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# ECONOMICAL COMPARISON OF STEEL-FRAMED GREENHOUSE SYSTEMS

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***Abstract***
*Since greenhouses are highly expensive structures, they need to be designed carefully with the use of modern technology of the day. Especially in the design of high-cost steel-framed greenhouses, system selection and dimensioning play an important role in economical design of load-bearing members. This study was conducted to investigate the effects of two different roof types (gothic and gable), two different truss spacings (2.5 and 3 m) and three different truss spans (6, 8 and 9.6 m) on cross-sections of load-bearing steel members, overall weight and final cost of greenhouse systems. Overall width of the systems was 48 m, length was 60 m and height was 4.5 m. Totally, 12 different greenhouse systems were designed and analyzed with the use of SAP2000 software, AutoCAD software, Excel worksheets, relevant standards and regulations. It was concluded based on present findings that gothic roof system with 3 m truss spacing and 9.6 truss span was lighter and more economical than the other systems. In terms of safety, gothic and gable roof systems with 6 m truss span and 2.5 m truss spacing were superior to other systems.*

*Keywords: Construction, Greenhouse, Quantity takeoff, SAP2000*

## 1. INTRODUCTION

When the relevant production and quality standards are not met and modern technology is not applied properly or completely, various problems are encountered in greenhouses. Such problems include load-bearing system failures, heating, ventilation and cooling problems. Significant yield and quality losses can be encountered in cultivation activities carried out in simple structures designed without taking into account the local climate conditions. Either more or less building materials are used in greenhouses built without static and strength calculations. Excessive material uses bring about extra costs and increase indoor shading ratios. On the other hand, insufficient material uses may result in structural failures and financial losses accordingly. A profitable greenhouse cultivation can only be realized with greenhouse projects that do not have technical problems, can meet appropriate environmental conditions, have a long economic life, have a completed infrastructure and with a low investment, maintenance and repair costs. Since greenhouses are highly expensive structures, they need to be designed carefully and with the modern technology of the day. Especially in design of high-cost steel-framed greenhouses, type and dimensions of the system should be so selected as to prevent structural failures and to allow economical transfer and bearing of dead and live loads.



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Besides agricultural and economic problems, greenhouse cultivation has various other engineering problems to be solved. Main problems related to greenhouse engineering include design, construction, heating ventilation and air conditioning (HVAC), lighting and automatic control of growing conditions. Research on these engineering problems may have significant contributions to development of greenhouse industry. To overcome these problems, greenhouse productions should be done according to plans and projects. In this way, proper design and dimensioning of structural members will be possible and construction costs could be reduced significantly. Greenhouse design, drawings and calculations with classical methods may take long time. Therefore, design software are commonly used in greenhouse design. In classical designs, cross-sectional analyses are not conducted and resultant members are not able bear dead and live loads, ending up structural failures. Since optimizations are not made for material uses, less durable greenhouses emerge with greater expenses.

Engineering principles should be kept at forefront in greenhouse design. Structural members should be so designed as to provide sufficient strength against the loads exerted on them and to fulfill expected functions accordingly. On the other hand, considering the desire of producers to strengthen the greenhouse construction and reduce the construction cost, effects of wind and other external environmental conditions on greenhouse construction should be determined. While increasing the safety in greenhouse design, costs increase since cross-section and dimensions of structural members are increased. Therefore, economic dimensioning is an important criteria, but it is still taken into consideration at minimum level. Selected materials and the cost of these materials should be taken into consideration. Structural members should so be dimensioned as to safely bear the loads exerted on them and prevent potential structural failures.

In this study, optimum design of steel-framed greenhouses with different roof types, truss spans and spacings was performed and effects of these parameters on construction costs were determined. Economic comparisons were made and economic load-bearing systems suitable for plant production were determined. The most economical planning models with different load-bearing systems and materials were generated with the use of computer-aided static and dynamic analyses.

## 2. MATERIAL AND METHOD

Initially, greenhouse overall dimensions were determined. Then, taking relevant standards into consideration, snow loads, wind loads, loads exerted by cover material, loads exerted by plants hanged on roof and the other loads to be bearded were determined. Analyses and designs were made for structural members. For preliminary designs, galvanized steel was preferred as the primary material, steel profile types were determined and polycarbonate was selected as the cover material.

Present greenhouse systems were analyzed and dimensioned with the use SAP2000 structural analysis software (v22.0.0/2020). The software uses finite element method in analyses. Besides this software, AutoCAD (v2020) was also used as a supplementary software (CSI, 2016).

Construction Unit Price tables of the Ministry of Environment, Urbanization and Climate Change were used for analysis and pricing of the items listed in bill of quantities (Anonymous, 2022).

In this study, design and analyses of greenhouse systems under static loads and wind loads were carried out in accordance with the relevant standards and “Regulation on design, calculation and construction of steel structures” (TS 648, 1980; TS 12741, 2001; Yüksel and Yüksel, 2012;



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Anonymous, 2018; TS EN 10025-2, 2019; TS EN 10025-5, 2019; TS EN 13031-1, 2020; TS 498, 2021; TS EN 1993-1-1, 2022; TS EN 13031-1 /AC, 2022).

