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REVIEW PAPER

Review of Structural and Functional Characteristics of Greenhouses in European Union Countries, Part II: Typical Designs

B. von Elsner[1]; D. Briassoulis[2]; D. Waaijenberg[3]; A. Mistriotis[2]; Chr. von Zabeltitz[1]; J. Gratraud[4]; G. Russo[5]; R. Suay-Cortes[6]

[1]Institute of Horticultural and Agricultural Engineering, University of Hannover, Herrenhaeuser Str. 2, D-30419 Hannover, Germany; e-mail corresponding author: elsner@itg.uni-hannover.de
[2]Department of Agricultural Engineering, Agricultural University of Athens, 75 Iera Odos Street, 11855 Athens, Greece; e-mail: briassou@auadec.aua.ariadne-t.gr
[3]IMAG-DLO, P.O. Box 43, 6700 AA Wageningen, The Netherlands; e-mail: d.waaijenberg@imag.dlo.nl
[4]CEMAGREF, 361, Av. JF. Breton, P.O. Box 5095, 34033 Montpellier, France; e-mail: jean.gratraud@cemagref.fr
[5]Institute of Agricultural Buildings, University of Bari, Via Amendola 165/A, 70126 Bari, Italy; e-mail: scarasci@agr.uniba.it
[6]Bio-equipment Engineering Dept, ENSAM University, Placa Viala, 34060 Montpellier, France; e-mail: suay@ensam.inra.fr

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The most characteristic greenhouse designs used in six European Union countries contributing to this work are presented in detail. Their advantages and disadvantages are critically described in relationship to the data presented in the first part of this work. In this way the origin of the various greenhouse designs is clarified and the influence of climate, availability of construction materials, tradition, and local regulations is analysed. The outcome of this work may be utilized to improve the various greenhouse designs dominating the European market.

1. Introduction

Cultivation in greenhouses has steadily expanded throughout Europe during the recent decade. This kind of production has been proved to be a highly competitive and profitable sector of agriculture in most of the European countries. In the first part of this publication (Von Elsner *et al.*, 2000), the local conditions influencing the greenhouse design were investigated. The causes giving rise to the large variety of greenhouse types existing in Europe, built with different covering materials and designed to fit the local climate, were presented.

In the present work, the most representative greenhouse types in six European countries (participating in the relevant research project) are presented in detail. This systematic presentation allows the evaluation of the influence of various factors, such as the climate, the local building regulations, the cultivated crops and the availability of building materials, on the greenhouse design.

Climate is a major factor influencing both the structural and the functional characteristics of greenhouses. The design of a greenhouse aims at exploiting the external climatic conditions for improving the indoor microclimate. For this reason, the overall greenhouse design is strongly influenced by the climate and the latitude of the location. Moreover, various load requirements for greenhouses depend on the climatic conditions. This is reflected in the national and international standards for greenhouse construction.

It is obvious that there is no straightforward solution for designing a greenhouse. Improvements are continuous and originate from both experience and scientific research. All major types of greenhouses have important functional and structural advantages and disadvantages. The choice of a greenhouse type by the grower depends on local technical, legal and economic conditions. In many cases, local tradition and considerations of compatibility with existing greenhouses play an important role in the decision making. In particular, local economic considerations as well as the open European and international market strongly influence the popularity of certain greenhouse types.

The mechanical behaviour and the radiometric and physical properties are important factors taken into account in the selection of the covering materials. In fact, the large variety of covering materials make the selection of the cover a very complex technical problem while the optimal design of the ventilating openings remains a mostly unresolved problem. Glass has been the traditional greenhouse covering material in Northern Europe. Nevertheless, the use of flexible covering materials which allows designs with improved structural and functional characteristics such as higher light transmittance, *etc*., has increased. Tunnel greenhouses and multispan greenhouses with arch-shape roof are the most representative types built with plastic films.

Most of the available greenhouse designs in Europe follow the corresponding national standards and codes of practice. A draft European standard for commercial production greenhouses prEN13031-1 (prEN 13031-1, 1997), currently under development, represents a first attempt for standardizing the greenhouse design methodology at an European level.

In Section 3, detailed descriptions of the structural and functional characteristics of the most representative greenhouse types currently used in six European Union countries are given. This thorough overview provides a clear picture of the present state-of-the-art greenhouse technology in the most important horticultural countries in Europe.

2. Greenhouse structures

2.1. *The most important greenhouse types*

2.1.1. *Glass and rigid plastic greenhouses*

Glass has been the traditional greenhouse covering material in Northern Europe where greenhouses were extensively used before the appearance of plastic covering materials. It has important advantages, such as

(1) very low degradation due to environmental causes and agrochemicals;
(2) low thermal radiation transmittance ('greenhouse' effect); and
(3) high visible radiation transmittance (light).

Glass or rigid plastic covered greenhouses are characterized by long lifetime and are usually well-equipped systems.

Greenhouses covered with glass or rigid plastic sheets are categorized into wide-span greenhouses, and Venlo-type greenhouses, named after the Dutch town Venlo, where they first appeared. This distinction is based on the roof design. The Venlo-type greenhouse has only one glass pane placed in glazing bars between gutter and ridge. On the contrary, the wide-span greenhouse has more than one glass pane on the roof between gutter and ridge.

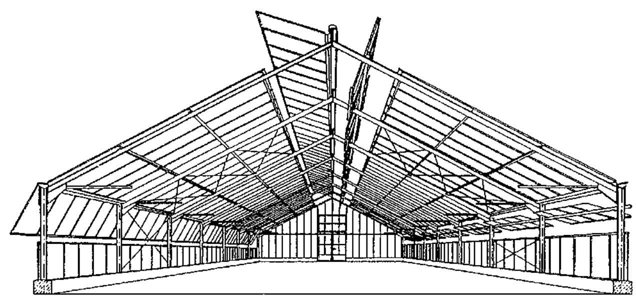

Fig. 1. Wide-span glasshouse with roof and sidewall ventilation

Both types are constructed with a metallic (steel or aluminium) frame. The most typical covering material is glass (Briassoulis *et al*., 1997a, 1997b).

Figure 1 shows a wide-span greenhouse. These greenhouse types can be built as single span or multispan structures, where neighbouring spans are connected along the gutter. The span width varies between 6 and 15 m. They are equipped with continuous ventilators at the ridge and, if needed, at the sidewalls.

Figure 2 shows a Venlo-type construction with a standard roof width of 3·2 or 4 m. The roof is supported by columns, placed under each gutter, or one under every second or third gutter. In the second case, the gutter(s) between the columns is (are) supported by a trellis girder. More information about typical designs of Venlo-type greenhouses is given in Section 3.5.1.

Both types have important advantages and disadvantages.

(1) Venlo-type greenhouses are standardized to a large degree. As a result, their construction and maintenance is easier and cheaper. A large variety of equipment is available for Venlo-type greenhouses, while the design-related physical processes influencing the indoor climate has been extensively studied.

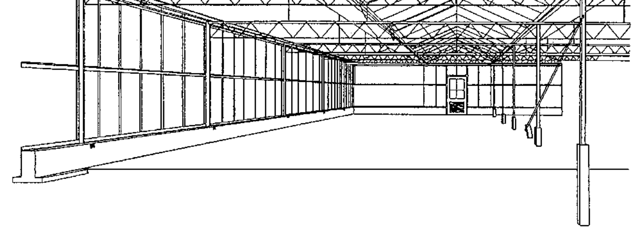

Fig. 2. Venlo-type glass-covered greenhouse with trellis girders

(2) Wide-span greenhouses offer larger indoor volume and better ventilation capacity.

Attempts have been made to replace glass with rigid plastic sheets, such as polymethyl methacrylate (PMMA), polycarbonate (PC), and polyvinyl chloride (PVC), that exhibit higher insulating performance. However, these materials are still too expensive. For this reason and due to the reduction in light transmittance (when used as a double-layer sheet), they are rarely used so far (Briassoulis *et al.*, 1997a, and 1997b).

2.1.2. *Low plastic tunnels*

Low tunnels and walk-in tunnels could be called miniature greenhouses. Their typical dimensions are shown in *Fig. 3*. Many types of tunnels, consisting of a semi-cylindrical supporting framework covered with plastic film, have been developed. The supporting framework can be made of curved wood, bamboo or steel. The arches are secured into the ground at a spacing of 2–3 m. The plastic film is stretched over the arches and buried into the ground along the sides. In addition to the supporting arch, a string or wire retains the film in place. The film can be lifted between the supporting arch and the retaining wire on both sides for ventilation.

