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REVIEW PAPER

Review of Structural and Functional Characteristics of Greenhouses in European Union Countries: Part I, Design Requirements

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The present work is an overview of the factors influencing the greenhouse design such as the climate, the local building regulations the indoor climate requirements and the necessary functional characteristics. The variations with respect to these factors observed throughout most of the European Union countries are described in detail and their influence to the greenhouse design is critically investigated. Such an analysis of the main factors influencing the greenhouse design is considered necessary before the most common greenhouse types used in Europe are presented (Part II). This systematic review is expected to support the effort for developing a common design methodology for greenhouses at European level.

1. Introduction

1.1. *Purpose of greenhouse structures*

Greenhouses are highly sophisticated structures, which aim at providing ideal conditions for satisfactory plant growth and production throughout the year. The growth factors — light, temperature, humidity and air composition — should be delivered and maintained at optimal levels.

Daylight, the visible part of the global radiation, is one of the essential growth factors for a greenhouse. Therefore, greenhouses have to be designed and built with light-translucent covers in such a way that enough light reaches the plants, especially in seasons when the sun is low in the sky. Some greenhouses used for special cultures, or located in regions with high sun radiation, may need shading during periods of high irradiation. Heat must be supplied when the temperature falls below a desired indoor temperature. Heat losses through the covering materials should be as low as possible. Greenhouse covers should provide maximum solar radiation transmittance combined with minimum heating requirements during the cold season. In cases of high indoor temperatures, which exceed the optimal value, the surplus heat has to be dissipated by ventilation or artificial cooling.

A well-designed greenhouse must provide the necessary climatic conditions for plant growth and production throughout the year and maintain the important climate factors as close as possible to specified optima. Thus, greenhouses are required to allow high light transmittance, low heat consumption, sufficient ventilation efficiency, adequate structural strength and good overall mechanical behaviour, low construction and operating costs.

1.2. *Historical and regional developments*

Attempts to adapt the environment to the needs of crop production by means of protective structures dates back to ancient times (van den Muijzenberg, 1980). By the end of the Roman Empire, those old techniques for protected cultivation disappeared. Greenhouses appear

Table 1
Greenhouse areas in the countries of the European Union (Meneses & Monteiro, 1993; PlastEuroFilm, 1994; Horticultural Statistics, 1994; Castilla & Hernandez, 1995; Scarascia-Mugnozza, 1995; Briassoulis *et al.*, 1997; CEPLA, 1992)

EU country	*Area covered by greenhouses and high tunnels, ha*	*Percentage of plastic-covered greenhouses and high tunnels, %*
Austria	350	20
Belgium	1800	5
Denmark	550	2
France	10 082	70
Germany (West)	4300	10
Greece	4200	95
Italy	26 600	91
The Netherlands	10 316	2
Portugal	4390	98
Spain	28 350	99
Sweden	400	14
United Kingdom	2180	15
Total	93 518	74

again at the late 15th to 18th centuries in England, France and the Netherlands. However, the use of greenhouses for commercial production started in the middle of the 19th century and increased rapidly after 1945.

Table 1 shows the recent data concerning the total greenhouse area and the percentage of plastic-covered greenhouses in the countries of the European Union (Meneses & Monteiro, 1993; Horticultural Statistics, 1994; PlastEuroFilm, 1994; Castilla & Hernandez, 1995; Scarascia-Mugnozza, 1995; Briassoulis *et al.*, 1997; CEPLA, 1992). Glasshouses are mainly located in the countries of Northern Europe. In the South, including the South of France, plastic-film-covered greenhouses dominate.

High concentrations of greenhouses are observed in specific regions with favourable climatic conditions. For example, 68% of the Dutch greenhouses are concentrated near the West coast of the Netherlands, while 45% of the greenhouse area in Greece is located in the isle of Crete. Most of the greenhouses in France are also located along the Mediterranean coast and about 15000 h of the Spanish greenhouse area are located in the region of Almeria. More details concerning statistics of greenhouses in Europe may be found in Briassoulis *et al.* (1997).

1.3. *Objectives of the present paper*

The main objective of this paper, Part I, together with Part II (von Elsner *et al.*, 2000) is to describe the present status of greenhouse technology in the European Union (EU) countries participating in a European network on greenhouses (see Acknowledgements) by analysing the corresponding design requirements and the factors influencing them. Of course, a relatively significant greenhouse production also exists in the UK and Denmark. Specific information from these countries is not included in this work but it may be found in the national standards. Nevertheless, this work is quite representative of the current situation in Europe and it contributes to a better understanding of the large diversity in the design of, and the equipment for, the European greenhouses due to different climate, local traditions, availability of resources and materials and plants variety. The overview of the European greenhouse technology offers the opportunity for a critical presentation of the regional or national practices with respect to the current technical and economic constraints. This systematic and collective presentation of the technical problems related to the greenhouse construction in Europe and the solutions adopted by local producers will help the dissemination of technical knowledge and allow the assessment of the existing greenhouse technology at an international level.

Specifically, the present review analyses the climatic conditions in the EU countries under consideration, the design requirements imposed by the local climatic, technical and economic conditions and the basic functional and structural characteristics of greenhouses. Although the functionality of a greenhouse can be fully analysed only by studying the complete system, the scope of the present work is limited to the formulation of various structures, covering materials and ventilation openings. It should be noted that space limitations along with the large variation in the structural design details, some of them being also confidential, restrict the relevant presentation of structural characteristics to the most basic representative greenhouse designs of the countries involved. The limitation in scope of the present work nevertheless enables the study of greenhouse structures and their functionality in a comprehensive and complete way.

Equipment that is not directly related to the greenhouse structural system is not considered in this work. Natural ventilation openings serve as both functional elements and structural components of the greenhouse affecting both the greenhouse cover and the design of the supporting structure. Their functionality is influenced by the overall greenhouse design. For this reason they are considered in the present study, while other climate control equipment such as heating systems, forced ventilation and others are not.

2. Main design requirements

2.1. *Climate elements and their influence on the design of a greenhouse*

Greenhouses are used for protecting crops against wind, rain, hail and snow as well as plant diseases or extreme temperatures. The most important climatic factors influencing the structural design and the quality of the indoor microclimate are the temperature, the global solar radiation, the precipitation and the wind intensity. Thus, local meteorological conditions strongly influence not only the indoor climate control equipment of greenhouses but also their structural design. Harsh weather conditions are the most common cause of failure of greenhouse structures. Therefore, the greenhouse design must follow regulations related to the local climate. As the use of greenhouses now extends all over Europe, the design, the covering material and the equipment must satisfy requirements imposed by the various local climatic conditions.

Each of the above-mentioned climatic factors generates a combination of effects which have either favourable or negative influence on the functionality and the stability of the greenhouse depending on the particular local circumstances. For example, wind generates varying pressures on the greenhouse cover and corresponding stresses in the frame and foundations, which can cause damage in cases of extreme wind speeds. On the other hand, moderate wind stimulates natural ventilation, which is necessary for optimal indoor climate control.