### 2.1.1. Material properties and standards

Along with the standards on load-bearing steel systems; high-strength Class-S355 structural steel profiles with sufficient quality properties and quite a large range of use were used. These profiles are readily available in Turkey and widely preferred in steel structures. For Class-S355 steel, yield stress was taken as 355 N $mm^{-2}$ and fracture stress was taken as 510 N $mm^{-2}$ (TS EN 10025-2, 2019; TS EN 10025-5, 2019).
As the roof and side cover material, 8 mm polycarbonate (PC) material was selected (TS EN 13206:2017+A1, 2020).
Thin-walled square and rectangular profiles, thick-walled rectangular profiles, pipe profiles, C-profiles and fasteners were used in the building design. Galvanized steel bolts were used as fasteners and weldless and modular connections were provided. Welded nodes, which are easy and fast to produce, were preferred in truss system.
The support connection, which connects the beams, gutters and columns in one piece as the column head, is specially shaped from 4 mm thick sheet metal. Dual-roof ventilation system was used as the ventilation system. Individual footings with 60x60x80 cm dimensions were used as foundation style. These footings constructed under each column transmit the loads to the foundation ground by spreading the loads under the column or load-bearing wall. These individual footings were connected with tie-beams.

### 2.1.2. Greenhouse dimensions

From the preliminary interviews with the greenhouse construction companies and the catalog examinations, it was determined that column spacing of the greenhouse should be 2.5-3 m, beam spans should be 6, 8 or 9.6 m and column height should be 4.5 m. Therefore, these values were taken into consideration present designs. Greenhouse width was specified as 48 m and greenhouse length as 60 m. At truss spans of 6, 8 and 9.6 m, there will be 8, 6 and 5 spans, respectively. Entire ground space of all systems was set as 2880 $m^2$ with 25 axes for 2.5 m truss-span greenhouse systems and 20 axes for 3 m truss-span greenhouse systems.
Greenhouse roof systems were designed as gable and gothic roof. Ventilation openings were arranged on the roof as not to be less than 20% of the floor space. Side ventilation openings were designed as a guillotine ventilation system (Zabeltitz, 1990). Greenhouse door was designed as 4.8 x 4.8 m at 9.6 m truss span, 4 x 4 m at 8 m truss span and 3 x 3 m at 6 m truss span.

***Table 2.1. Dimensions of greenhouse systems***

| | Gothic Roof | Gable Roof |
|---|---|---|
| Greenhouse width | 48 m | 48 m |
| Greenhouse length | 60 m | 60 m |
| Greenhouse floor area | 2880 $m^2$ | 2880 $m^2$ |
| Greenhouse sidewall height | 4.5 m | 4.5 m |
| Greenhouse roof slope | 26$^o$ | 26$^o$ |
| Truss spacing | 2.5 m and 3 m | 2.5 m and 3 m |
| Span | 6 m, 8 m and 9.6 m | 6 m, 8 m and 9.6 m |

### 2.1.3. Effective loads


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External loads acting on the load-bearing systems are calculated according to the materials used and the roof characteristics and converted into uniformly distributed loads and effected on the structure. Wind load, cover load and plant load were taken as external loads in calculations. Wind speeds and other climate data were taken into consideration as design criteria in SAP2000 software. Earthquake dynamic loads were not taken into considerations since these loads do not have significant effects on greenhouses with low total weight. In this way, selection of larger members and shading effect of these larger members were prevented.
Tomatoes and cucumbers were considered to be cultivated in selected greenhouses. Thus, plant load was taken as 0.20 kN $m^{-2}$. Load of gutter and other elements was taken as 0.13 kN $m^{-2}$. Greenhouse roof and side cover is planned to be made with 8 mm thick polycarbonate sheets, thus cover load was selected as 1.5 kgf $m^{-2}$. The load exerted by ventilation equipment to be used for roof ventilation systems was taken as 0.07 kN $m^{-2}$ (Saltuk, 2005; Yüksel and Yüksel, 2012; TS EN 13206:2017+A1, 2020; TS EN 13031-1, 2020; TS 498, 2021).
*Snow load*: Snow load is a seasonal live load and depends on geographical and meteorological conditions. Potential snow loads were taken from snow load tables of Tokat province 3rd region (TS 498, 2021). Calculated snow load values were converted into linear load on purlins and gutters of greenhouse structure.
*Wind load*: Wind load is also a seasonal live load and largely depends on prevailing wind direction, building height and geometry (TS 498, 2021). Present greenhouse heights vary between 0-8 m. For buildings of 0-8 m high, wind speed was taken as 28 m $s^{-1}$ and q (wind pressure) was taken as 0.5 kN $m^{-2}$. Wind load is taken into account by combining the effects of pressure, suction and friction (TS 498, 2021). Calculated wind loads were converted into linear load on purlins, columns and gutters of greenhouse structure.