Low tunnels are normally built only for one cropping period and taken down for tillage. They are used for protecting plants against low temperature, wind, rain and hail, birds and insects. They are normally unheated.

The main advantages of low tunnels are their low cost and the simple construction. On the other hand, they provide small heating capability, allow poorly controlled ventilation and make plant husbandry difficult.

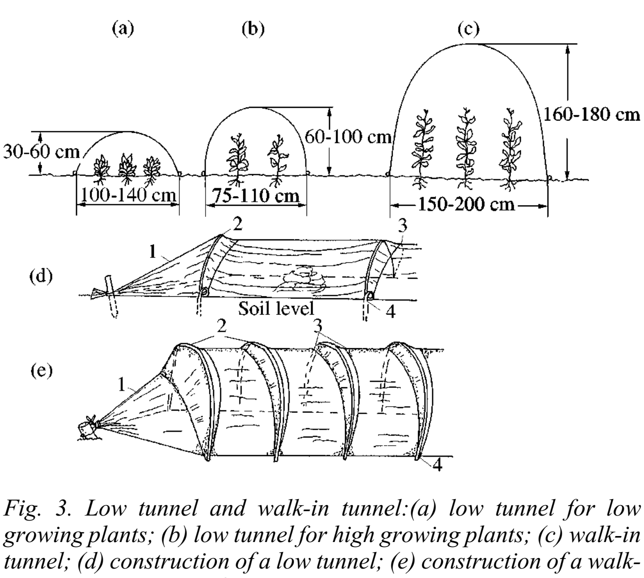

Fig. 3. Low tunnel and walk-in tunnel:(a) low tunnel for low growing plants; (b) low tunnel for high growing plants; (c) walk-in tunnel; (d) construction of a low tunnel; (e) construction of a walk-in tunnel; (1), plastic film; (2), support hoops; (3), retaining cord or wire; (4), soil anchor

2.1.3. *Plastic film greenhouses*

In many countries, especially in those with a warm climate, plastic film covered greenhouses are extensively used. The first plastic film covered greenhouses were developed as plastic covers installed over simple wooden frames, which also were used to support the culture. Even though plastic film greenhouses passed through several stages of development and important improvements have been introduced, they still remain cheaper than glasshouses. Moreover, if their design follows certain specifications, they provide important advantages with respect to their functionality.

However, several of the existing plastic film greenhouse designs have also disadvantages. Among them

(1) in most cases, too much work is required for installing and replacing the film;
(2) the film stability deteriorates due to ageing caused by solar radiation and friction against the structure;
(3) poorly fitted films flutter against the structure, weakening the resistance of the cover to storms;
(4) inadequate condensation behaviour of the film combined with horizontal flat segments of the roof can cause falling of drops condensed on the film; and
(5) the ventilation is inadequate in multispan greenhouses.

A large variety of plastic film greenhouses have been developed worldwide. They range from simple structures of wood with nailed-on plastic film and round-arched tunnels to complex constructions. A few characteristic types are described below (Von Zabeltitz, 1990).

2.1.3.1. *Tunnel greenhouses*. The simplest form of plastic film greenhouse is the single-span tunnel greenhouse. *Figure 4* shows the dimensions of two typical tunnels made of galvanized steel tubes. Here, the width of the tunnels is 9 m as an example, the height 3·25 m and

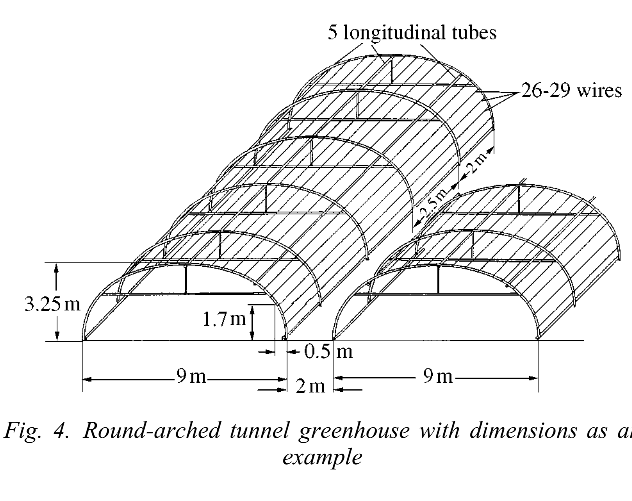

Fig. 4. Round-arched tunnel greenhouse with dimensions as an example

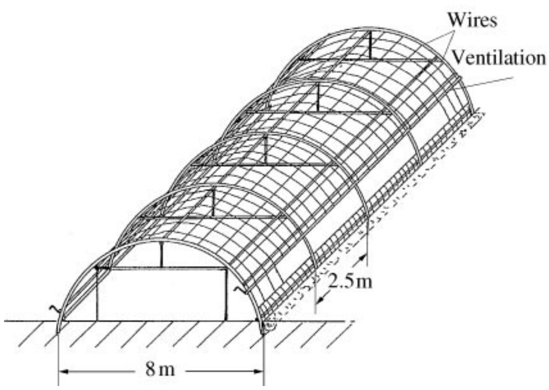

Fig. 5. Round-arched tunnel greenhouse with continuous sidewall ventilation

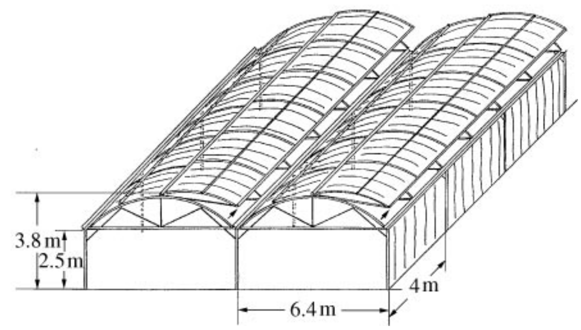

Fig. 7. Plastic film construction with continuous roof ventilation

the length 40–60 m. The space between the arches next to the gables is 2 m (because of higher wind loads), while the intermediate arches have distances of 2·5 m from each other. Steel tubes and wires are used to stabilize the structure in the longitudinal direction. However, using wires in plastic film greenhouses is a disadvantage, since the film area in contact with the wires can be damaged by friction (Briassoulis *et al.*, 1997a, 1997b). A space of 2 m is recommended between two tunnels. The most important advantage of the single-span tunnels is the relatively simple construction system and its good wind resistance. On the other hand, tunnel greenhouses have some functional disadvantages (Von Zabeltitz, 1990; Feuilloley *et al.*, 1995). The ventilation is insufficient when the 'sheet parting' mechanism is used (see *Fig. 15*). However, a roll-up ventilation system in the sidewalls can improve the ventilation efficiency (*Fig. 5*) (Feuilloley *et al.*, 1995).

2.1.3.2. *Plastic pitched roof greenhouses.* Different types of pitched roof greenhouses with plastic film cover are built around the world (*Fig. 6*). The columns are made of wood, steel or concrete. In many cases, they are simple structures. The roof frame is made of wood. The plastic film often is nailed onto wooden laths, which makes the replacement of the film difficult and reduces the film durability (Briassoulis *et al.*, 1997a, 1997b).

2.1.3.3. *Arch-shaped roof greenhouses.* The frame of arch-shaped roof greenhouses is made of steel tubes. The shape of the roof is either a round arch (*Fig. 7*) or a Gothic arch shape roof (*Fig. 8*). Gothic arch structures have advantages over round arches because condensation water can flow off better on the inner side of the film. Therefore, fewer water drops fall onto the plants. Gothic arches also reduce the snow load because snow can slide easier down the roof to the ground or the gutter. However, the mechanical resistance of the Gothic arch is lower than that of the normal arch due to curvature discontinuity.

Roof and/or side openings provide ventilation. Plastic film structures have been developed, where one-half of the roof can open (*Fig. 7*). Greenhouses with ventilators along the ridge can also be equipped with rolling ventilators at the sidewalls (*Fig. 9*).