Snowfall influences the structural stability, the mechanical behaviour of the cover as well as the heating requirements of a greenhouse. Hail is a common cause of damage of the greenhouse cover. Rainwater must be drained off and collected to avoid flooding of the greenhouse ground. Water should not be allowed to remain on the cover because, in the case of freezing, it may destroy its components, such as the glass panes in glass-covered greenhouses, due to volume expansion. Therefore, the roof angle must be optimally selected with respect to the local rain and snowfall levels. On the other hand, rain can provide high-quality irrigating water if the greenhouse gutters are properly designed to transport the water to storage tanks, etc.

Intense solar radiation can cause degradation of important structural and functional properties of plastic components due to contact with hot metallic elements of the frame and ultra-violet ageing. On the other hand, solar radiation is the main source of photosynthetic energy for plant growth and production. Therefore, the global solar irradiance and its variations during the year is a very important climatic factor influencing the greenhouse productivity. Hence, the solar radiation transmittance of the greenhouse must be optimized with respect to the crop needs and the local climate. Especially in regions with low solar radiation, improving the total solar radiation transmittance of the greenhouse is a major engineering task. On the contrary, in areas where high levels of solar radiation are expected, additional equipment (shading screens) are necessary to reduce the radiation intensity and to prevent overheating of the plant leaves.

Finally, temperature is the most critical climatic factor for the greenhouse functionality. Maintaining an optimal indoor temperature is the main objective of protected cultivation. The cover insulating properties and the heating system must be selected to fit to the heating needs during local cold winter periods. Local hot summer conditions require cooling systems and large ventilator openings.

2.2. *General design criteria*

The local climate, the general structural design and load characteristics, and the locally available materials comprise the general design criteria for greenhouses.

With respect to climate, Europe can be divided in two zones. In Northern and Central Europe, the climate is characterized by cold winters and moderate summers (temperate climate). In Southern Europe the winters are moderate and the summers hot (Mediterranean climate). The solar irradiance in the Mediterranean countries is two to three times more intense than in Northern Europe. Differences with respect to climate resulted in the development of different types of greenhouses. For this reason, the greenhouses in Europe can be distinguished into greenhouses designed for a temperate climate and greenhouses designed for Mediterranean climate.

Greenhouses can also be classified with respect to their construction characteristics (width, single or multispan, sidewall height, roof shape and slope), covering materials (glass, rigid plastics, plastic film or combinations of these) and construction materials (steel, aluminium, wood or combinations of these).

In Central and Northern Europe most greenhouses are covered with glass, whereas most of the greenhouses in Southern Europe are covered with plastic film. Presently, the area covered by plastic film greenhouses is larger than the area corresponding to glass greenhouses (Table 1).

The main problems for greenhouses in a temperate climate are

(1) low outside temperature in winter;
(2) significant wind and snow loads, and hail;
(3) insufficient light in winter; and
(4) occasionally hot summers.

Therefore, greenhouses for temperate climates should have the following characteristics:

(1) sufficient stability against wind and snow loads, taking into account relevant national or European standards;
(2) an efficient heating system;

(3) high light transparency;
(4) efficient insulation against heat losses at low outside temperatures; and
(5) sufficient ventilation and shading in summer.

The main problems for greenhouses in regions with a Mediterranean climate are

(1) temperatures below the biological optimum in winter nights, making heating necessary for one to three months;
(2) high temperatures during daytime in spring and summer;
(3) high air humidity at night;
(4) low global radiation in winter;
(5) significant wind loads, and sometimes unexpected snow loads and hail; and
(6) poor water availability and in certain areas poor water quality.

Therefore, greenhouses in a Mediterranean climate should have the following characteristics:

(1) high total light transparency;
(2) good heat insulation, especially for unheated greenhouses;
(3) heating equipment to increase the minimum temperature during night time;
(4) efficient ventilation by ventilators capable of being controlled;
(5) high stability with respect to wind and in some regions to snow loads;
(6) gutters and tanks, which collect rain water for irrigation purposes;
(7) greenhouse volume as large as possible;
(8) availability to water saving irrigation systems; and
(9) protection from insects by nets.

Since there are more plastic-film greenhouses in the EU than glass greenhouses, there are extra design criteria specifically for plastic-film greenhouses:

(1) tensioning of films to avoid damage due to fluttering;
(2) film installation to allow easy replacement;
(3) insulation of those parts of the structure heated by solar radiation and in contact with the film;
(4) prevention of condensed water falling from the cover onto the crops; and
(5) minimizing light losses through misting of the covers.

A successful and efficient greenhouse design requires accurate knowledge of local climatic conditions in more detail than the above-described scheme for the climatic division of Europe. National regulations provide extra information concerning the temperature, solar radiation and wind zones in most EU countries. Moreover, meteorological data books (Wallen, 1977; DIN 4710, 1982; Gruenewald, 1983; Wallen, 1970) are also useful for analysing and predicting the structural and functional behaviour of greenhouse designs in specific locations. Finally, preliminary climatic measurements at the location of the construction may be required before the installation of large greenhouses.

2.3. *Loads and standardization*

Greenhouses are lightweight structures, which must have high solar radiation transmittance for optimum plant growth. The structures must also be able to withstand loading due to wind, snow, rain and hail, as well as permanent, imposed and service loads. Damage to greenhouses, and especially to plastic-film greenhouses, is very often caused by storms and heavy snowfalls, because the main structural components are not designed to withstand such loads. In order for the greenhouses to satisfy sufficient margins of safety and to avoid severe damage, the greenhouse structure should be designed in accordance with relevant standards, which offer guidance for the calculation of various design loads.

Standards for glass greenhouses are in use in several countries with a temperate climate. Specifically, the following standards are reported in the present paper: France (NFU 57060, 1991), Germany (DIN V 11535-1, 1994), Italy (UNI 6781-71, 1971), The Netherlands (NEN 3859, 1996), United Kingdom (BS 5502: Part 22, 1993) and additionally the United States (ASAE: EP 288·4, 1992).

Similar standards, applicable to plastic-film greenhouses are needed for all climatic regions. Standards or Codes of Practice for these types of greenhouses have already been prepared in several countries. The French standards NFU 57063 (1991) for tunnels and NFU 57064 (1991) for multispan plastic greenhouses, the British draft standard BSI Document (BSI Document no. 91, 1991) and the Dutch Code of Practice for greenhouses with flexible claddings (Waaijenberg, 1997) are reported as an example.

A greenhouse standard for all countries of the European Community is currently under preparation through the European Committee for Standardization CEN/TC-284 (prEN13031-1, 1997).