### 2.1.4. Load combinations
LRFD (Load and Resistance Factor Design) load combinations specified in 5.3.1 LRFD article of the "Regulation on design, calculation and construction principles of steel structures" published by the Ministry of Environment and Urbanization (Anonymous, 2018).

## 2.2. Method
Initially, preliminary designs were conducted for two different roof types, 3 different truss spans and two different truss spacings (12 different systems). Loadings, materials and profile types were determined. Designed systems were modeled with the use of SAP2000 software in accordance with "Regulations on calculation, design and construction principles of steel structures" (Anonymous, 2018) and the other relevant regulations and standards. Then, finite element analysis of the models was performed (CSI, 2016; Fırat, 2019).
Resultant bill of quantities was converted into cost calculations with the use of Unit Price Lists unit price lists of the Ministry of Environment, Urbanization and Climate Change (Anonymous, 2022) MS Office Excel worksheets. Results were compared again with the use of Excel software.

### 2.2.1. Preliminary design of greenhouse systems
Following the identification of loadings, material classes and profile type (TS EN 10025-2, 2019; TS EN 10025-5, 2019; TS EN 13206:2017+A1, 2020), 12 different systems (6 m, 8 m and 9.6 m truss spans and 2.5 m and 3 m truss spacing) were analyzed.


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With the use of 3D drawing feature of AutoCAD 2020 software, greenhouse layouts, axis definitions and system models were made.
With the use of SAP2000 software, structural modeling phases were arranged as; material definition, cross-section definitions of structural members, importing the modeled structure in AutoCAD software, section assignments of the transferred elements, definition of load types and formation of load combinations.

*Table 2.2. Profiles used in greenhouse systems*

| Structural members | 6 m span | | | |
|---|---|---|---|---|
| | 2.5 m spacing | | 3 m spacing | |
| | Gothic roof | Gable roof | Gothic roof | Gable roof |
| **Footing** | RHS 150x100x3.2 mm | RHS 150x100x3.2 mm | RHS 180x100x3.2 mm | RHS 180x100x3.2 mm |
| **Truss** | CHS 76.1x2 mm | CHS 76.1x2 mm | CHS 76.1x2 mm | CHS 76.1x2 mm |
| **Diagonal** | CHS 33.7x2 mm | CHS 33.7x2 mm | CHS 33.7x2 mm | CHS 33.7x2 mm |
| **Transverse** | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 60.3x2 mm |
| **Purlin** | C80 | C80 | C100 | C100 |
| **Head purlin** | C80 | C80 | C80 | C80 |
| | **8 m span** | | | |
| **Footing** | RHS 150x100x3.2 mm | RHS 180x100x3.2 mm | RHS 180x100x3.2 mm | RHS 180x100x3.2 mm |
| **Truss** | CHS 88.9x2 mm | CHS 88.9x2 mm | CHS 101.6x2 mm | CHS 88.9x2.5 mm |
| **Diagonal** | CHS 33.7x2 mm | CHS 33.7x2 mm | CHS 33.7x2 mm | 3 CHS 3.7x2 mm |
| **Transverse** | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 60.3x2 mm |
| **Purlin** | C100 | C100 | C120 | C120 |
| **Head purlin** | C80 | C80 | C80 | C80 |
| | **9.6 m span** | | | |
| **Footing** | RHS 180x100x3.2 mm | RHS 180x100x3.2 mm | RHS 180x100x3.2 mm | RHS 200x100x4 mm |
| **Truss** | CHS 88.9x2 mm | CHS 101.6x2 mm | CHS 101.6x2 mm | CHS 101.6x2 mm |
| **Diagonal** | CHS 48.3x2.5 mm | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 60.3x2 mm |
| **Transverse** | CHS 60.3x2 mm | CHS 60.3x2 mm | CHS 76.1x2 mm | CHS 60.3x2 mm |
| **Purlin** | C100 | C100 | C120 | C120 |
| **Head purlin** | C80 | C80 | C80 | C80 |

### 2.2.2. Static analysis of greenhouse systems with SAP2000 software

Following the identification of member cross-sections and loadings of system models, static analysis was conducted in accordance with the LRFD method.
Since the "Regulation on the Design, Calculation and Construction of Steel Structures" (Anonymous, 2018) is not included in regulations and standards defined in SAP2000 software, analyses were carried out using the AISC 360-10 (2010) standard, which also includes that regulation.
The factor to be taken into consideration while performing the stress control is that all the elements in the lower and upper headings must be of the same cross-section due to the ease of application and constructive reasons, although it is not a requirement specified in the regulations. For this reason, the end forces in the lower and upper head elements are examined one by one, and stress control is made according to the load that occurs only in the most unfavorable loading situation. Stress control according to the steel quality (S355) and profile section (U profile, L profile or Box profile) selected before the analysis is done automatically by the system (Yakut, 2007).
As a result of static analysis, the SAP2000 software calculates the most unfavorable stress states that may occur in the elements in the most unfavorable condition and the stresses that the elements


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can carry, according to the LRFD method, of the elements with two different roof types and different truss spans and spacings. The highest capacity utilization rates that will occur in the load-bearing members are given in Table 2.3.