2.1.3.4. *Inflated, double plastic film, greenhouses.* Recently, a new type of plastic film greenhouses with higher

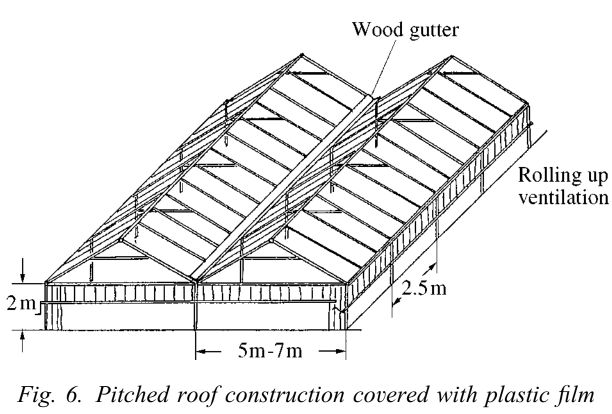

Fig. 6. Pitched roof construction covered with plastic film

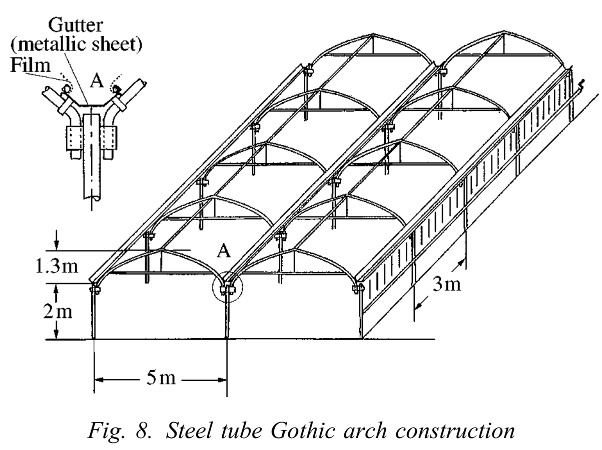

Fig. 8. Steel tube Gothic arch construction

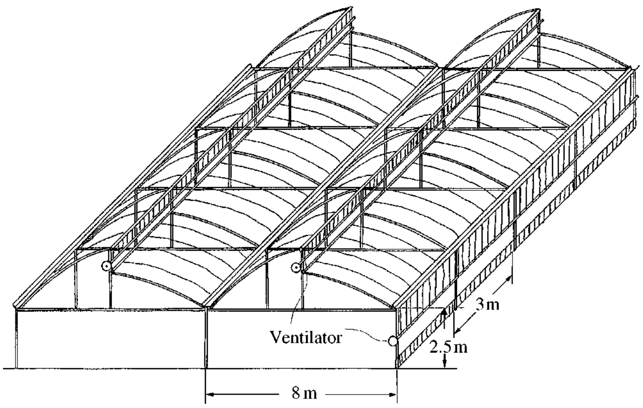

Fig. 9. Plastic covered greenhouse with ridge and sidewall ventilation

insulation performance has been developed for use under cold climatic conditions. The cover of these greenhouses consists of two layers of plastic film tightly fixed together along the frame elements of the walls and the roof. The space between the films is inflated at a pressure of 40–60 Pa. In this way, the insulating performance and the resistance of the structure to wind or snow loads is enhanced.

2.2. *Materials for greenhouse construction*

Greenhouses are preferably constructed from cheap and easily available materials. Wood, bamboo and steel are usually suitable for the construction of plastic film greenhouses. The frame of glass and rigid plastic greenhouses is usually made of aluminium or steel. Foundations are usually constructed of concrete. All these materials have advantages and disadvantages. For example, wood can swell and shrink due to humidity. Encouraged by humidity, fungi and insects can infest the wood, causing rotting and decay. Therefore, wood has to be protected for longer usage. In addition, it has to be protected from termites.

The choice of the construction material depends on the local prices for timber and steel. For the time being, wood construction is cheaper in many countries. Wood used in greenhouse frames is (or should be) protected by impregnation with protective substances, namely synthetic or natural resins or chemicals, such as zinc chloride, copper sulphate or borax. Toxic substances should be avoided whenever possible. Steel has to be protected from corrosion. Nowadays, steel is usually galvanized with zinc, but zinc drained into the irrigation water may cause important environmental pollution problems. Aluminium does not need anticorrosive protection.

2.3. *Ventilators in greenhouses*

2.3.1. *Venlo-type greenhouses*

The Venlo-type greenhouse was designed so that it can easily be built with standard glass panes (*Fig. 2*). The ventilators are not continuous. The windows usually consist of two or three half-glass panes or, more rarely, of one whole glass pane. They are placed at both sides of the roof near the ridge (*Fig. 10*) and can open at a maximum angle of 44°. For operating the windows a 'swing mechanism' (*Fig. 10*) or a 'truss rail mechanism' (*Fig. 11*) is used (Waaijenberg, 1995). The latter has the advantage of being situated above the trellis (truss) girder so that it does not increase the total shadow due to extra frame elements.

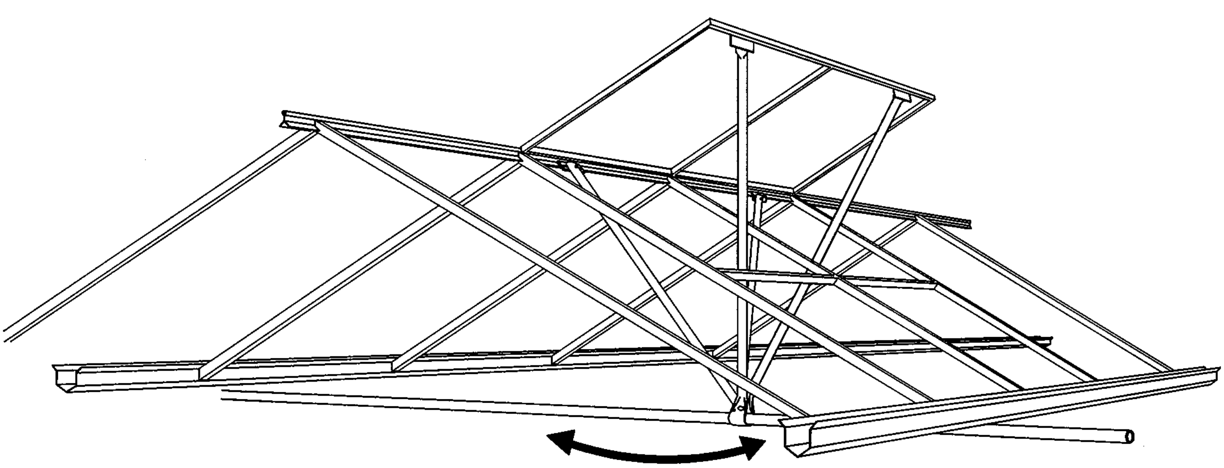

Fig. 10. 'Swinging mechanism' for the operation of ventilation windows in a Venlo-type greenhouse

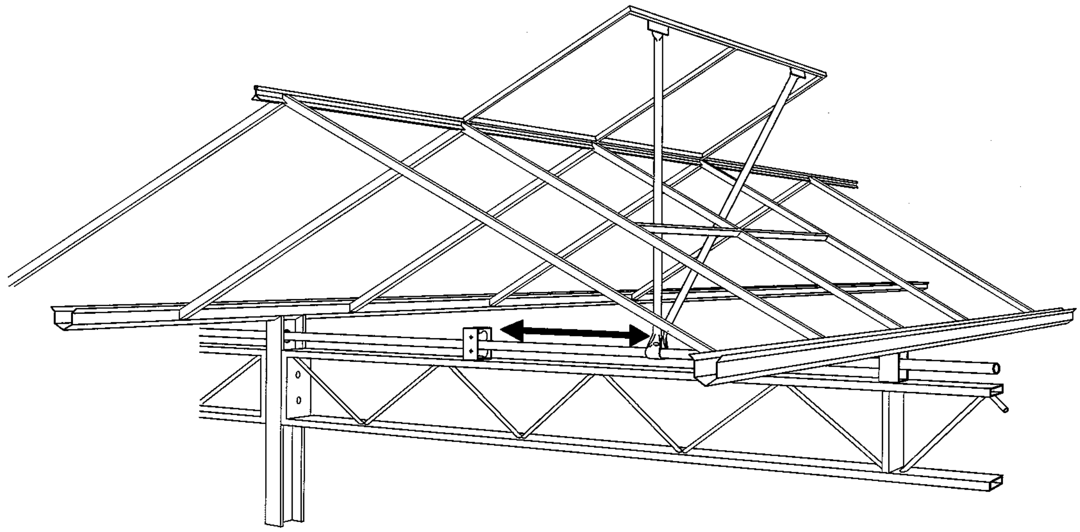

Fig. 11. 'Truss rail mechanism' for operation of ventilation windows in a Venlo-type greenhouse on top of the trellis girders

2.3.2. *Wide-span greenhouses*

Wide-span glasshouses used to be the most common greenhouse type in Northern Europe before the introduction of the Venlo type.

