and Uğurlu [23] conducted research on the effect of the architectural design of the barn on the behavior of the animals. In order to conduct this research, they observed the animals for 24 h and recorded their actions, the places they had been during the day, and the times that they had spent in those areas.

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The results of the research indicated that animals in the facilities spent more than 50% of the day in the yards, clearly underscoring that the choice of the construction type is important for the welfare of the animals as well as the efficiency. Particularly in metal product fabrication, a large amount of waste is generated, which causes energy consumption to increase [24]. For these reasons, the selection of appropriate materials is of great significance in terms of protecting nature.

II. METHODOLOGY

Various structural alternatives for industrial dairy facilities were studied. Such facilities are important as viewpoint of the overall cost per covered areas. In this regard, the structural systems affect the overall cost.

This study was conducted to investigate the costs of alternative systems using different structures and materials, production methods, implementation techniques, and technical characteristics, in order to propose appropriate solutions and to investigate structures that can be constructed with minimum energy consumption. Different models of structures and materials were considered and designed to find the optimum economical ones and less energy consumption used in the fabrication of materials of the structures [25]. The SAP2000 [26, 27, 28] software was applied to analyze the different structures, the Turkish structural codes TS498 [29] and TS500 [30] were employed in the design of the structures.

III. LAYOUTS OF INDUSTRIAL DAIRY FARMS

Two important criteria to be considered in a layout plan are the geographical orientation and the dominant wind direction. Planning the long side of a dairy calf barn perpendicular to the dominant wind direction is preferable because it ensures more efficient natural ventilation in the barn. Similarly, ride areas, which are usually designed to be parallel to the long sides of dairy barns. In order to design an industrial dairy farming facility, six basic structures must be included, along with their independent and interrelated functionalities. These six basic structures are the dairy barn, calf barn, milking shed, delivery room/infirmary, feed storage, and administrative building [25].

IV. LOADING, MATERIALS AND DESIGN CRITERIA

The loads were applied to the structures according to Turkish structural design code (TS 498). The following loading are applied to the structures in the design:

Roof cladding dead loads: 0.15 kPa (double insulated galvanized trapeze sheet).

Beam's self-weight load: 0.10 kPa (average beam weight).

Snow load: 0.75 kPa.

Wind load: 0.20 kPa (suction effect).

Earthquake load parameter Ao = 0.40.

Effective ground acceleration coefficient (first-degree seismic zone)

R = 4.00.

I = 1.00 (building importance coefficient)

S(T) = 2.50 (spectrum coefficient, max.).

Live load reduction coefficient for calculation of the equivalent seismic load: n = 0.30

Soil class: Z3

Soil bearing capacity: 15 t/m².

The frame span: 6 m,

The roof pitch: 25%.

HEA, NPU, and IPE steel profile are used in the structural models.

The steel type ST37 class, the timber material type GL24h class, and C25-class concrete are used.

For ST37-class steel, yield strength of steel of 240 MPa and for GL24h-class glued-laminated timber, allowable stress of 9.6 MPa are applied.

Alternative models for structural systems were analyzed including buckling calculations. In the strength calculations for the structural systems, the shear force effect was calculated separately, and it was found not to have a critical effect compared to those of the bending moment and the axial forces. The analysis was performed using SAP2000. Sectioning in the structural models using glued-laminated timber was performed according to the allowable stresses in tie and compression bars.

V. ALTERNATIVE MODELS FOR STRUCTURES

To select the structural models, the aim was to compare the economic and load analysis results obtained for different type materials and forms of structural members. Table 1 presents the types of material used for different structural models.

Table 1. Types of material used in structural models.

Model no.	Structural models' composition
1	Steel column + steel beam
2	Steel column + steel beam
3	RC column + steel beam
4	RC column + steel beam
5	RC column + Glued-laminated timber
6	RC column + Glued-laminated timber
7	Steel column + Glued-laminated timber beam
8	Steel column + Glued-laminated timber beam
9	Prefabricated RC column + Prefabricated RC beam
10	Steel column + Steel truss
11	Steel column + steel beam

2-span twin mono-pitch portal frames (TMPPFs) is selected for the structural models 1, 3, 5, 7 and 9. The scheme for these structural models is shown in Fig. 1.

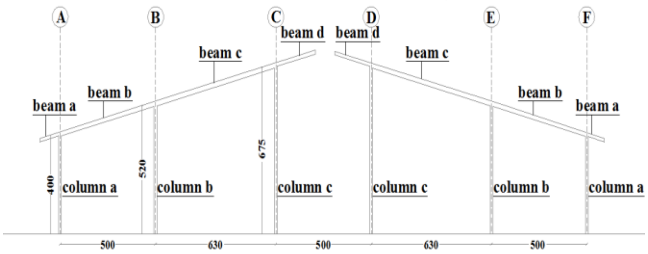

Fig. 1. View of structural models 1, 3, 5, 7 and 9 [25].