***Table 2.3. Maximum capacity use ratios at the worst-case scenario (%)***

| Structural members | 6 m span | | | |
|---|---|---|---|---|
| | 2.5 m spacing | | 3 m spacing | |
| | **Gothic roof** | **Gable roof** | **Gothic roof** | **Gable roof** |
| **Column** | 52.35 | 51.61 | 50.86 | 50.14 |
| **Truss** | 24.21 | 21.40 | 31.44 | 41.92 |
| **Diagonal** | 24.21 | 21.40 | 31.44 | 41.92 |
| **Transverse** | 24.21 | 21.40 | 50.86 | 50.14 |
| **Purlin** | 75.77 | 69.08 | 94.47 | 90.30 |
| **Head purlin** | 24.21 | 21.40 | 50.86 | 50.14 |
| **Gutter** | 24.21 | 21.12 | 24.59 | 26.34 |
| | **8 m span** | | | |
| **Column** | 86.26 | 81.60 | 57.04 | 78.23 |
| **Truss** | 40.53 | 49.54 | 44.21 | 57.59 |
| **Diagonal** | 40.53 | 49.54 | 44.21 | 57.59 |
| **Transverse** | 61.66 | 56.57 | 57.04 | 60.60 |
| **Purlin** | 86.26 | 81.60 | 81.96 | 78.23 |
| **Head purlin** | 86.26 | 81.60 | 57.04 | 78.23 |
| **Gutter** | 23.68 | 26.17 | 30.76 | 32.68 |
| | **9.6 m span** | | | |
| **Column** | 57.39 | 93.66 | 57.77 | 90.26 |
| **Truss** | 53.07 | 54.29 | 18.39 | 45.40 |
| **Diagonal** | 53.07 | 72.39 | 18.39 | 45.40 |
| **Transverse** | 53.07 | 93.66 | 30.61 | 72.84 |
| **Purlin** | 98.41 | 93.66 | 93.48 | 90.26 |
| **Head purlin** | 57.39 | 93.66 | 57.77 | 90.26 |
| **Gutter** | 25.42 | 30.33 | 18.39 | 37.29 |

### 2.2.3. Bill of quantities and cost analyses

Following the analyses of greenhouse systems with SAP2000 software, resultant tables were transferred to MS Office Excel format. By making arrangements of the results transferred to the Excel software, bill of quantities were determined for greenhouse systems (Table 2.4, Table 2.5).
The unit prices to be used in calculating the costs of greenhouse constructions were taken from 15.165.1001 and 15.165.1002-numbered items of 2022/3 Construction and Installation Unit Prices Book. Unit price analyses are provided in Table 2.6 and Table 2.7.

***Table 2.4. Bill of quantities for gothic roof style (kg)***

| | 2.5 m truss spacing | | | 3 m truss spacing | | |
|---|---|---|---|---|---|---|
| | Truss span | | | | | |
| **Structural members** | **6 m** | **8 m** | **9.6 m** | **6 m** | **8 m** | **9.6 m** |
| Column | 14.923 | 13.871 | 11.009 | 14.534 | 11.194 | 9.525 |
| Truss upper and lower headings | 9.324 | 10.935 | 10.921 | 7.832 | 10.528 | 10.515 |
| Transverses | 953 | 979 | 782 | 972 | 998 | 1.018 |
| Diagonal | 2.834 | 2.834 | 5.074 | 2.380 | 2.380 | 4.341 |
| Gutter | 7.625 | 5.931 | 5.083 | 7.625 | 5.931 | 5.083 |
| Purlin | 5.694 | 4.694 | 3.912 | 6.259 | 5.754 | 4.795 |


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| | | | | | | |
|---|---|---|---|---|---|---|
| Side purlin | 683 | 617 | 655 | 655 | 588 | 626 |
| **TOTAL** | **42.035** | **39.860** | **37.437** | **40.257** | **37.373** | **35.903** |

***Table 2.5. Bill of quantities for gable roof style (kg)***

| | **2.5 m truss spacing** | | | **3 m truss spacing** | | |
|---|---|---|---|---|---|---|
| | **Truss span** | | | | | |
| **Structural members** | **6 m** | **8 m** | **9.6 m** | **6 m** | **8 m** | **9.6 m** |
| Column | 14.923 | 12.926 | 11.009 | 14.534 | 11.194 | 12.706 |
| Truss upper and lower headings | 9.194 | 10.782 | 12.358 | 7.723 | 11.256 | 10.381 |
| Transverses | 953 | 979 | 782 | 972 | 998 | 801 |
| Diagonal | 2.328 | 2.328 | 4.281 | 1.955 | 1.955 | 3.596 |
| Gutter | 7.625 | 5.931 | 5.083 | 7.625 | 5.931 | 5.083 |
| Purlin | 5.694 | 4.694 | 3.912 | 6.259 | 5.754 | 4.795 |
| Side purlin | 683 | 617 | 655 | 655 | 588 | 626 |
| **TOTAL** | **41.400** | **38.257** | **38.080** | **39.723** | **37.677** | **37.989** |