Their ventilators are continuous windows extending along the longitudinal axis of the greenhouse. The roof openings usually are placed near the ridge (*Fig. 1*), or more rarely near the gutter. Also, continuous side ventilators exist along the sidewalls of these greenhouses. Generally, wide-span plastic greenhouses are not standardized as a product (*e.g.* shape and dimensions are not standardized). Therefore, each designer makes his own variations for the size and the location of the ventilators. The maximum opening ratio varies depending on the climate in which the greenhouse operates and the cultivation for which it is used.

The operating mechanism for the windows depends on the covering material in use. A typical operating mechanism for the roof ventilators consists of a turning shaft with gears translating toothed rods on a rack and pinion principle (*Fig. 12*). Similar operating mechanisms are used for the side ventilators.

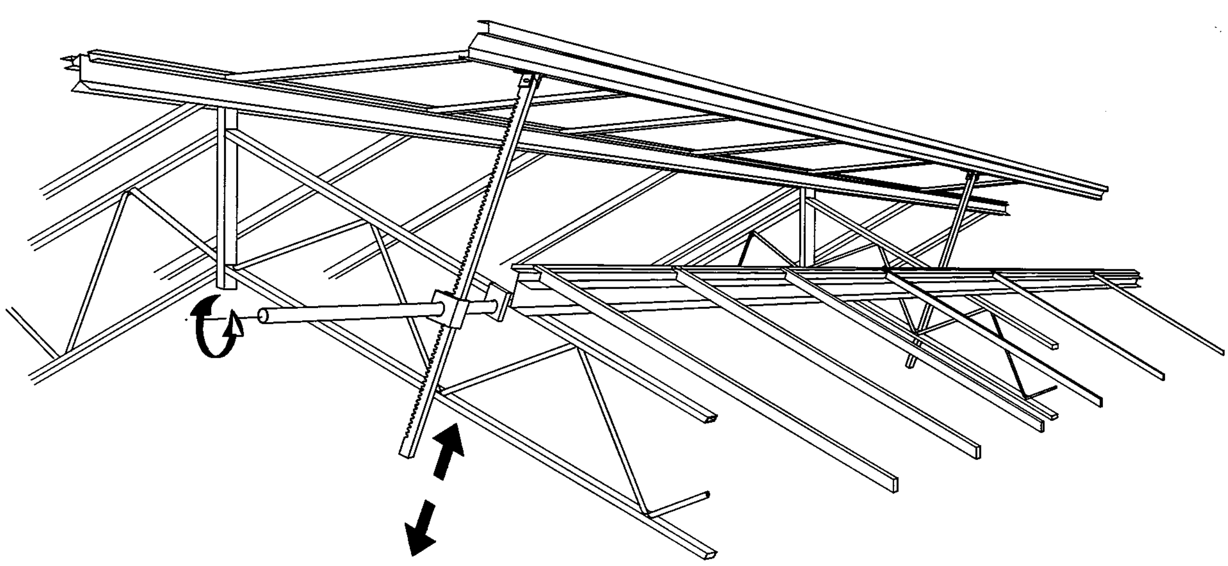

Fig. 12. Typical operation mechanism for continuous ventilators using a rack and pinion device to convert rotary into linear movement

2.3.3. *Multispan plastic greenhouses with arch-shaped roof*

These are semi-rigid plastic or plastic film covered greenhouses with metallic frames. This type of greenhouse is widely used in Southern European countries. For this reason, it is usually equipped with large ventilators.

The usual roof ventilators consist of continuous longitudinal segments of the roof moving outwards. In some designs, half of the roof can pivot around the ridge (*Fig. 7*). In other cases, the roof ventilators are placed just above the gutter. These design variations are the result of structural considerations, while the functionality with respect to ventilation is more or less the same. However, maintaining large opening ratios is desirable even though not necessary, for obtaining high ventilation efficiency. Similar large opening ratios can be obtained in film-covered greenhouses by rolling or folding the roof cover (Waaijenberg, 1995).

The side ventilators usually are gaps in the sidewalls created by rolling up or down the plastic film (*Fig. 13*). Special care is taken in designing the rolling mechanism so that the film remains properly stretched during operation in order to avoid tearing by flapping. Moreover the operation mechanism should close the ventilators tightly when it is needed.

2.3.4. *Tunnel greenhouses*

These are plastic film covered structures with metallic frames. The ventilators are usually continuous side openings operated by a rolling mechanism (*Fig. 5*). However, more rarely, windows opening outwards are used. In a few recent designs, inflated plastic tubes control the ventilation through the side openings.

In addition, opening the greenhouse doors at the gables usually enhances ventilation. In a few designs, a 'swing half-moon' ventilator is added at the upper part of the gable (*Fig. 14*).