The main loads, which have to be taken into account in the greenhouse design, are

(1) dead load or permanent load;
(2) imposed loads (crop loads);
(3) installations;
(4) snow load;
(5) wind load; and
(6) seismic load

Specific combinations of these loads, given in the standards, should be considered for a safe design. Since the calculation of safety factors for these loads takes into account extremes of weather data over the lifetime of the greenhouse, the above standards classify greenhouses according to their intended minimum lifetime (reference period). This classification is based on the estimation of the lifetime of greenhouses from the economic and technical point of view. It should be noticed that the lifetime of greenhouses is much shorter than the lifetime of conventional buildings; thus the loads should be calculated accordingly.

2.3.1. *Loads*

(1) *Dead load.* The calculation of dead load is based on the unit weights of the structural components and the covering materials. In some cases, the weight of fixed equipment such as heating, lighting, irrigation systems, shading and thermal screens is also included in the dead load calculations (NFU 57060, 1991; DIN V 11535-1, 1994; BS 5502: Part 22, 1993). Other standards exclude the weight of installation from the dead load calculations, even if it is permanent, considering it separately (NEN 3859, 1996).

(2) *Installation load.* Loads applied to the greenhouse structure by supporting elements (*e.g.* wires) of service loads, such as heating, cooling, lighting, shading, irrigation, ventilation and insulation equipment, represents a separate permanent load defined as installation load.

(3) *Crop load.* In greenhouses where the structure supports the weight of crops, which are suspended through vertical strings, special crop loads have to be considered. If crops are suspended on separate horizontal wires, the horizontal tensile forces transmitted to the gables have to be taken into account.

(4) *Snow load.* The calculation of snow load is based on measurements of snowfall on the ground given in special meteorological maps (*e.g.* ENV 1991-2-3, 1995). The reference recurrence period is considered equal to 50 years. The exposed area of the greenhouse is calculated by taking the horizontal projection of the roof. The basic snow load is multiplied by several coefficients to account for the shape of the roof (mono-pitch, double-pitch, *etc.*), the slope of the roof, the exposure of the roof to snow, the recurrence period, the lifetime of the greenhouse and the heating or not of the interior (ENV 1991-2-3, 1995).

(5) *Wind load.* The wind pressure is calculated as a function of the wind pressure coefficient corresponding to the cover segment under consideration and the dynamic wind pressure.

Wind loads appear as pressure and suction forces on the surface of the greenhouse. The dynamic wind pressure depends on the effective height of the greenhouse, which is defined as the distance between ground level and the average height between gutter or eaves and the highest point of the roof (NEN 3859, 1996; ENV 1991-2-4, 1995).

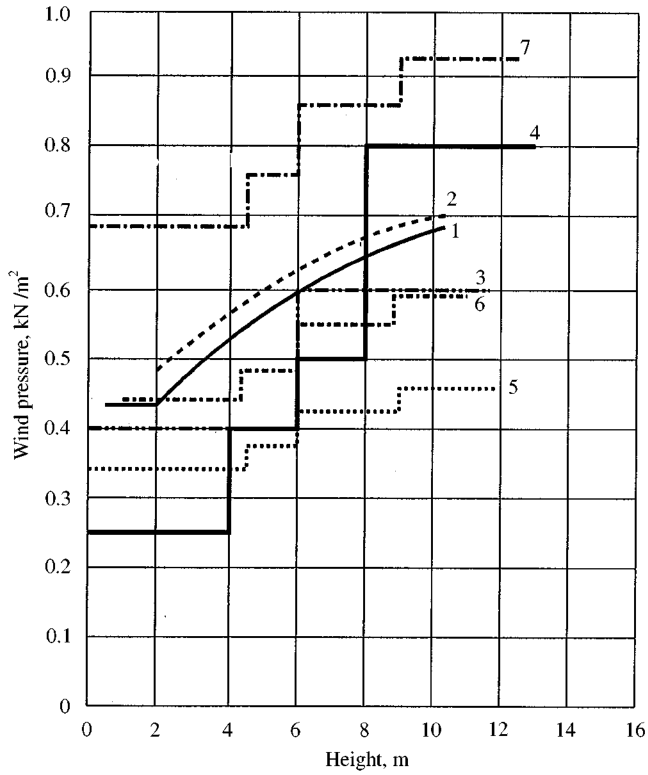

Fig. 1. Dynamic wind pressure depending on greenhouse height: (1) NEN 3859, 1996, The Netherlands; (2) ISHS Draft 01, 1991, for European greenhouse Standard; (3) UNI 6781-71, 1971, Italy; (4) DIN 1055, 1986, Germany; (5) ASAE-EP 288·4, 1992, for 70 km/h wind speed; (6) ASAE-EP 288·4, 1992, for 80 km/h; (7) ASAE-EP 288·4, 1992, for 100 km/h

It should be noted that the various standards adopt different approaches for the calculation of wind loads. As a result, design loads may differ significantly, depending on the standards used. Values of the dynamic wind pressure and its dependence on the height given by various standards are shown in *Fig. 1.*

The wind pressure coefficient determines the pressure and suction forces as a function of the dynamic wind pressure and depends on shape and location of the cover segment for which the wind forces are calculated. Local pressure coefficients are higher at the gable corners, and the gable and sidewall roof sides. The width of glass panes in those areas should be smaller than in the other surfaces. Especially in wind exposed regions, the continuous ventilators of glass greenhouses when using the same glazing bars should end a certain distance before the gable.

Typical wind speeds can be taken from wind maps (*e.g.* ENV 1991-2-4, 1995). However, local wind speeds depend strongly on the terrain and can vary considerably from the typical values given in area maps. The basic wind forces derived from standards are calculated by taking into account the cross-section of the building with respect to the wind, its shape and height, the altitude and topography of its location and its expected lifetime (reference period). Both external and internal pressures have to be taken into account to determine wind loads on the structure.

(6) *Seismic load*. No provision for seismic load calculations of greenhouse structures is offered by the corresponding national standards for greenhouse design. Thus, consideration of seismic loading has to follow the corresponding Eurocode for conventional buildings (ENV 1998, 1994).

2.3.2. *Foundations and anchoring*

The foundation of a greenhouse structure should safely sustain the worst combination of the different loads and transmit them safely to the ground. The allowable bearing pressures of the soil have to be taken into consideration, as suggested, for instance, in BSI (BSI Document no. 91, 1991) and DIN 1054 (1976). In some temperate climatic regions, the lowest point of the outer foundations for glass greenhouses have to be placed below the frost-free depth (*e.g.* 0·80 m in Germany).

Owing to the lightweight structure design of greenhouses, special attention should be paid to the ability of the foundations to resist uplift forces under wind action. For concrete foundation blocks, the maximum upward vertical load should not exceed the weight of the foundations (NFU 57060, 1991; BSI Document no. 91, 1991).

For low cost structures, such as tunnels, the foundation of the structure is achieved by light anchoring (by using male tube in the ground on which the arch is connected or screw anchors).