***Table 2.6. 15.165.1001-numbered unit price analysis***

| Pose No | **Analysis** | | | | **Unit** |
|---|---|---|---|---|---|
| **15.165.1001** | **Preparation and installation of every kind of steel sections in a single or combined fashion (rafters, one-way slabs, continuous beams, simple roof purlins and rafters, lintels, corner support metals, columns, girders and etc manufactures)** | | | | **(Tons)** |
| Pose No | Definition | Unit | Quantity | Unit Price | Amount (TL) |
| | **Material:** | | | | |
| 10.130.1708 | Steel sections (with attritions) | Kg | 1020 | 13.80 | 14 076.00 |
| 10.200.1708 | Plain black sheet (5% for welded, bolted and riveted connections) | Kg | 51 | 13.80 | 703.80 |
| | **Labor:** | | | | |
| 19.100.1089 | Steel manufacture workshop | Hours | 7 | 891.37 | 6 239.59 |
| 19.100.1113 | Mobile crane | Hours | 2 | 382.79 | 765.58 |
| 10.100.1019 | Cold steel worker | Hours | 2 | 45.00 | 90.00 |
| 10.100.1062 | Regular worker (loading, unloading, horizontal and vertical transport at job site) | Hours | 2 | 32.50 | 65.00 |
| | Material + workmanship | | | | 21 939.97 |
| | 23% contractor profit and general expenses | | | | 5 484.99 |
| | **Cost of 1 Ton** | | | | **27 424.96** |


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***Table 2.7. 15.165.1002-numbered unit price analysis***

| Pose No | Analysis | | | | Unit |
|---|---|---|---|---|---|
| **15.165.1002** | **Truss manufacture from steel sections and installation** | | | | **Ton** |
| Pose No | Definition | Unit | Quantity | Unit Price | Amount (TL) |
| | **Material:** | | | | |
| 10.130.1708 | Steel sections (with attritions) | Kg | 1020 | 13.80 | 14 076.00 |
| 10.130.1708 | Steel sections (5% for welded, bolted and riveted connections) | Kg | 51 | 13.80 | 703.80 |
| | **Labor:** | | | | |
| 19.100.1089 | Steel manufacture workshop | Hours | 8 | 891.37 | 7 130.96 |
| 19.100.1113 | Mobile crane | Hours | 2.5 | 382.79 | 956.98 |
| 10.100.1018 | Hot iron worker | Hours | 2 | 45.00 | 90.00 |
| 10.100.1062 | Regular worker (loading, unloading, horizontal and vertical transport at job site) | Hours | 2 | 32.50 | 65.00 |
| | Material + workmanship | | | | 23.022,74 |
| | 23% contractor profit and general expenses | | | | 5 755.69 |
| | **Cost of 1 Ton** | | | | **28 778.43** |

## 3. RESULTS AND DISCUSSION

For 2.5 m truss spacing of gothic roof, total system weight was identified as 42 035 kg at 6 m truss span, 39 860 kg at 8 m truss span and 37 437 kg at 9.6 m truss span. For 3 m truss spacing of gothic roof, these weights were respectively identified as 40 257 kg, 37 373 kg and 35 903 kg. For 2.5 m truss spacing of gable roof, system weight was identified as 41 400 kg at 6 m truss span, 38 257 kg at 8 m truss span and 38 080 kg at 9.6 m truss span. For 3 m truss spacing of gable roof, these weights were respectively identified as 39 723 kg, 37 677 kg and 37 989 kg. Steel weights per unit area of greenhouse systems are given in Figure 3.1.

Average weight was calculated as 38 811 kg for gothic roofs and 38 854 kg for gable roofs. The difference between the average weights of different roof styles was not found to be significant (Figure 3.2) since cross-sections of steel sections selected to be within lateral displacement limits specified in TS EN 13031-1 (2020) were larger than the designs made according to the "Regulation on Design, Calculation and Construction of Steel Structures" (Anonymous, 2018).