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Single-span TMPPFs is used in models 2, 4, 6 and 8 as shown in Fig. 2.

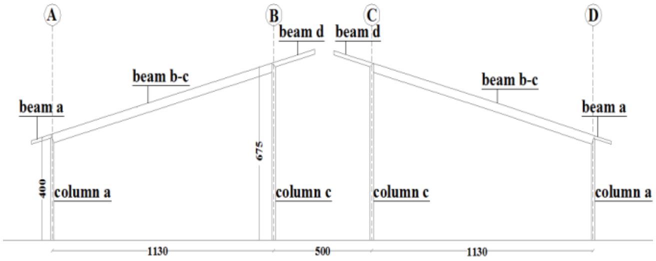

Fig. 2. View of structural models 2, 4, 6 and 8 [25].

A Gable steel frame is used for structural model 10. The truss structures are employed as beams in this model. The scheme for structural model 10 is shown in Fig. 3.

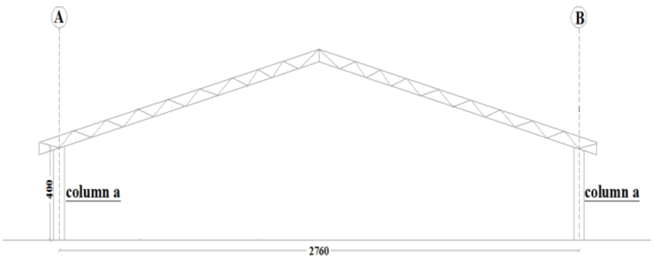

Fig. 3. View of structural model 10 [25].

A conventional Gable steel frame is used for structural model 11. The scheme for structural model 11 is shown in Fig. 4 [25].

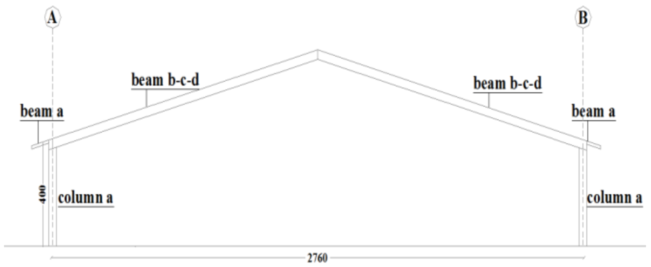

Fig. 4. View of structural model 11 [25].

VI. COMPARISON OF THE MODELS

Within the scope of this study, the structural models were formed applying different spans of 500 cm, 630 cm, and 1130 cm with different materials and the costs of these alternative structural models were compared. The structural models were analyzed by performing cost comparisons considering different combinations of materials, structural forms, and spans in the structural models. For the cost analyses, the costs of the structural member structure materials, assemblage and installation, labor, consumables, auxiliary materials, and pre-production and post-production transportation were taken into account. For each structural model, the aforementioned influencing parameters were implemented, and cost tables were generated. The structural system costs may vary during the construction process. The alteration results from variations in material procurement, material prices, production and installation rates, labor costs, transportation costs, and the like. The cost analysis part of this study is only valid for 2016 and may change due to variations in the parameters considered in this analysis. Yet, it may still be used as a guide. In particular, the cost of steel differs according to shifts in the material unit prices. In order to reduce the effect of the cost variation, Taykon Çelik's unit price analyses were used for material unit prices and labor unit costs. The costs of the structural materials with different cross-sectional dimensions were calculated. The costs of the fasteners, production, installation, and transportation were included in the cost analysis since the initial setup costs were also considered. However, the duration of construction, tax and insurance expenditures, as well as the operation and maintenance costs, were not included in this study, even though they affect the overall costs. In the cost analysis, the local transportation cost calculations were based on the Izmir region, since the implementation area was assumed to be in that region. Consequently, different materials, structural forms, and span lengths were used, and the structural models were examined based on the cost analysis.

A. Cost Analysis of Structural Models

The general assumptions and statements considered when performing the cost analyses of the structural system models were as stated below.

For all of the structural models, costs for 180 m^2 (6 m × 30 m) modules counterbalanced for covered spaces were calculated. The unit costs were determined by dividing the overall cost by 180 m^2. In order to protect the steel materials from acid-containing environments, hot-dip galvanized coating was proposed. The procurement of steel material was assumed to be from the Istanbul region. After being manufactured in Izmir, the steel was assumed to be sent to the Sakarya region for hot-dip galvanized coating and then transported back to Izmir region.

The structural models were analyzed in terms of the components' sections and the spans lengths. Additionally, in order to maintain the efficiency of the system, cost analyses were performed for each alternative. The model in which prefabricated reinforced concrete was used for the components of the structure was the lowest-cost model.