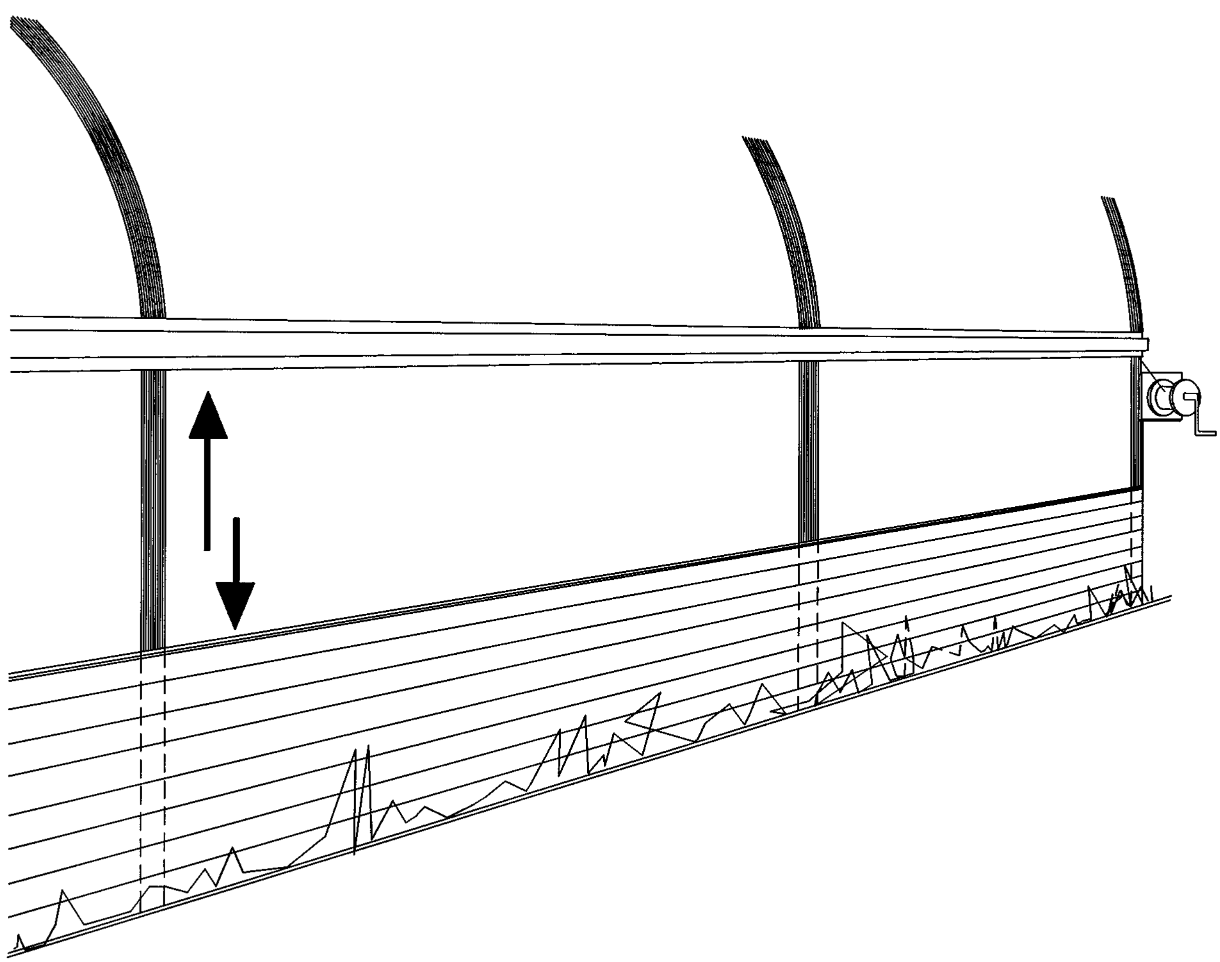

Fig. 13. Rolling-down side ventilator in an arch-type greenhouse

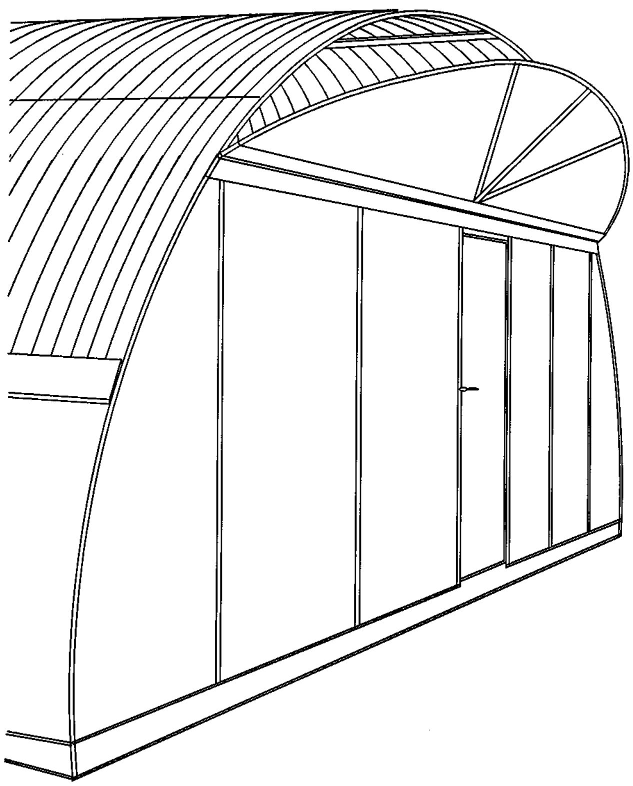

Fig. 14. 'Swinging half-moon' ventilator in the front gable of a tunnel greenhouse

In the case of simple tunnels where the film is not attached to the frame, but stretched over it, ventilators exist only at the gables. However, it is possible to have side ventilators also in this type of greenhouses by using the 'sheet parting technique' (*Fig. 15*).

2.3.5. *Plastic pitched roof greenhouses*

These are usually simple wooden structures covered with plastic film. They are poorly equipped, so they generally lack mechanically operated ventilators. Nevertheless, the main design characteristics of the ventilators are similar to those of the commercial greenhouse types described above.

Hand-made greenhouses are usually wide-span structures with one or two spans. The side ventilators are more common since they are easier to construct and operate. Plastic films, which are manually rolled or folded like curtains, close these side ventilators.

Roof ventilators are generally avoided since they weaken the roof cover. However, the sheet parting technique can be used for creating temporary ventilators.

When the greenhouses are operated in hot countries, parts of the cover are permanently removed during the summer for increasing the ventilation.

3. Analysis of the structures with respect to the design requirements and the adjustment to local influences

3.1. *Greenhouse cultivation in France*

Of the total greenhouse area of approximately 10 000 ha, two-thirds is used for vegetables and one-third for ornamentals (flowers, potplants) (Briassoulis *et al.*, 1997a, 1997b). The area covered by plastic greenhouses is mostly concentrated in the south of France.

The standardization of greenhouses in France has been stimulated by insurance companies, which are interested in avoiding extensive damage. All insured greenhouses must be designed in accordance with the corresponding standards. Compliance of the industrially produced greenhouses with the standards is certified by specialized agencies supervised by the government, and is enforced through the loaning services of banks which finance only insured greenhouse structures.

3.1.1. *Most common greenhouse types in France*

3.1.1.1. *Glass greenhouses.* More than 95% of the glasshouses are covered with single glass panes (drawn sheet and tempered glass). Glasshouses for vegetables are mostly of the Venlo type, while glasshouses for flower production are usually wide-span structures with pitched roof, 9·6 or 12·6 m wide.

3.1.1.2. *Plastic multispan greenhouses.* Multispan plastic covered greenhouses in France usually have arch-shaped roofs. Before 1990, the span width of plastic multispan greenhouses was 6·4 m. Recently, the span width increased to 8 or 9·6 m. The height from gutter to ground varies between 3 and 4 m. Roofs are mostly covered by plastic film (more than 95%), and more rarely (5%) by semi-rigid plastic sheets. The walls are usually covered by semi-rigid plastics (PVC mainly, and Glass Reinforced Polyester). During recent years, the use of plastic multispan arch-shape roof greenhouses (*Figs 7 and 8*) expanded and they gradually replace the older tunnel greenhouses.

3.1.1.3. *Tunnel greenhouses covered by plastic film.* Most of the tunnel greenhouses are covered by polyethylene (PE) film 120–200 μm thickness with a life expectancy of 2–3 yr. In France, the tunnel greenhouses can be categorized into two characteristic types.

Small tunnels of 4–5 *m width.* The arches are made of steel pipes. They are fixed into the ground with metallic anchors (usually of the screw type). The film is placed lengthways and fixed on the arches with strings. Rolling up the film along the greenhouse sides ventilates the tunnel. It is possible to connect frames of such tunnels and form multispan structures.

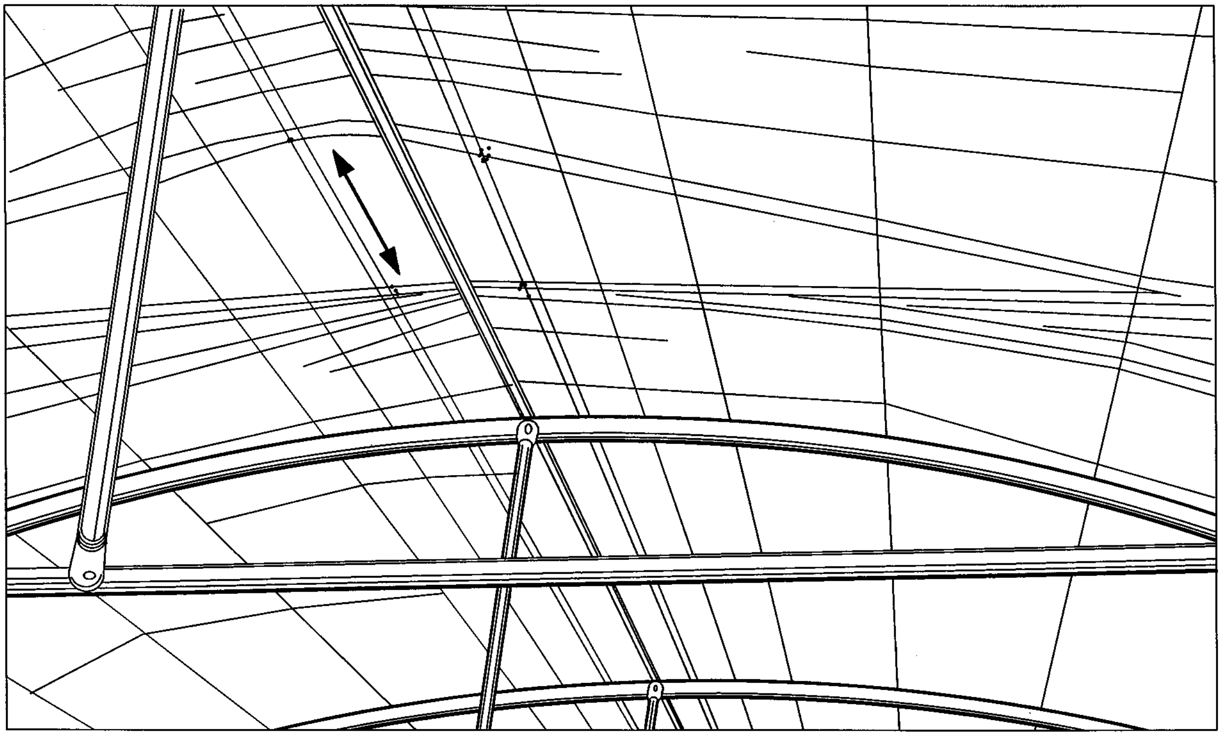

Fig. 15. 'Sheet parting technique' ventilator

Large tunnels of 7–10 m width. The most common width of large tunnels is 8 m. The arches are made of steel tubes. The film is placed transversely onto the frame and fixed to the ground by burying its edges into the soil. The tunnel is usually ventilated by a 'sheet parting' mechanism (*Fig. 15*).