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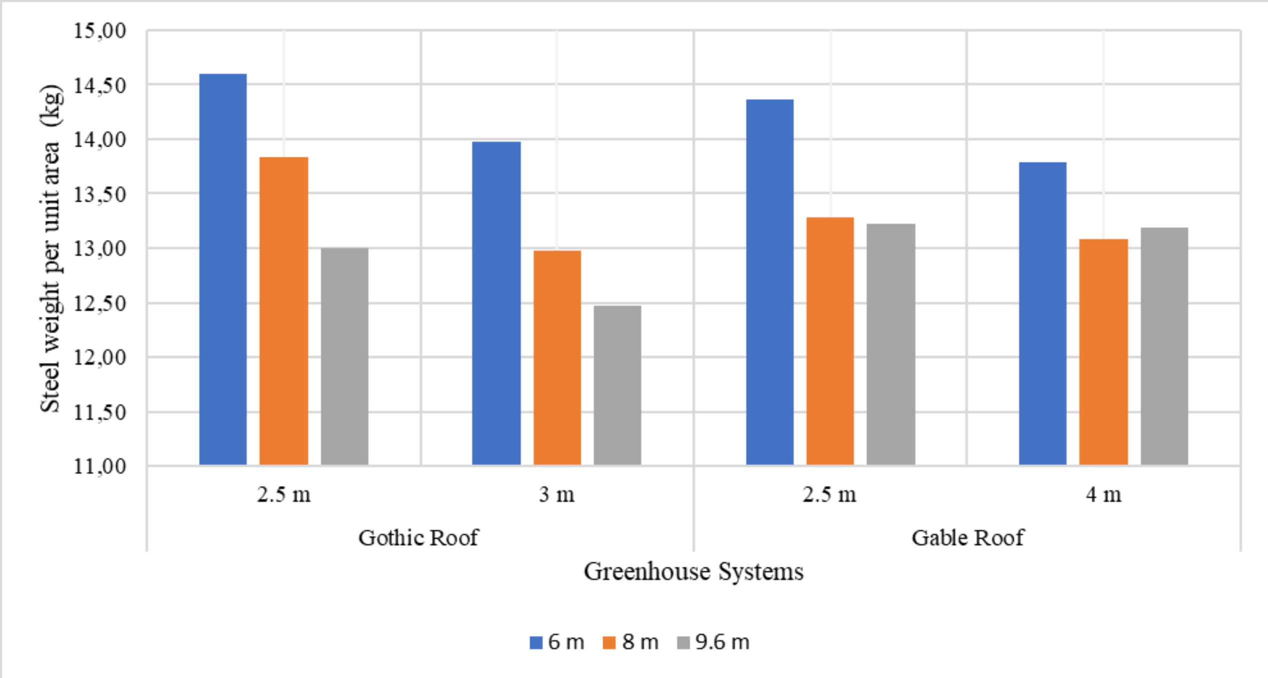


***Figure 3.1. Steel weight per unit area (kg)***

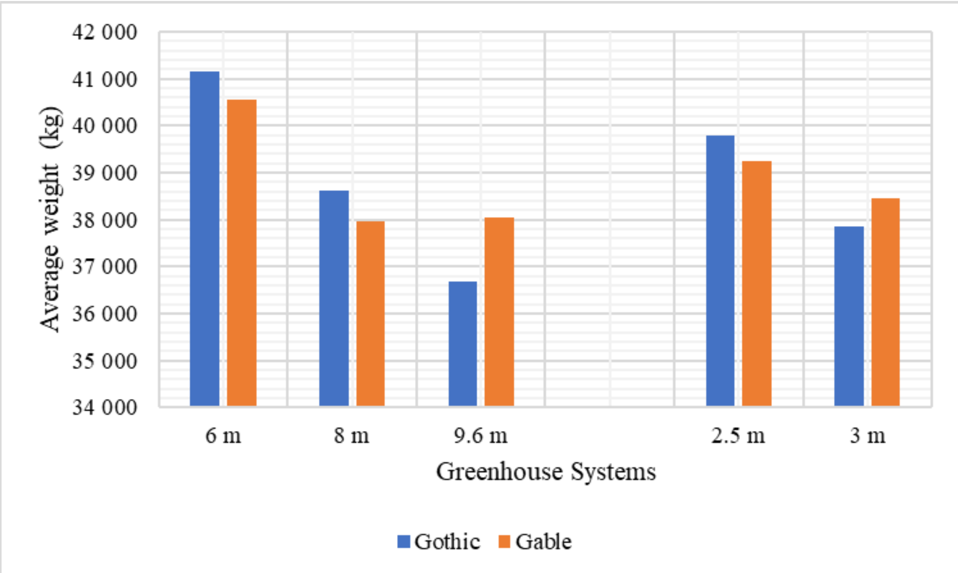


***Figure 3.2. Average weight of greenhouse systems***

Overall average weight was calculated as 40 854 kg for 6 m truss span, 38 292 kg for 8 m truss span and 37 352 kg for 9.6 m truss span (Figure 3.2). Average weight of 9.6 m truss span was 9.3% lighter than 6 m truss span and 2.52% lighter than 8 m truss span. Although there was an increase in the cross-sections of the profiles when the truss spans increased, greenhouse weights decreased since there was a decrease in the amount of material to be used.

System average weight was calculated as 39 512 kg for 2.5 m truss spacing and 38 154 kg for 3 m truss spacing. Average weight of 2.5 m truss spacing was 3.56% lighter than 3 m truss spacing.