2.3.3. *National load requirements and standardisation*

2.3.3.1. France. Loads for greenhouses in France are calculated based on specific standards. Thus, loads for glasshouses (normal/extreme) are calculated according to the standard NFU 57060 (1991), for plastic multispan greenhouses, according to NFU 57064 (1991) and according to NFU 57063 (1991) for tunnels. Snow and wind loads vary depending on the region. The country is divided into four areas with respect to snow and three areas with respect to wind loads. Following the separate standards for the different greenhouse types, the horizontal snow load varies from 0·21 to 0·98 kN/m^2 depending on the type and load zone.

The wind loads in the three zones for the corresponding greenhouse types cover a range from 0·29 to 0·91 kN/m^2 for design wind speeds of 22–38·6 m/s, respectively.

As snow and wind loads depend on the type of greenhouse, an all-inclusive coefficient is formed, which also includes the expected economical and technical life duration of the greenhouse.

2.3.3.2. Germany. Greenhouses are handled, in terms of load, calculations as ordinary buildings. So the German standard DIN 1055 'Design load for buildings' (DIN 1055, Blatt 1-6, 1994) has to be used. This standard consists of several parts, which cover: design data for building materials and installation which are used to calculate the dead loads; data describing soil properties, such as unit weight, angle of friction, cohesion and wall friction; and description of climatic loads, such as wind, snow and ice loads.

Greenhouses are standardized in a code applicable to all greenhouses, concerning load requirements, namely DIN 11535 (1974) and in a second code which is a product standard DIN 11536 (1974), concerning greenhouse structures of galvanized steel. These standards have been revised in the draft of 1987 and the second draft of 1993, which led to the new issues of DIN 11535-1 (1994) (load requirements) and DIN V 11535-2 (1994) (product standard), respectively.

The important items with respect to load requirements are summarized in the standard DIN 11535-1 'Greenhouses — basic principles for design and construction' (DIN V 11535-1, 1994).

(a) Germany is divided into four regional classes with respect to the geodetic height, which is related to the expected snow load. The range of classes for the snow load varies from 0·75 to 5·5 kN/m^2. A special regulation permits a reduction of the snow load if the building is permanently heated up to 12°C. So in most cases, a snow load of 0·25 kN/m^2 has to be taken into account for heated, single covered, greenhouses. If double covers are used, a heating temperature of 18°C is required. For heated greenhouses used as garden centres, a load of 0·75 kN/m^2 has to be taken into account.
(b) Wind load depends on the height of the building. So greenhouses with an effective height below 4 m have to be able to withstand a wind speed of 20·4 m/s (speed of 73 km/h; dynamic pressure of 0·25 kN/m^2); greenhouses up to 8 m height have to be designed for a wind speed of 28·3 m/s (102 km/h; 0·5 kN/m^2). Depending on the geometric shape of the building, appropriate aerodynamic pressure coefficients must be considered for the surface of every sector of the structure.
(c) Additional and service loads must be considered.
(d) Load combinations reflecting the worst-case loading, must be calculated.

(e) The stability of the overall construction has to be certified according to relevant standards. This incorporates the requirement that deformation of bars and structural parts must be within specific allowable limits. The foundation has to be set below the frost layer of the ground. The gutter must be designed as a structural element, connecting the roofs of multi-span greenhouses and also functioning as rain collector. All steel parts must be protected against corrosion, *e.g.* by galvanizing or coating them.

The standard DIN 11535 (1974) and the revised draft DIN V 11535-1 (1994) will be withdrawn when the European standard for greenhouses is published.

2.3.3.3. Greece. In Greece, the design practice over the last decade has adopted the German DIN standards for the design of buildings and other structures even though the use of other international standards is not excluded. Usually, the design of metal and wooden structures follows the corresponding German standards, DIN 18800 (1983–1996) and DIN 1052 (1988–1996).

Financing of greenhouses is subject to the approval of the structural design on the basis of the 'Technical Greenhouse Specifications' (Agricultural Bank of Greece, 1986) and suggests the following minimum loads for the design of greenhouses in Greece: wind velocity of 120 km/h; snow load of 0·25 kN/m^2; crop load of 0·15–1·00 kN/m^2; and concentrated vertical load of 0·50–1·00 kN.

The Greek specifications for greenhouses actually cover only actions on greenhouses (as far as the structural design is concerned). This document is enforced only in cases when the greenhouse construction follows procedures, which require the economic involvement of the Agricultural Bank of Greece or the Ministry of Agriculture. Otherwise, this standard has no legal value. Nevertheless, the corresponding design standards in effect for conventional buildings (*e.g.* steel structures) are the only standards which are legally required for the design of greenhouses and, in fact, they are used in that way in cases of legal claims for damages, *etc*. The newly developed Eurocodes for actions, design of steel structures, *etc*., are expected to replace the currently used national or international standards.

2.3.3.4. Italy. The building rules for the design and construction of metal structures for greenhouses go back to 1971 with the standard UNI 6781-71 (1971) and, with partial adjustments, they are still the only reference for the designer although not being legally required. According to the present law, the designer should refer to the provisions of the law for buildings, despite the fact that building characteristics and uses are quite different from those of greenhouses.

The range of the effective velocity of the wind, which has to be taken into account, varies from 24 to 31 m/s. The wind load is calculated following the standard ENV-1991-2-4 (1995).

Regarding snow load, Italy is divided into three zones with snow load on the ground equal to 1·60 kN/m^2 (zone I), 1·15 kN/m^2 (zone II) and 0·75 kN/m^2 (zone III) depending on the altitude.

2.3.3.5. The Netherlands. In the past, the development and design of greenhouses was mainly based on experience. Strength calculations were rarely carried out. This changed drastically in 1978 with the introduction of the Dutch standard NEN 3859 'Greenhouses—structural requirements' (NEN 3859, 1996) and the NPR 3860 'Greenhouses' (NPR 3860, 1985). At the same time, a testing authority (TNO-Bouw, Delft) was set up to verify design calculations and to test specific construction details experimentally. The combined effect of the standard requirements and the testing authority forced the greenhouse builders to make complete static calculations for every newly developed type of greenhouse. As a result, a minimum market quality was ensured.

The standard NEN 3859 (NEN 3859, 1996) contains information on: the definition, scope and economic lifetime of a greenhouse (fixed to 15 years for glass-covered greenhouses); the dead weight of the greenhouse and cladding material (0·16 kN/m^2 for a single glass greenhouse); wind and snow loads for greenhouses (snow load of 0·25 kN/m^2); load caused by suspended crops (0·15 kN/m^2 for tomatoes and cucumbers); load caused by installations (minimum of 0·07 kN/m^2); concentrated vertical service load of 1 kN on the structure and 0·35 kN on the glazing bars; material specifications for steel, aluminium, concrete, *etc*.; maximum deformations and displacements (to avoid breakage of glass panes); and load combinations and load factors.

Since 1992, The Netherlands, together with other European countries, is strongly involved in an effort for the development of a European Standard for Greenhouses, namely prEN13031-1 (1997) through the CEN organization in Brussels.