Table 2. Comparison of structural models' unit costs [25].

Model no.	Cost (Euro)	Module (m^2)	Unit Cost (Euro/m^2)
1	5,833.48	180	32.41
2	7,101.30	180	38.95
3	5,057.00	180	28.09
4	5,986.62	180	33.26
5	6,148.96	180	34.16
6	7,821.89	180	43.45
7	8,021.52	180	44.56
8	9,323.56	180	51.79
9	4,433.09	180	24.62
10	7,733.27	180	42.96
11	10,486.76	180	58.26

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The model in which glued-laminated timber material was used for all of the beam s and spans was the highest-cost model. When steel truss was used for the beams, the performance-cost efficiency increased in direct proportion to the span. Increasing the span also increased the cost when the other construction materials rather than steel were used. The results of these assessments are given in Table 2 and Fig. 5.

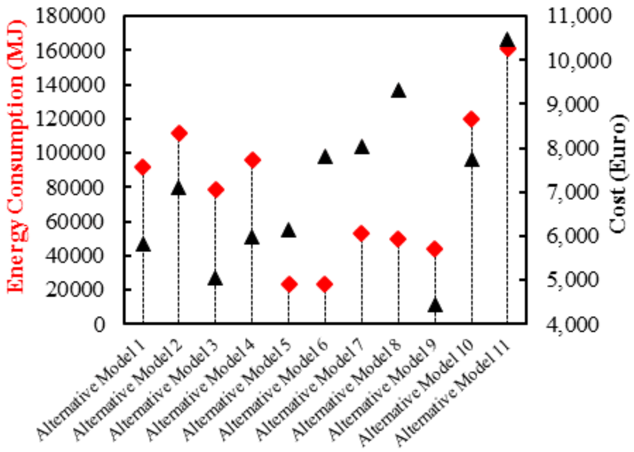

Fig. 5. Energy consumption versus cost relationship [25].

As can be seen in Fig. 5, structural model 9, in which prefabricated RC members were used for all components, is the best option in terms of construction cost. This may result from the low cost of the materials as well as the short span. Structural model 11 has the highest construction cost, which may be due to the increased span and high unit price of the steel profiles.

B. Energy Consumption

The building materials constituting the systems examined within the scope of this study were steel column and girders for structural model 1, steel columns and girders for structural model 2, RC columns and girders for structural model 3, RC columns and girders for structural model 4, RC columns and glued-laminated timber beams for structural model 5, RC columns and glued-laminated timber beams for structural model 6, steel column sand glued-laminated timber beams for structural model 7, steel columns and glued-laminated timber beams for structural model 8, prefabricated RC columns and prefabricated RC beams for structural model 9, steel columns and steel trusses for structural model 10, and steel columns and steel beams for structural model 11.

In order to produce 1 kg of steel, 0.59 kg of coal, 1.4 kg of iron, 0.05 kg of limestone, 0.14 kg of steel scrap, and 12 L of water are needed, with an energy consumption of 24.8 MJ [31, 32, 33, 34].

In order to produce 1 kg of glue-laminated wood, 1.1 kg of timber, 0.60 kg of solvent-based impregnation substance, and 0.70 kg of phenol/resorcinol glue are needed, with an energy consumption of 1.5MJ [35, 36, 37, 38].

In order to produce 1 kg of concrete, 0.16 kg of Portland cement, 0.57 kg of aggregate, 0.55 L of water, 0.1 kg of reinforcement, 0.1 kg of fuel oil, and 0.18 kg of coal are needed, with an energy consumption of 2MJ [34, 39, 40, 41, 42, 43].

In accordance with these data, a comparison of the total energy consumption of the structural models is shown in Fig. 6. To generate Fig. 6, the mass of 1 m³ of concrete was considered equal to 2350 kg, and the mass of 1 m³ of glued-laminated wood was considered equal to 1100 kg.