Recently, a new tunnel type with columns appeared in the market. The important advantage of this structure is that it allows several arches to join together and form a multi-tunnel (or multispan) greenhouse (*Fig. 16*). Foundations are necessary for this greenhouse type. Ventilation is obtained either by rolling up the film at the sidewalls or through ventilation windows in the roof.

3.2. *Greenhouse cultivation in Germany*

Greenhouse cultivation expands all over Germany. More than 80% of the greenhouses in Germany are glass-covered greenhouses. During the last decade Venlo-type glasshouses became more and more popular amongst the German growers as a result of the relatively high prizes of the wide-span glasshouses. Plastic film greenhouses are mainly used for unheated production of vegetables, summer flowers, shrubs and tree nurseries.

3.2.1. *The German standard greenhouse*

The Glasshouse Manufacturer Association, the Growers Association, research institutes and planning authorities stimulated the development of a standardised greenhouse design.

The product standard DIN 11536 'Greenhouse in steel construction, galvanized, 12 m nominal width' (DIN 11536, 1974) was first created in 1971 and specifies the following characteristics (Von Zabeltitz, 1986):

(a) length (3·065 m) of a unit element, which is the distance between two consecutive lines of columns, the width of a 6, 9, 12 or 15 m greenhouse (only the 12 m type is standardized) being a multiple of this unit length;
(b) vertical sidewalls 2·3 or 2·8 m high;
(c) pitch slope with a ratio of 1:2 (26·5°) to guarantee proper slippage of snow, an efficient indoor climate control with efficient ventilation, high light transmittance and enough space for the installation of shading systems or other equipment;
(d) dimensions of the glass panes 0·60 × 1·74 m, this size being easier to handle during repair works than the 2 m pane;
(e) the gutters at both sides of the greenhouse forming structural elements and allowing for the expansion of the greenhouse to a multispan block;

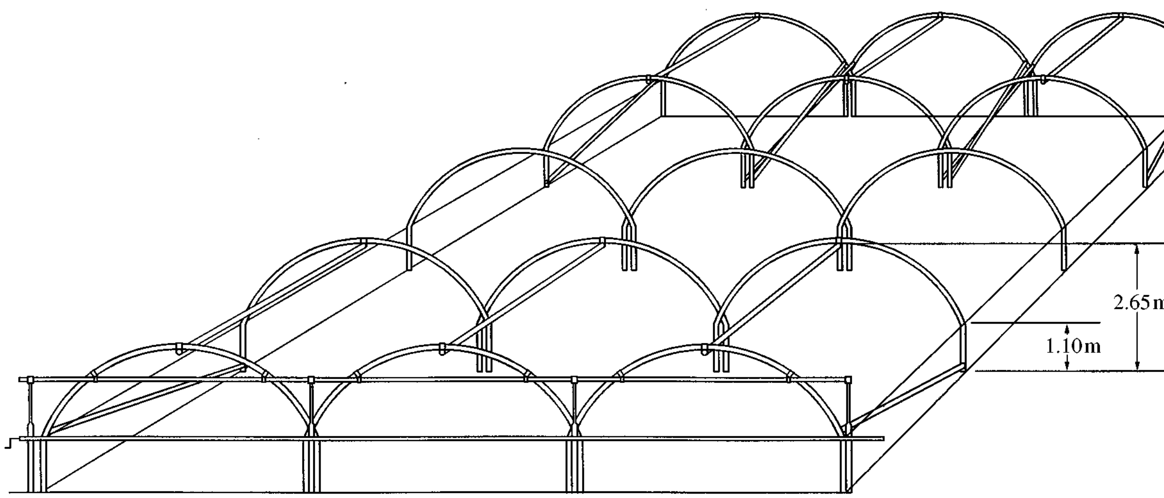

Fig. 16. Multitunnel film-covered greenhouse in France

(f) the ventilation opening at the ridge with a width of 1·74 m and opening up to 15° over the horizontal plane; and
(g) the design being certified, without the need for an additional recalculation by a structural engineer.

This standard had been revised and extended in 1994 to a new code: DIN 11535-2 'Greenhouses; steel and aluminium construction 12·8 m in width with a longitudinal grid dimension of 3·065 m' (DIN 11535-2, 1994). The main advances in technology were incorporated. It includes two types of greenhouses with 24 and 26·5° pitch angle of the roof and takes into account the possibility of using aluminium as the frame material. The solar radiation transmittance of the greenhouse cover should exceed 93% for a period of 10 yrs.

Nevertheless, many German growers favour the Venlo-type glasshouses, because they are lighter and cheaper.

3.3. *Greenhouse cultivation in Greece*

The first greenhouses in Greece appeared in 1955–1956. However, the rapid expansion of the covered agricultural area began after 1961, following the introduction of the plastic films as a covering material. Today, greenhouse cultivation is one of the most significant and dynamically developing sectors of the Greek agriculture. According to the statistics of the Ministry of Agriculture and the Agricultural Bank of Greece, between 1967 and 1994 the area of greenhouses increased from 269 to 4200 ha (Von Elsner *et al.*, 2000).

Greenhouse types in Greece can be generally classified as

(a) 'commercially built' greenhouses (*i.e.* greenhouses designed and constructed in accordance with specifications set by the industries following national or international standards); and
(b) 'grower-built' greenhouses (*i.e.* greenhouses made by the farmers themselves; usually the design and construction of these structures is empirical).

The most common structural materials used for greenhouses are wood, steel and aluminium. All these materials are used separately or in combinations. Steel is the dominant structural material in the category of the commercially built greenhouses, whereas wood is preferred as a construction material for the grower-built greenhouses. The covering materials for the "commercially built" greenhouses are glass or plastic whereas the covering material for the grower-built greenhouses is almost exclusively plastic film. In general, PE film is the predominant covering material for all categories (Briassoulis *et al.*, 1997a, 1997b; Tsirogiannis, 1996).

The area of plastic film greenhouses increases continuously, while the area of glasshouses remains almost stable. The majority of greenhouses (60% in 1994) have no heating equipment, whereas only a small percentage of them (13% in 1994) have a heating system sufficiently satisfying their needs.

Most of the greenhouses made in Greece are used for the cultivation of vegetables (92%). The majority of the greenhouses (57% in 1994) are grower-built structures (mainly wooden structures with plastic film cover). These simple structures have a lot of disadvantages and defects such as lack of functionality, insufficient ventilation, low resistance against loads, *etc.*

3.3.1. *Most important greenhouse types in Greece*

In the past, when grower-built structures represented the large majority of greenhouses in Greece, the main designs were the 'Ierapetra' type and the 'Macedonian' type with pitched roofs and the 'Filiatra' type with arch-shaped roofs. These types or their variations have also been used as a model for the design of the Greek 'commercially built' greenhouses. Today, the most common grower-built and commercially built greenhouse types in Greece—which are constructed either in a single or a multispan form – are the tunnel type, the arch-shaped roof type with vertical sidewalls and the pitched roof type. Table 1 shows the typical suggested dimensions of the basic structural units of the different greenhouse types in Greece (Grafiadelis, 1980; Agricultural Bank of Greece, 1986; Castilla, 1994). Comparing the designs promoted by the greenhouse industries with the grower-built ones, the heights of the ridge and the gutter are lower, the slope of the roof varies only between 15 and 20° (*Fig. 6*) at the typically grower-built greenhouses (Tsirogiannis, 1996; Grafiadelis, 1980), whereas the commercially built types are equipped with larger roof and side ventilators.

3.4. *Greenhouse cultivation in Italy*

Greenhouses are widespread all over Italy with a greater concentration (about 60% of the total) in southern regions, where the so-called Mediterranean greenhouse has been established (Castilla, 1994; Stanghellini, 1994; Tesi, 1991). It consists of low-cost structures, with plastic film covering and no heating equipment. 'Cold greenhouses' cover approximately 70% of the total protected area, whereas the remaining 30% of the protected area is equipped with indoor microclimatic control systems (Tesi, 1991; Scarascia-Mugnozza, 1995).

3.4.1. *Greenhouse structures in Italy*

In Italy, 90% of the protected area is covered with plastic material. Only 10% of the total greenhouse area correspond to glass-covered structures. Approximately 87% of the greenhouse area is used for vegetables and 13% for flowers or potplants.

Two major tendencies are currently observed in the Italian greenhouse market.