Wind is the most important load for greenhouses in the Netherlands, because storms are the most frequent cause of damage. For example, the total damage to greenhouses, installations and crops due to two storms in January and February 1990, amounted to about 200 million guilders (price level 1990). The basic wind load (extreme thrust pressure) depends on the effective height of the greenhouse (average roof height). Its calculation is based on an extreme hourly average wind speed of 19·26 m/s (70 km/h) measured at a height of 10 m above the ground and taking a gust factor of 1·7 into account.

(Therefore, the maximum wind speed in a gust is 32·7 m/s, which is about 118 km/h.)

2.3.3.6. Spain. The Spanish Greenhouse Standard is UNE 76-208-92, 'Multispan greenhouses covered with plastic materials — design and construction' (UNE 76-208-92, 1992). Primarily, this standard defines the main characteristics and dimensions of the construction, as well as the materials. Secondly, the standard defines and determines the actions, load combinations for the design calculations and the displacements and deflections allowed for some structural and covering components of the greenhouse. Finally, it offers suggestions on the ventilation.

This standard does not cover either glasshouses or the popular 'Parral-type' plastic film greenhouse.

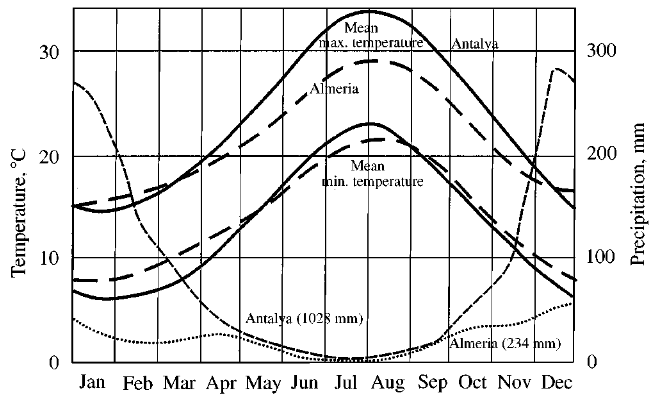

Fig. 2. Mean daily minimum and maximum temperatures and mean monthly precipitation (with yearly precipitation in paranthesesa) for two Mediterranean regions (Almeria, Spain; Antalya, Turkey); ——, temperatures for Antalya; — —, temperatures for Almeria; —-—, precipitation for Antalya; ...., precipitation for Almeria

2.4. *Indoor climate requirements*

2.4.1. *Microclimatic requirements for greenhouses*

The general crop needs and the local climatic conditions impose specific requirements on the greenhouse structure. However, national traditions have a strong and sometimes misleading influence on the greenhouse design.

A simple and efficient method for checking the suitability of a region for protected cultivation is the comparison of its climatic data to those of other regions where greenhouse production of the same crop has been successful.

Most of the plants grown in greenhouses are warm-season species. Their climatic requirements for plant growth can be defined and summarized as follows (Sirjacobs, 1989; Baudoin *et al.*, 1990; Verlodt, 1990; Krug, 1991).

(1) Plants can be killed by frost. The absolute minimum temperature in the greenhouse has to be above 0°C. The risks of subzero temperatures can be neglected when the daily minimum outside temperature exceeds 7°C.
(2) Plants grown under protected cultivation are mainly adapted to average temperatures ranging from 17 to 27°C. Taking into account the warming-up effect of solar radiation in greenhouses, one can define the climatic limits of suitability between 12 and 22°C mean daily outside temperature if the greenhouses are not heated.
(3) If the mean daily outside temperature is below 12°C, greenhouses have to be heated, particularly at night. When mean daily temperatures above 22°C are common (summer in Mediterranean countries), artificial cooling may be necessary or cultivation in greenhouses has to be stopped (depending also on the relative humidity outside). With mean temperatures between 12 and 22°C natural ventilation is sufficient.
(4) The absolute maximum temperature for plants should not be higher than 35–40°C.
(5) A minimum of 500–550 h of sunshine for the three winter months (November, December and January) is desirable. This corresponds to a daily insolation of about 2300 W h/m^{2}d. The limit for effective production is 1000 W h/m^2 d (Krug, 1991). Artificial lighting may be used for intensive production.
(6) The minimum threshold for soil temperature is 15°C.
(7) Verlodt (1990) suggests a threshold of the average night temperature as 15–18·5°C for heat-requiring plants such as tomato, pepper, cucumber, melon and beans.
(8) Relative humidity of 70–90% is regarded as being within a safe range.

Different climatic conditions impose different design requirements on the greenhouse structure as is demonstrated by the following example. *Figure 2* shows the mean daily maximum and minimum temperatures and the mean monthly precipitation for two Mediterranean regions, Antalya in Turkey, and Almeria in Spain (von Zabeltitz, 1992). Almeria is the most important region for protected cultivation in Spain with a greenhouse area of about 15 000 ha, while 6000 ha of greenhouses are concentrated in the Antalya region of Turkey.

Almeria is a very dry area with low precipitation in winter and summer. The total yearly precipitation is 234 mm. Antalya has high precipitation mainly in winter. The total yearly precipitation is 1028 mm. This means that gutters are necessary for greenhouses in Antalya to drain off the rainwater and to protect the crops from

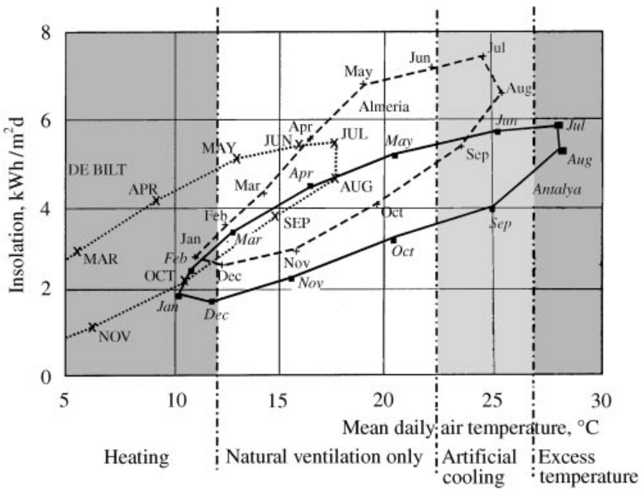

Fig. 3. Mean daily insolation versus mean daily temperature for Mediterranean regions (Almeria, Spain; Antalya, Turkey) and a temperate climate region (De Bilt, the Netherlands)

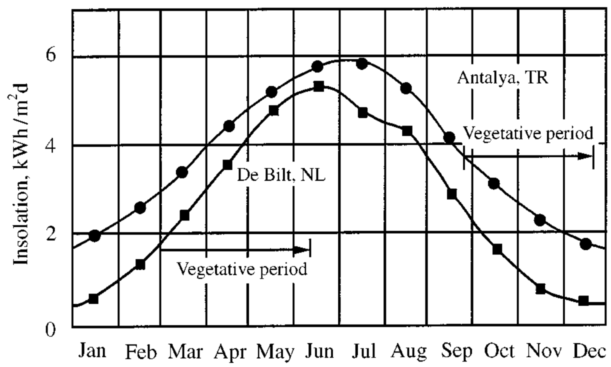

Fig. 4. Mean daily insolation for a Mediterranean (Antalya, Turkey) and a temperate climate region (De Bilt, the Netherlands)

water penetrating through the sidewalls. Collecting the rainwater for irrigation is recommendable and profitable. The mean daily maximum temperatures are higher in Antalya in summer and the mean daily minimum temperature is a little lower in Antalya than in Almeria. This means that greenhouses in Antalya need a higher ventilation efficiency in spring, summer and autumn. Therefore, the typical Almeria greenhouse type is not transferable to Antalya or other regions in the same broad climatic zone as Antalya.