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Profile cross-sections increased with increasing truss spacing, but average weight decreased since the amount of material used decreased. Then, a decrease in costs was observed again.
To see the change in the results if different steel sections are used in greenhouse load-bearing members, in gothic roof system with 8 m truss span and 2.5 m truss spacing, SAP 2000 was used for analysis of the system with column sections of IPE160, truss sections of 2L70x6/0/, diagonals of 2L50x5/0/ and purlins of UPN80. Overall weight of the greenhouse system was calculated as 85 773 kg and it was 115.19% heavier than the system with the same span, spacing and roof type. In terms of greenhouse safety and bearing capacity, the displacement perpendicular to the gutter was 41.85 mm, the displacement parallel to the gutter was 45.16 mm and the highest capacity utilization ratio of the load-bearing members in the worst-case scenario was 98.83% for trusses and 77.91% for columns. It was seen that present steel sections were more advantageous in terms of both weight and bearing capacity.
Bill of quantities and cost analyses of steel greenhouse systems are provided in Table 3.1, Table 3.2 and Table 3.3. For total cost calculations, unit prices of 27 424,96 ₺ ton$^{-1}$ (Table 2.6) and 28 778.43 ₺ ton$^{-1}$ (Table 2.7) were used. Among 6 m span systems, gable roof system with 3 m truss spacing was identified as the most economical system ( 1 110 971.80 ₺). Among 8 m span systems, gothic roof system with 3 m truss spacing was identified as the most economical system (1 050 209.74 ₺). Among 9.6 m span systems, gothic roof system with 3 m truss spacing was identified as the most economical system (1 011 221.07 ₺).

***Table 3.1. Bill of quantities and cost analysis for 6 m truss span***

| | | | | | |
|---|---|---|---|---|---|
| **Gothic roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 24.18 | 663 244.96 |
| | 15.165.1002 | Ton | 28 778.43 | 17.85 | 513 736.13 |
| | | **TOTAL** | | **42.04** | **1 176 981.09** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424 96 | 23.79 | 652.321.60 |
| | 15.165.1002 | Ton | 28 778 43 | 16.47 | 474.018.73 |
| | | **TOTAL** | | **40.26** | **1 126 340.33** |
| **Gable roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 24.18 | 663 244.96 |
| | 15.165.1002 | Ton | 28 778.43 | 17.22 | 495 440.24 |
| | | **TOTAL** | | **41.40** | **1 158 685.20** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 23.79 | 652 321.32 |
| | 15.165.1002 | Ton | 28 778.43 | 15.94 | 458 650.47 |
| | | **TOTAL** | | **39.72** | **1 110 971.80** |

***Table 3.2. Bill of quantities and cost analysis for 8 m truss span***


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| | Pose No | Unit | Unit price (₺) | Quantity | Cost (₺) |
|---|---|---|---|---|---|
| **Gothic roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 21.40 | 586 829.97 |
| | 15.165.1002 | Ton | 28 778.43 | 18.46 | 531 321.19 |
| | | **TOTAL** | | **39.86** | **1 118 151.16** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 18.71 | 513 160.49 |
| | 15.165.1002 | Ton | 28 778.43 | 18.66 | 537 049.25 |
| | | **TOTAL** | | **37.37** | **1 050 209.74** |
| **Gable roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 20.45 | 560 916.40 |
| | 15.165.1002 | Ton | 28 778.43 | 17.80 | 512 379.51 |
| | | **TOTAL** | | **38.26** | **1 073 295.91** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 18.71 | 513 160.49 |
| | 15.165.1002 | Ton | 28 778.43 | 18.97 | 545 795.01 |
| | | **TOTAL** | | **37.68** | **1 058 955.51** |

***Table 3.3. Bill of quantities and cost analysis for 9.6 m truss span***

| | Pose No | Unit | Unit price (₺) | Quantity | Cost (₺) |
|---|---|---|---|---|---|
| **Gothic roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 17.53 | 480 742.55 |
| | 15.165.1002 | Ton | 28 778.43 | 19.91 | 572 901.70 |
| | | **TOTAL** | | **37.44** | **1 053 644.25** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 16.25 | 445 726.36 |
| | 15.165.1002 | Ton | 28 778.43 | 19.65 | 565 494.71 |
| | | **TOTAL** | | **35.90** | **1 011 221.07** |
| **Gable roof** | **2.5 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27.424.96 | 17.53 | 480 742.55 |
| | 15.165.1002 | Ton | 28.778.43 | 20.55 | 591 428.10 |
| | | **TOTAL** | | **38.08** | **1 072 170.65** |
| | **3 m truss spacing** | | | | |
| | **Pose No** | **Unit** | **Unit price (₺)** | **Quantity** | **Cost (₺)** |
| | 15.165.1001 | Ton | 27 424.96 | 19.22 | 527 032.59 |
| | 15.165.1002 | Ton | 28 778.43 | 18.77 | 540 223.51 |
| | | **TOTAL** | | **37.99** | **1 067 256.09** |

Present cost analyses revealed that average cost of greenhouse systems with 9.6 m truss span was 2.3% more economical than the average cost of systems with 8 m truss span and 8.8% more economical than the average cost of systems with 6 m truss span. The average of cost of the systems with a truss spacing of 3 m, on the other hand, was 3.5% more economical than the average of cost of the systems with 2.5 m truss spacing. In terms of overall costs of gothic and gable roof systems, there was no significant difference between them. Average costs of greenhouse systems are given in Table 3.4.