(1) The use of low technological input greenhouses steadily expands. They are simple structures used for vegetables and low-temperature flower crops. They are designed to require low investment and low operating costs and to exhibit fairly good energy efficiency. They usually consist of a pitched roof structure (*Fig. 6*) built of lightweight steel, timber or concrete, covered with plastic films, usually without heating system or rarely with simple supplementary heating equipment (Tesi, 1991; Scarascia-Mugnozza, 1995).
In Sicily, greenhouses are usually built of wood and/or concrete, covered by single- or double-layer plastic film. Ventilation is obtained by rolling or folding the film upward along the sidewalls (*e.g. Fig. 13*).

(2) Improved modern greenhouses with high technological input used for flower growing, ornamental plants and nurseries are also developed. Their frame is usually made of steel and they are equipped with control systems for a more efficient regulation of the indoor microclimatic parameters, aiming at high-quality products, low-energy consumption and reduced labour cost.
The most common greenhouse types of this category are either multispan arch-shaped roof structures covered with plastic film (*Fig. 7*), or pitched roof frames covered with glass or rigid plastic (*Fig. 1*). This kind of greenhouses are ventilated with openings situated in the sidewalls in the case of only a few

Table 1
Characteristics of the basic structural unit of the most common greenhouse types in Greece according to the 'Technical Greenhouse Specifications' (Agricultural Bank of Greece, 1986)

Dimension	*Tunnel*		*Arch-shaped roof*		*Pitched roof*	
	Commercial	*Grower-built*	*Commercial*	*Grower-built*	*Commercial*	*Grower-built*
Derived from traditional type	—	—	'Filiatra'		'Ierapetra'	'Macedonia'
Min. height of the ridge, m	3	3	3·5	3·1	3·5	3·1
Min. height at the gutter, m	—	—	2·6	2·2	2·6	2·2
Slope of the roof, deg.					20–30	
Minimum width per span, m	7	7	5	5	5	5
Minimum side opening ratio, %	7	10	7	10	7	10
Minimum roof opening ratio, %	18	10	18	10	18	10

spans (less than three) and by means of additional openings in the roof in the case of more spans.

3.5. *Greenhouse cultivation in The Netherlands*

The Netherlands is the European country with the longest tradition in the use of greenhouses for extended commercial production of vegetables and flowers. The Dutch greenhouse is a highly sophisticated unit well equipped which allow optimal conditions for the growth and the production of plants. The construction of such a greenhouse requires a relatively high initial investment, which aims at maximum production.

The covered greenhouse area in The Netherlands is a little more than 10 000 ha (in 1997) of which 93% is heated (LEI-DLO and CBS, 1998). An area of 4250 ha is used for the cultivation of vegetables and fruit and 5800 ha for ornamentals (flowers, potting plants, shrubs, *etc*). The most important concentration of greenhouses is located in the west part of the country in the so-called Zuid-Hollands glasdistrict (Westland): here 4800 ha is situated. The two provinces Noord- en Zuid-Holland (North- and South-Holland) together count 6900 ha (68% of the total area).

Glass is the most commonly used covering material for greenhouses in The Netherlands due to its high light transmittance, its long lifetime and the local greenhouse building tradition and the low costs of standard glass panes. About 97–98% of the total greenhouse area is covered with single glass (Von Elsner *et al*., 2000).

In the Netherlands where labour costs are high, the durability and the easy maintenance of the greenhouse is important. The greenhouse frame is usually made of galvanized steel or aluminium and it is covered with glass.

3.5.1. *Greenhouse structures in The Netherlands*

The glasshouses can be divided into two categories: the wide-span houses and the Venlo-type houses. About 85–90% of the newly built greenhouses in the Netherlands are of the Venlo type (Waaijenberg, 1992).

A wide-span greenhouse is a conventional construction with steel or aluminium purlins attached to steel trusses. These purlins together with the steel or aluminium gutter support the glazing bars, on which the glass is placed. The span width of the wide-span house is standardized on a multiple of 0·8 m, and thus may be 6·4, 8, 9·6 or 12·8 m. Its disadvantage is the higher investment cost compared to a Venlo-type greenhouse.

The Venlo-type greenhouse, is the most popular greenhouse type in the Netherlands. It consists of a structure covered by multiple small-pitched roofs of 3·2 or 4 m span. They are built in continuous big blocks covering a total ground area of 1–2 ha per grower (average area of newly built greenhouses).

In order to achieve a sufficiently high crop production level, even during periods of the year when little light is available, greenhouses were developed with a better light transmittance. A modern Dutch greenhouse has many new improved features such as smaller glazing bars and gutter profiles (steel and aluminium), increased truss spacing and integration of installation and structural parts (Waaijenberg, 1992).

Plastic film covered greenhouses correspond only to 1–2% of the total greenhouse area. The most common types of plastic-covered greenhouses built in the Netherlands are the tunnel and the film-covered multispan greenhouse with arch-shaped roof. To improve the quality of plastic film greenhouses, an initiative has been taken to develop a special construction guideline for this category (Waaijenberg, 1997). It establishes rules for the calculation of loads in plastic greenhouses, tunnels, shading halls, *etc*., and provides the strength of materials (steel, aluminium, concrete and plastic). It also offers practical advises for the design of the foundation, the structure and the cladding of this greenhouse type.

The Venlo-type greenhouse is developed due to the availability of standard glass panes with traditional sizes of 0·73 by 1·65 m for the roof. The standard span width is 3·2 m, consisting of two glass panes of dimensions 1 m by 1·65 m or 1·125 m by 1·65 m joined at the ridge (*Fig. 2*). Extra trusses do not support the ridge, since the glass panes and the glazing bars are self-supporting. During the recent years, there is a change in the glass pane dimensions. New glass panes of 0·80 m by 2·08 m or 1 m by 2·08 m, allow the span width to increase to 4 m. Trellis girders (trusses) are used to support the roof and gutters and the service loads inside caused by equipment, transport systems and crops (*Fig. 2*). Their lengths are, respectively, 6·4 m (2 times 3·2 m) and 8 m (2 times 4 m). The centre-to-centre distance of the columns in the direction parallel to the gutter is 4 m or 4·5 m (Waaijenberg, 1992).

The foundation of a greenhouse column mostly consists of a pre-fabricated concrete pole cast in a concrete block at a certain depth below the surface. The dimensions of these concrete blocks depend on a number of parameters, such as the greenhouse height, the number of connected spans, the number of stability bracings, the soil type, *etc*.

A few years ago, attempts have been made for developing greenhouses with insulating covering materials, such as double glass, synthetic double-web sheets or coated glass with low emissivity. Similar structures with high thermal insulation were also developed by applying a second glass layer to an existing single cladding. Although these designs clearly improved the insulating performance, they also reduced the light transmittance while the investment costs were often too high to be economically attractive for the grower. Now single glass with a thickness of 4 mm is the most popular covering material for greenhouses. Only for the gables and sidewalls a system with two parallel glass panes of 4 mm supported by glazing bars with double grooves is used.

In Dutch horticulture about 70% of the total glasshouse area is equipped with a type of fixed or movable screen for energy saving, shading or blackout. The screens can be used for several functions and contribute to a more efficient control of the indoor greenhouse climate. In many cases when the screens have to combine different requirements, they are constructed as a double screen.

3.6. *Greenhouse cultivation in Spain*

Greenhouses in Spain are spread along the Mediterranean coast. With 28 000 ha of covered area, Spain is the leading country in the use of plastic film covered greenhouses in the Mediterranean basin and the European Union (Von Elsner *et al.*, 2000). The densest concentration of plastic film greenhouses is located in the southern region of Almeria in the south of Spain.

3.6.1. *Parral-type of greenhouse structure in Spain*

The so-called 'Parral-type' is the plastic film greenhouse most frequently met in the Almeria region. These low-cost structures are used to grow vegetables from September throughout June.

The basic structure of the Parral-type is made of wooden posts placed vertically. Their upper ends are connected together by continuous tension wires. Outward facing buttresses give stability to the whole construction (*Fig. 17*) (Pérez Parra, 1992).

The tension wires support two galvanized steel wire nets, which hold the film tight between them ('sandwich' structure). In this way, the stability of the cover is ensured in a region where wind speed is quite high.