An example of the indoor climate control requirements imposed by the different climatic conditions is shown in *Fig. 3*. The mean daily insolation is plotted against the mean daily temperature for two Mediterranean climate regions, Almeria and Antalya, and for a temperate climate, De Bilt, Netherlands. If the minimum global radiation is considered to be 2·3 kW h/m^2 d, the Antalya region is below this figure in December and January. If the threshold for heating greenhouses is 12°C, they must be heated from December to the end of February in Antalya. Heating is necessary in January in Almeria. During summer there is lower insolation but higher mean temperatures in Antalya than in Almeria. In both regions, crop production without artificial cooling by forced ventilation or evaporation of water, is not possible from June to September. Insolation is comparable in Antalya and De Bilt during summer, but heating is necessary from September to May in the Netherlands.

Further design requirements are imposed by the differences in the duration and the beginning of the production season. *Figure 4* shows the average daily insolation for Antalya, Turkey and De Bilt, Netherlands. The total global radiation is higher in Antalya than in the Netherlands. Nevertheless, in the Mediterranean regions transplanting starts in September/October and the plants are developing with decreasing light intensity up to the middle of the cropping season when light intensity is at a minimum. In northern countries, such as the Netherlands, transplanting starts in February and crops grow with increasing light intensity, with a maximum of light intensity in the middle of the cropping season. The sum of insolation is nearly the same for a growing period of about nine months in the South from September to May and in the North from February to October (von Zabeltitz, 1988). As light is a limiting factor during the growing season in the South, the light transmissivity of greenhouses has to be increased as much as possible.

3. Greenhouse design and functional characteristics

Greenhouses have to provide optimal climate conditions for healthy plant growth and high production. The design strongly influences not only the mechanical behaviour of the greenhouse structure, but also internal climate factors such as temperature, air humidity and light transmittance. The physical properties of the covering material also influence the quality of the indoor microclimate, while its mechanical properties influence the structural design and the mechanical behaviour of the greenhouse. For example, glass-covered greenhouses normally have a pitched roof, while plastic-film greenhouses can have a pitched roof, a saw-tooth shed roof and a round or Gothic arched roofs. For this reason, functional aspects of the greenhouse structure such as total light transmittance and ventilation, as well as physical properties of the covering material, such as condensation behaviour and dirt behaviour, impose design requirements on the greenhouse structure.

3.1. *Height of the greenhouse*

The average height of a greenhouse characterizes its volume. A large greenhouse volume results in a slow response of the indoor environment to changes of the external weather conditions. Therefore, higher greenhouses exhibit smaller fluctuations in their indoor micro-climate. On the other hand, higher greenhouses have increased energy consumption and are more demanding in terms of structural stability due to larger wind loads. The height of a greenhouse is optimized with respect to these two competing factors.

High greenhouses offer several other important advantages. For example, their ventilation efficiency is higher since pressure differences along higher roofs are larger due to faster wind speeds, while the chimney effect induced by sidewall and roof ventilators is enhanced. Moreover, higher greenhouses allow more space for climate control equipment such as thermal or shadowing screens, fogging systems, artificial lighting, *etc*. For these reasons, the current trend in greenhouse technology is towards higher greenhouses.

3.2. *Light transmittance of greenhouses*

The intensity of the incoming solar radiation is an important parameter influencing the indoor climate as well as the photosynthetic activity of the plants. The greenhouse structure and the covering material are responsible for solar radiation losses. Specifically, the transmitted global radiation is reduced by

(1) absorption and reflection at the covering material;
(2) shading by greenhouse structural components;
(3) dirt on the covering material; and
(4) condensation on the covering material.

The total transmittance T_r of a greenhouse is defined as the ratio of the transmitted solar radiation q_{rg} to the outside incoming radiation q_{ro}:

$$T_r = q_{rg}/q_{ro}$$

Several researchers have measured and calculated the transmittance of greenhouses (Schulze, 1954; Stoffers, 1967, 1990; Nisen, 1969; Kirsten, 1973; Bot, 1983, Critten, 1983, 1989; van den Kieboom & Stoffers, 1985).

The solar radiation transmittance is influenced by the orientation of the greenhouse and the sun elevation. *Figure 5* shows the average transmittance of various greenhouse types with east–west and north–south orientation in December and June (Nisen, 1969). The following conclusions can be drawn from this figure.

(1) Light transmittance increases with roof slope in pitched roof constructions.

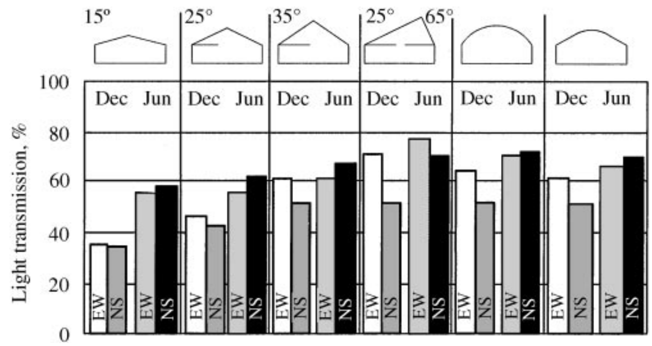

Fig. 5. Average solar radiation transmittance for different greenhouse types and orientation (EW – east-west orientation; NS – north-south orientation)

(2) Light transmittance is higher for east–west orientation in winter and lower in summer than north–south orientation.
(3) In the Northern Hemisphere, a saw-tooth or shed-roof with the steeper and shorter roof side to the south has a better transmittance than a pitched roof.
(4) Greenhouses with curved roofs have better transmittance than greenhouses with a pitched roof of 25° slope.