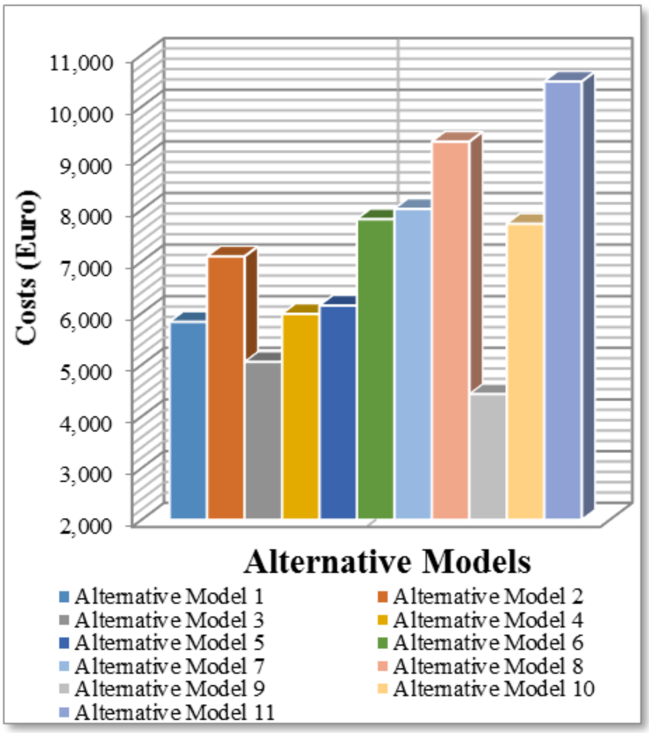

Fig. 6. Cost of structural models [25].

Fig. 6 shows that the energy consumption increases with the increasing amount of steel used in the structural models. The lowest energy consumption was calculated for structural model 6 (23374 MJ), and the highest energy consumption was calculated for structural model 11 (160704 MJ). When structural model 6 (23374 MJ), which had the lowest energy consumption, and structural model 9 (43767 MJ) were compared, it was concluded that no direct connection could be established between the costs of the structural models and their energy consumptions. This result is thought to be due to the different weights of the steel materials required to produce these systems.

VII. DISCUSSION

For structural models 1 and 2, all components were chosen to be made of steel, but with different spans. Increasing the span resulted in a 21.7% increase in the construction cost. On the other hand, different columns with identical stabilities and the use of prefabricated RC structural models 3 and 4 resulted in a 15%-16% decrease in the construction cost. Furthermore, structural models 1, 2, 3, and 4 may lead to high energy consumption. Structural models 7 and 8 used steel for the columns and glued-laminated timber material for the beams. Increasing the span resulted in an increase in the quantity of material used for the beams.

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Since the beam's material was quite expensive, the general construction cost increased by 16% when the span was increased.

On the other hand, the use of ordinary RC members instead of steel columns with identical horizontal stabilities decreased the construction cost by 27%. An increase in the clarity was determined to be an important cost-increasing factor, since it increases the quantity of the material used in the construction, especially with glued-laminated timber materials. Additionally, comparisons of models 5 and 7 and of models 6 and 8 verified this finding. Structural models 5, 6, 7, and 8 were the systems for which the lowest energy consumptions were observed.

In structural model 10, steel columns and steel beams were used, while in model 11, the steel trusses were used for the inclined roof components in the other; the construction costs differed by 35%. This result verifies that, when the span is increased, steel trusses are more economical than steel beams. However, the highest energy consumptions were observed for structural models 10 and 11, and the highest cost was observed for structural model 11.

In structural model 9, prefabricated RC members were used for all components, and this model was the most economical alternative. With the specified conditions, the material cost of the prefabricated RC components was lower than those of steel and glue-laminated timber. Structural model 9 can be produced with low energy consumption and the lowest cost. However, since increasing the span may increase the cross-sectional areas of all structural members, this model should be considered as the system with the lowest cost within the specified measures.

VIII. CONCLUSIONS

The costs of various alternative systems using different structure models and materials were investigated to find appropriate solutions for the structures that can be constructed with minimum energy consumption.

In all of the examined structural models, reducing the number of columns generated a comfortable environment in terms of usage, but a cost increase of 20%-23% occurred due to the increase in the cross-sectional areas of the structural members.

•Using RC or prefabricated members, for the columns are more economically advantageous than using steel profiles regardless of the span.

•Using steel members for the columns are economically more advantageous than using glued-laminated timber regardless of the span.

•The cost of the structural system is directly proportional to the span length of the structural members.

•The selection of steel profiles instead of RC members for the columns resulted in higher construction costs. Although the selection of steel beams with short spans instead of glued-laminated timber beams has advantages. The structural model in which prefabricated RC members were used for the structural components and the spans were short was the model with the lowest construction cost.

•Increasing the span resulted in increased construction costs. In a comparison of structural models 7 and 8, although the same construction materials were used, increasing in the span resulted in a 16% increase in the cost. The use of prefabricated RC members as the structural components with short spans resulted in the lowest-cost alternative. This may have resulted from the cost of the material is lower than that of steel, as well as the short spans.

•Structural model 11 had the highest construction cost. This is a consequence of the longer spans, which resulted in the use of more construction material.

•The use of steel beams rather than steel trusses resulted in a cost difference of 35%.

The energy consumption increased with increasing the weight of the steel used in the structural models. The lowest energy consumption was found for structural model 6 (23374 MJ), and the highest energy consumption was found for structural model 11 (160704 MJ).

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