Experienced technicians are required to erect this type of structures. The nets and the film must be stretched correctly and carefully, otherwise the films may flutter in the wind. Wind is the most important factor of the Almeria climate. Parral greenhouses have flat or slightly pitched roof (less than 10°). In many cases, the ridge axis has an east–west orientation to resist the prevailing winds. The deposition of dust is intense and frequent in the area and results in reducing the solar radiation transmittance of the cover. Moreover, in winter, the angle of incidence of solar radiation on the horizontal roof is large. Therefore, the reflectance of the cover is high. The Parral-type greenhouse is poorly designed with respect to optimal control of the indoor climate. During the coldest months, average outdoor minimum temperatures are between 7 and 9°C. Under these conditions, plant growth is retarded due to the lack of a heating system. On the other hand, crops can also suffer from excessive heat. Under such circumstances, the poorly designed natural ventilation openings of the Parral-type greenhouse are not sufficient to lower the indoor temperature to the desirable level. Therefore, more efficient natural ventilation systems are required to improve growing conditions. Summer months are not suitable for greenhouse cultivation in the area.

4. Conclusions

The present review describes the current state-of-the-art with respect to various greenhouse designs prevailing in six European Union (EU) countries where 90% of the

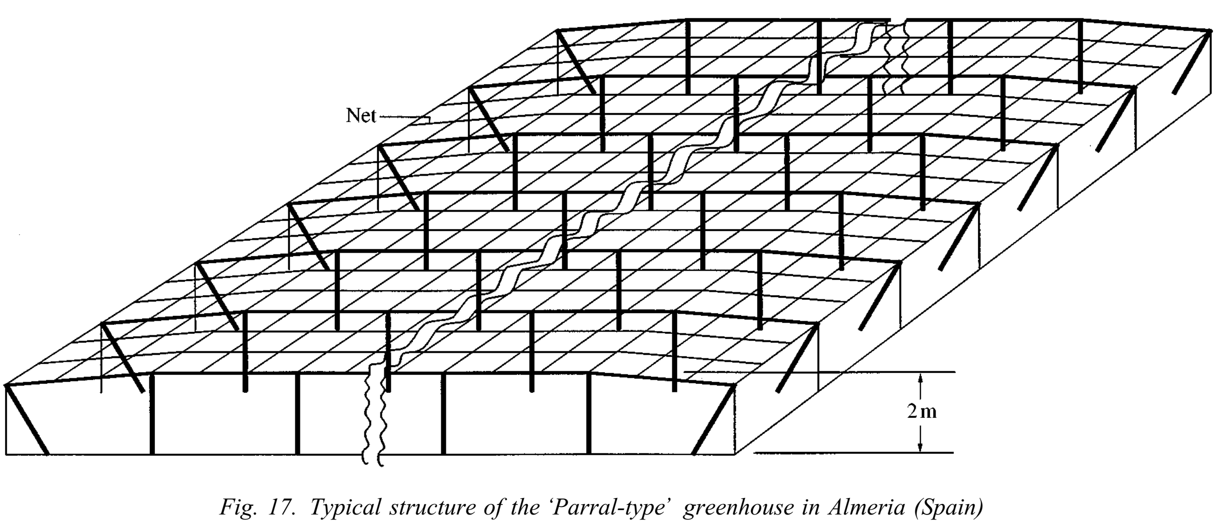

Fig. 17. Typical structure of the 'Parral-type' greenhouse in Almeria (Spain)

total EU greenhouse-covered area is located. Even though, important protected cultivation activity also exist in other EU countries (*e.g.* UK and Denmark), it was not possible to include any specific designs of those countries here due to lack of the corresponding information. However, the scope of this work is not only to describe systematically the most important types of greenhouse structures used in several European countries but also to explain the causes, which have led to the development of such a large variety of greenhouse designs as well as the current trends. In this way, it contributes to a further clarification of the design requirements for greenhouses as well as promotes technology transfer between the EU countries. Summarizing this presentation, the main factors influencing the greenhouse design requirements are stressed.

4.1. *Influence of climate*

Climate is the main factor influencing the greenhouse design. The optimization of a greenhouse structure with respect to local climatic conditions still remains a challenge for the designer not only from the technological but also from the financial point of view. The large diversity in climatic conditions between the regions of the European Union makes it impossible for a manufacturer to offer greenhouses suitable for all kinds of climate. For this reason, local markets have been developed where locally designed structures became popular (*e.g.* Almeria in Spain, The Netherlands, Crete in Greece). Each of these designs aims at solving specific problems related to the local climate. For example, high solar radiation transmittance is a major requirement in particular for greenhouses in the North. For this reason designs with highly translucent cover and small structural elements were developed.

Related to climate are also the financial parameters such as the energy prices. Gas, electricity and petrol prices influence the greenhouse design. For example, if the cladding area increases by increasing the pitch angle, the solar radiation transmittance improves but the insulation performance of the cover decreases.

Climate variations impose important barriers for the international or even the inter-European trade of greenhouses. Greenhouse builders must have the knowledge for developing suitable structures for their export customers.

4.2. *Influence of available materials*

The selection of the building and covering materials is based on both technical and economic requirements. The low price of standard glass panes in the North European countries combined with its high solar radiation transmittance, its high infrared absorption and its durability to environmental factors have made glass the most favourable covering material in the North of Europe. Despite the recent developments in the production of rigid plastic sheets with functional and structural properties of higher quality, glass remains popular.

In the early-industrialized Northern European countries the use of steel for building the greenhouse frame was a natural development. Moreover, steel structures allow smaller volume of the structural elements—casting a smaller shadow—than wooden frames.

In the Southern European countries, plastic films are the most common covering materials for greenhouses. The plastic film is a relatively cheap product, which can easily fit to any greenhouse frame while it can offer good functional properties such as high solar radiation transmittance and good insulation performance. The southern European growers have no trouble to use it as a cover on any kind of simple structure.

Although steel is nowadays quite common as a frame material for the southern European greenhouses, wood is also extensively used since possible losses of light are not considered as first priority. Wood offers higher flexibility in the greenhouse structure and the grower can intervene when it is necessary to adapt the frame to specific local conditions (grower-built greenhouses in Greece and Italy).

4.3. *Influence of tradition*

Tradition is also a factor influencing the developments in greenhouse technology. Successful designs of the past usually remain in use for a long time even after new improved products appear in the market. The lack of compatibility between old and new products is usually the main reason that growers prefer older techniques. Moreover, the experience and the skill acquired through using specific techniques make it more difficult to advocate drastic changes. In most cases, greenhouse growers started their production by using simple cheap constructions. When they were successful, they invested their profits in building better-equipped, more sophisticated greenhouses. However, a level of compatibility between the modern and the old greenhouses was preserved. In this way, the influence of local tradition generated specific trends in the European greenhouse technology.

4.4. *Standardization versus adaptability*

Designing economic and efficient greenhouses requires a successful exploitation of experience, materials and equipment, which are available locally. The availability of the necessary structural materials and accessories in a standardised form can strongly support the development of efficient greenhouse designs. In return, the standardization of important functional and structural features of the greenhouse can lead to the production of cheaper and more efficient greenhouse components.

However, a degree of adaptability is required when very diverse climatic and socio-economic conditions are taken into account. In several cases, however, the incompatibility of the structural components undermines the intended target for a cheaper greenhouse by increasing the building costs. Moreover, the poor co-operation between industries that are producing the main structural components for greenhouses, makes it difficult to realize the optimization of the design in an efficient way. In that respect standardization is required where this is acceptable by the market.

4.5. *Greenhouse design and standardization*

In all European countries, horticulture under cover is a profitable branch of agriculture involving considerable industrial activities. Despite the large number of innovations applied in the present day greenhouses, no design can be considered the perfect unique solution. Greenhouse construction must meet local needs and climatic conditions. For this reason, the standardization of greenhouses at a European level involves difficult technical, economic, social and legal problems. However, a certain degree of European harmonization is required in order to facilitate the trade of greenhouses and greenhouse components among the EU countries.

At this moment, the Eurocodes for design of conventional building structures in Europe represent a common methodology for designing compatible greenhouse structures in Europe. In addition, a recent effort for the preparation of a draft European standard for greenhouse design (prEN 13031-1, 1997) attempts to unify the load calculation methods and the designing methodology in all EU countries. The general methodology provided in this standard follows the methodology of the corresponding Eurocodes in a complementary way. Consequently, it can be adapted to regional conditions by the appropriate safety or combination coefficients in accordance with existing national standards.

The effort for the development of a European standard for greenhouse design, is the starting point for the development of a unified approach with respect to construction regulations in greenhouses all over Europe. This, along with the implementation of the various relevant Eurocodes and European Standards for materials, is expected to contribute to the integration of the corresponding European market. The review contributes to this unification process by presenting the most successful greenhouse types used in EU countries and explaining the reasons of their success.

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