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*Table 3.4. Average costs of greenhouse systems*

| System | Average cost (₺) |
|---|---|
| 6 m truss span | 1 143 245 |
| 8 m truss span | 1 075 153 |
| 9.6 m truss span | 1 051 073 |
| 2.5 m truss spacing | 1 108 821 |
| 3 m truss spacing | 1 070 826 |
| Gothic roof | 1 089 425 |
| Gable roof | 1 090 223 |

While the average cost of systems with 2.5 m truss spacing was 1 108.821 ₺, it is 1 070 826 ₺ for systems with 3 m truss spacing. Systems with a truss spacing of 2.5 m were more economical than the systems with a truss spacing of 3 m (Table 3.4). There was no significant difference between the costs of gothic and gable roof systems.

Among the gothic roof systems, the lowest unit area cost was calculated as 351.12 ₺ $m^{-2}$ for 9.6 m truss span, 364.66 ₺ $m^{-2}$ for 8 m truss span and 391.09 ₺ $m^{-2}$ for 6 m truss span. Likewise, the lowest cost per unit area of the gable roof systems were calculated as 370.58 ₺ $m^{-2}$, 367.69 ₺ $m^{-2}$ and 385.75 ₺ $m^{-2}$ for systems with 9.6 m, 8 m and 6 m truss spans, respectively (Figure 3.3).

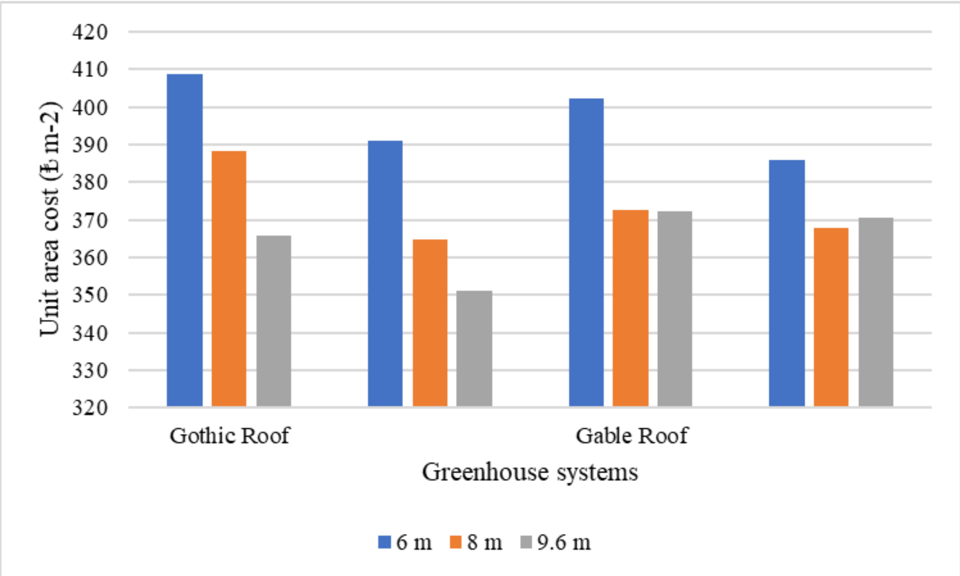


***Figure 3.3. Unit area costs***

Truss span and truss spacing not only affect the weight of greenhouse systems, but also affect the bearing capacity. Cross-sections of steel sections increased linearly with increasing truss spacing and spans. Since the amount of material used decreased with increasing truss spacing and spans, bill of quantities also decreased. With the increase in truss span and spacing, there was a decrease in overall weights, thus a decrease in costs. Capacity utilization rates of the steels used in load-bearing systems also increased with increasing truss spacing and spans. This increase in capacity utilization rate shows that load-bearing member is exposed to more stress, but it also shows that the systems with small truss spacing and spans were stronger in terms of bearing capacity.


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## 4. CONCLUSION AND RECOMMENDATIONS

It was concluded based on present findings that gothic roof system with 3 m truss spacing and 9.6 truss span was lighter and more economical than the other systems. In terms of safety, gothic and gable roof systems with 6 m truss span and 2.5 m truss spacing were superior to other systems.

Present findings clearly elucidated the effects of truss spacing, truss span and roof styles on cross-sections of load-bearing steel members, overall weight and final cost of greenhouse systems. In this study, cost comparisons were made only for steel-framed greenhouses. Further research is recommended to include wood and aluminum-framed greenhouse systems. Likewise, effects of different greenhouse heights and truss styles on final cost of greenhouse systems can also be studied.

## 5. ACKNOWLEDGEMENTS

This study presents partial results of a Graduate Thesis

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