Figure 6 shows the calculated values of transmittance at different times of the day (Kirsten, 1973). A reduction of 10% by dirt and shading due to the structural components is taken into consideration. The best transmittance during winter is given by the arch roof of single-span greenhouses with an east–west orientation, followed by the saw-tooth and the pitched roof. The transmittance is slightly better under a pitched roof in summer than under

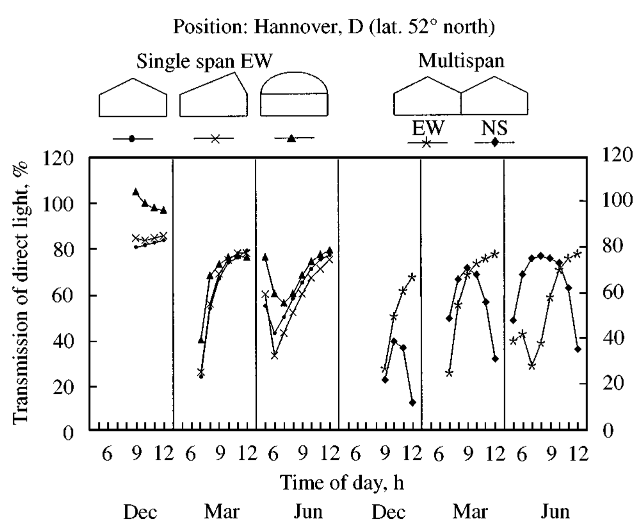

Fig. 6. Hourly dependence of the total solar radiation transmittance for different greenhouse types (Kirsten, 1973)

Table 2
Light transmittance of a Venlo-type greenhouse (Bot, 1983)

Date	*Light transmittance, %*	
	Orientation	
	East–west	*North–south*
21 December	45	35
21 February	58	53
22 March	59	62
21 April	60	67
21 June	65	70

a saw-tooth roof. The transmittance through multispan pitched-roof constructions is higher in winter for east–west than north–south orientation. There is more light in the greenhouse with north–south orientation in the morning during spring and summer. Table 2 gives average daily figures of transmittance for a Venlo-type glass greenhouse, calculated by Bot (1983).

3.3. *Condensation on the greenhouse cover*

Water condensation on the inner surface of the covering material influences the light transmission and the heat transfer through the cover. The structure of the patterns created by the condensed water vapour on the cover depends on the wetting tension of the covering material. One can distinguish different kinds of condensation behaviour. On most untreated plastic materials, condensation appears in small droplet form, which reduces light transmission considerably due to multiple reflections of the incoming solar radiation inside the drops (Hsieh & Rajvanshi, 1977; Jaffrin & Morisot, 1994). Eggers (1975) measured a reduction of 15–18% in light transmittance under an untreated plastic-film tunnel with drop condensation. The light transmittance of different covering materials with condensation has been measured on a test stand in Hannover (Faehnrich *et al*., 1989).

Treated, so-called 'anti-drop' or 'no-drop' materials exhibit film condensation, which can improve the solar radiation transmittance. On glass, water vapour condenses as a water film or in the form of spread drops which run-off. Half-spherical drops appearing on plastic material can drop down and drench the plants if the roof angle is too low.

Table 3 shows the light transmittance of various covering materials in dry condition and with condensation.

The results can be summarized as follows.

(1) Heavy condensation reduces light transmittance also on glass due to the creation of flat drops, which do not fall.

Table 3
Light transmittance of glass and polyethylene film in dry and wet conditions (Faehnrich *et al*., 1989)

Material	*Roof slope, deg*	*Light transmission, %*	
		Dry	*With condensation*
Glass	15	90·8	82·7
	30	89·9	81·9
Polyethylene film	15	90·8	82·7
	30	89·9	81·9
Polyethylene film, 'anti-drop'	15	87·1	88·1
	30	86·4	88·3

(2) Drop condensation reduces light transmittance through polyethylene film. Also drops fall down from roofs of small slope and encourage plant diseases. A minimum slope of 20–25° should be used for roofs of untreated plastic film to avoid heavy dripping on the plants.
(3) Light transmittance is less reduced under treated polyethylene or 'anti-drop' film.

Depending on the type of the material and the weather conditions, the effect of condensation on the heat transfer coefficient of the cover — and so on the heat loss — differs. For glass, condensation increases the heat transfer coefficient as the latent heat released to the glass, increases the glass temperature. The radiative heat loss of glasshouses depends only on glass and sky temperatures since glass is an opaque material to the thermal radiation spectrum. For plastic films, condensation changes the heat transfer coefficient due to several interrelated factors. The latent heat released to the film raises its temperature. In this way, the convective and thermal radiation losses increase. The thermal radiation transmissivity changes too. It decreases with increasing wetted area. So the internal surfaces of the greenhouse lose less thermal radiation to the sky. The magnitude of radiative heat loss itself depends on the sky temperature (clearer sky implies lower sky temperature). So the amount of condensation and the size of the wet area, the thermal transmissivity of the dry film and the cloudiness of the sky influence the overall heat transfer coefficient of a wetted plastic film. Therefore, total heat losses can be lower or higher in comparison to a dry film of the same plastic material depending on accidental combinations of competing factors. For this reason, several authors report an increasing effect of condensation on the heat transfer coefficient (Walker & Walton, 1971; Delwich & Willits, 1984; Garzoli, 1984; Weimann, 1986) while others report a decreasing one (Feuilloley *et al*., 1994).

Table 4
Influence of dirt laid down on greenhouse covers in the South of France, on diffuse light transmittance (Gratraud, 1990)

Cover type	*Diffuse light transmittance, %*			*Loss of light transmittance by dirt, %*
	Reference cover	*Rough cover*	*Washed cover*	
EVA film, exposed 18 month	79·1	66·0	74·9	8·9
EVA coextruded film, exposed 12 month	79·0	64·5	77·7	13·2
Glass, exposed 12 month		72·8	77·1	4·3

EVA (ethylenevinylacetate) film is a PE film, consisting typically 4–18% of VA.

3.4. *Dirt on the greenhouse cover*

Dirt on plastic films strongly influences the transmittance of the greenhouse cover (Gratraud, 1990). The altering effects of dust and condensation on the greenhouse cover are cumulative and can lead to light losses of nearly 40% in winter for a single-cover structure and even more for an inflated double-film greenhouse (see Table 4). These figures are smaller in summer since condensation occurs less frequently and the incidence angle on the dust layer is nearer to the normal. A high value of light loss due to dust can reverse the initial advantage of plastic greenhouses and result to a light transmittance lower than that of the glass. The foreseen extensive use of plastic greenhouses for light-demanding crops most certainly requires a satisfactory solution of the problems caused by dirt accumulation and condensation in drop form (Jaffrin & Morisot, 1994).

3.5. *Ventilation*

3.5.1. The ventilation process

The ventilation openings are essential functional elements of a greenhouse. Their location and design can strongly influence the quality of the indoor microclimate and the energy efficiency of the greenhouse. Since in most greenhouses the renewal of internal air is exclusively obtained by passive ventilation, the design of the ventilation openings should allow strategies for enhancing the ventilation rate under various weather conditions.

The ventilation capacity of a greenhouse is usually described by the opening ratio. This expresses the maximum opening area as a percentage of the covered ground area. However, the size of the ventilators is only one design parameter influencing the ventilation efficiency of a greenhouse. Thus, the characterization of the greenhouse ventilation efficiency merely by the opening ratio is misleading in many cases. A high opening ratio is only an indication of high ventilation capacity while the position, the shape and the operation of the ventilators also influence strongly the air renewal rate in greenhouses.

The two driving forces responsible for the passive ventilation in buildings are the external wind and the temperature difference between the interior and the environment. The latter case is also described by the term 'buoyancy effect' or 'stack effect', since gravity is the driving force of the air dynamics.

The wind-generated pressure distribution around the greenhouse cover induces internal airflow if there is a pressure difference among the opened ventilators. The pressure distribution at the cover depends on the shape of the greenhouse frame. In particular, they are strongly influenced by the shape of the roof and the ventilators. Clearly the position of the ventilation openings is critical for obtaining a strong pressure gradient along the greenhouse interior.

In the case of buoyancy effect, the pressure gradient is generated by the density difference between air masses of different temperature. The heavier, colder air moves downward under the influence of gravity and replaces hotter air, which is forced to move upwards. If the greenhouse is equipped with ventilation openings both near the ground level and at the roof, this type of ventilation replaces the internal hot air by external cooler one, during hot sunny days with weak wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings.

3.5.2. *Roof and side ventilators*

The ventilation openings are usually distinguished into roof and side ones. This distinction is based on the differences with respect to design and functionality.

The term 'roof ventilators' is used to characterize the openings located at a height above the working space in the greenhouse (*i.e.* 2 m height). It has been shown that the roof ventilators generally induce higher ventilation rates when wind driven ventilation is considered (Papadakis *et al*., 1996). The main reason for this effect is that the side ventilators usually are located at the lower part of the sidewalls, approximately 1 m above the ground. At this height, the wind speed is strongly reduced by the friction with the ground. Moreover, the effect of aerodynamically created pressure differences induced by the shape of the roof is stronger at the roof ventilators.

On the other hand, the sidewall ventilators are necessary for inducing gravity-driven ventilation when the wind speed is low. It has been shown that roof ventilators alone cannot create efficient ventilating airflow at low wind speed conditions (Mistriotis *et al.*, 1997). However, side ventilators are considered secondary in several greenhouse designs, particularly in Northern Europe where the ventilation needs are smaller.

3.5.3. *Specifications and requirements for ventilators*

The external climatic conditions under which a greenhouse operates and the crops, for which it is used, define its ventilation needs. In southern countries where the intensity of the sun radiation is strong, ventilation is the most common cooling method. On the contrary, the cooling effect of the ventilation is secondary in northern countries during autumn, winter and spring where the air exchange process is mostly used for regulating the internal levels of humidity and CO_2. Moreover, in northern countries the insulating performance of the greenhouse cover is more important than the ventilation efficiency. Therefore, the specifications for greenhouse design with respect to ventilation vary accordingly.

If local climatic conditions impose high ventilation efficiency as a basic requirement for a greenhouse, a few important specifications can be defined.

(1) High air renewal rates must be maintained under most weather conditions. Therefore, the greenhouse should allow both wind- and gravity-driven ventilation.
(2) The ventilation opening design has to minimize leakage ventilation when they are closed. In this way they prevent the loss of heat during cold nights.

The above specifications impose a few simple restrictions to the greenhouse design. First, both roof and sidewall ventilators are required for obtaining high ventilation rates under all wind conditions. Moreover, the ratio of the covering area divided by the covered ground area must be large to allow high opening ratios and more possibilities with respect to positioning (roof and side) and designing the ventilation openings. For this reason, large multispan greenhouse blocks are rare in southern countries.

On the other hand, leakage ventilation should be prevented in order to improve the insulating performance of the cover. This can be obtained by keeping the covering area small. Hence, large multispan greenhouses exhibit lower energy losses and are preferred in northern countries. Leakage ventilation is also influenced by the quality of the cover and the ventilator operating mechanism. Moreover, the size of the ventilators influences heat losses since most leakage ventilation is a result of poorly closed windows. For this reason, the authors suggest that the maximum opening ratio should not exceed 25% (von Zabeltitz, 1992). However, opening ratios as large as 40% are not rare in Mediterranean greenhouses (Feuilloley *et al.*, 1995).

The ventilator design should also fulfil a few other structural and functional requirements.

(1) Their size and form have to be compatible with frame structure and the properties of the covering material. In particular, the openings must not weaken the structural stability of the greenhouse.
(2) The reduction of the greenhouse light transmittance due to shadowing by the operation mechanism should be minimal. This can be obtained by incorporating the operation mechanism in other structural elements of the frame.
(3) The operation mechanism must tightly close the ventilators to avoid undesirable leakage ventilation.
(4) The shape and the operation of the ventilators have to be designed to protect the crop from direct rainfall even when they are opened.
(5) The ventilators must satisfy other operational needs of the greenhouse. For example, side ventilators can also be used as doors.

4. Conclusions

Greenhouse cultivation is a steadily growing, highly competitive sector of agriculture all over the world. In all European countries, horticulture under cover is a profitable branch of agriculture. However, local conditions influence the greenhouse design, giving rise to a large variety of greenhouse types built with different covering materials and designed to fit the local climate.

In this work (Part I), the European location-dependent factors influencing the greenhouse design such as the climate, the local building regulations, the indoor climate requirements and the functional characteristics are presented.

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 European national standards for greenhouse construction.

Regulations imposed at national or international level also influence the greenhouse design. In many cases legislative restrictions, even though necessary, discourage the innovative activities based on novel technology. In particular, safety rules concerning structural failures and the corresponding load requirements are hard to define since the greenhouse design is a multi-parameter optimization problem. For example, the requirement for very high light transmittance leads to designs with smaller and fewer structural elements, which may affect the structural stability of the greenhouse.

It is obvious that there is no perfect 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, but the particular choice of a greenhouse type depends very often primarily on the grower's personal point of view and experience. In many cases, local tradition and compatibility considerations to existing greenhouses play an important role in the decision-making. Moreover, local and European-wide economic considerations strongly influence the popularity of certain greenhouse types.

The radiation transmittance and the insulating performance as well as the ventilation capacity of a greenhouse are important factors taken into account in the design. The large variety of covering materials make the selection of the cover a very complex task while the optimal design of the ventilating openings remains a mostly unresolved problem.

The recently developed draft European standard for the commercial production of greenhouses is a first attempt for standardizing the greenhouse design methodology at a European level. This draft standard has been developed for establishing some specific designing procedures for actions and other design considerations, as a complement to the basic procedures of the corresponding Eurocodes for actions and structures. It is expected that the present work focusing on the variability of the European greenhouse design parameters will support and stimulate future research aiming at integrating the European greenhouse design considerations.

In Part II of this work, the most important greenhouse types used in EU countries are presented. The analysis of the structures with respect to the design requirements and the adjustment to local influences is worked out for the greenhouses types in Germany, The Netherlands, France, Italy, Spain and Greece.

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