Project Title:	The use of dynamic climate control systems for the production of high value ornamental crops in the UK – A technical assessment.
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Location of Project:	Farm Energy Centre & HRI Efford
	Various locations in Holland & Denmark
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Practical Section for Growers

1 Commercial benefits of the project

This project has identified and evaluated the potential benefits of applying dynamic environmental control strategies to the production of ornamental crops in protected facilities. Benefits relate to increases in energy efficiency and the potential improved management of the internal greenhouse environment.

2 Background

Recent increases in energy costs and the introduction of the Climate Change Levy (CCL) have brought the need to improve energy efficiency into sharp focus. With energy costs now accounting for up to 40% of the variable costs of production, growers of protected crops are now seeking practical methods of improving energy performance.

Over the next 10 years the protected horticultural industry in the UK will be under the spotlight to demonstrate improvements in energy efficiency. This is because it has recently committed to a 15% target through a voluntary agreement with the government. This agreement therefore further highlights the need for solutions to be found quickly and adopted by the industry.

Both researchers and commercial companies have recently suggested that the use of advanced control methods is a good way of improving energy performance and systems that move away from the traditional method of fixed ‘set points’ for temperature are claimed to make significant energy savings. These systems use control methods that allow the environmental set points to change dynamically to meet both the needs of the crop and the external weather conditions. Two such systems are:

- **Temperature Integration –** recently commercialised by leading greenhouse climate control companies in Holland**,** this method recognises that crops can accommodate changes in temperature so long as an ‘average set point’ is maintained. The period over which the average is calculated (which is known as the integration period) can vary from 24 hours to a number of days.

- **IntelliGrow –** developed by the Danish Institute of Agricultural Sciences (DIAS), this method uses a control policy that aims to maximise the photosynthetic response of the crop. To achieve this in practice, set points for temperature and CO_2 are allowed to change according to the amount of light available.

To further investigate the potential for these systems, a study visit to Denmark and Holland was carried out over the period 26 Feb to 2 Mar 2001.

3 Key Findings

The key findings of the study were as follows:

- **Can the new control systems help improve energy efficiency?** – Yes, using dynamic control systems can make improvements.
- **If so, how are the savings made? -** Energy savings are made through a combination of the following :

  i. Making improved use of 'free' solar energy. In practice this requires setting control equipment so that temperatures can increase above the traditional set point at times of significant solar gain.

  ii. Reducing temperature set points at times when the amount of light available is limiting plant growth.

- **What is the basis of the new systems? -** The basis of dynamic climate control systems is to modify the environment to maximise the plant performance. This is based on basic published plant physiology data. The novel feature is how the regular changes are achieved by using control functions on a climate control computer.
- **What levels of savings have been achieved in the experiments and trials? -** The Danes and Dutch have been conducting trials both at experimental stations and on grower holdings and have reported a maximum saving of 40%. This was achieved under strict experimental conditions. However, grower trials conducted over a whole season produced savings closer to 15%. This would appear to be more indicative of what is achievable under commercial conditions.
- **Are there any potential problems? -** There are potential problems with increased humidity, condensation and airflow. However the commercial experience suggests that adoption of the new systems provide the grower with a better understanding of the growing environment, which in turn leads to improved conditions within the greenhouse. Therefore, in practice, pest and pathogen populations do not build up to critical levels and plant health is improved.
- **Is every grower in Holland & Denmark using the systems? If not what is the resistance to take up? -** The resistance to taking up dynamic environmental control tends to be because of concerns regarding the response of crops grown in large production areas with mixed cropping. However the growers who are either using or trialling the new systems are very enthusiastic and are claiming a 15% energy saving with no compromise on scheduling or quality.
- **Can the systems be used on my current climate computer? -** Most commercial climate control computers can be adapted to enable growers to take up the key

principles of dynamic control. However, as a minimum, an investment of time will be required to understand system operation and train staff.

4 Action Points for Growers

In response to the findings of this study, growers should carry out the following actions.

- Train all necessary staff in the operation of climate control systems.
- Maintain control equipment on a regular basis including the calibration of all sensors.
- Allocate more management time (preferably on a weekly basis) to review control settings, environmental control strategies and resulting crop performance.
- Evaluate control strategies and set points for the crops being grown. Instigate the use of light dependent temperature (and CO_2) set points where appropriate.
- Investigate the upgrading of existing systems to incorporate the latest strategies including Temperature Integration.

5 Anticipated Practical and Financial Benefits

The major benefit of UK growers adopting dynamic environmental control technologies is an increase in energy efficiency. Savings in the order of 12-15% of heating costs per annum are anticipated. With heating costs for ornamental crop production in 2001 being predicted to be in the order of £4.50 - £7.00/m^2/annum, savings of up to £1/m^2/annum could be achieved.

Science Section

1 Background & Introduction

Recent increases in the cost of energy have alarmed many growers and highlighted the need to keep energy costs under control. In addition the Climate Change Levy (CCL), which is to be introduced from April 2001, will serve to further increase the cost of energy for growers. Both of these changes are clear indications that, in the future, improving the energy efficiency of crop production is going to be of increasing importance to all businesses in the protected cropping sector.

Although horticulture has been granted a 50% rebate on CCL, it is the intention of the UK Government that this will only be available for up to 5 years. To strengthen the case for continuation of this rebate, and to comply with requirements of EU State Aid, a voluntary energy efficiency agreement between the horticultural industry and the Government has been established. This agreement requires a 15% reduction in the specific primary energy consumption to be achieved over the 10-year period beginning in 2001. Improvements will be assessed in terms of the quantity of energy used per unit of production (i.e. kWh / plant for ornamental crops or kWh/kg for edibles).

Growers therefore need to act quickly to meet the requirements of this agreement and to respond to the economic pressures of a changing energy supply market.

The results of research (Rosenquist 2000, Research Station for Floriculture & Glasshouse Vegetables, Netherlands, 1998) suggests that using improved control strategies for greenhouse heating and lighting is a cost effective way of achieving significant efficiency improvements. At present most environmental control systems have fixed settings, known as set points. These are typically for temperature, CO_2 concentration and in some circumstances, relative humidity. This approach is used not because plants require constant conditions, rather that a fixed system is relatively simple to build and operate.

As a better knowledge of how plants respond to environmental conditions has been obtained, it was recognised that improvements could be made to this system. For example it has been shown (Hurd & Graves, 1984) that many plants can actually respond to the average temperature achieved over a pre-determined period. This therefore enables a temperature profile to be used, so long as average temperature set point conditions are achieved.

The application of this principle has led to both academic and commercial advances. Two developments of significant interest are:

- **Temperature Integration –** recently commercialised by leading greenhouse climate control companies in Holland, this work builds on research carried out in the UK & elsewhere (Bailey, 1994, Chalabi et al 1998) on edible crops. The control method used recognises that crops can accommodate changes in temperature so long as an 'average set point' is maintained. The period over which the average is calculated (which is known as the integration period) can vary from 24 hours to several days. The extent of the integration period is limited by the ability of individual crops to accommodate the induced temperature variations.
- **IntelliGrow –** developed by the Danish Institute of Agricultural Sciences (DIAS), this method uses a control policy that aims to maximise the photosynthetic response of the crop. To achieve this in practice, set points for temperature and CO_2 are allowed to change according to the amount of light available.

2 Research Method

To critically evaluate these recent developments and assess their likely commercial uptake by growers in the UK, a visit to Holland and Denmark was carried out over the period 26 February – 2 March 2001 inclusive. Research Institutes, control equipment manufacturers and commercial growers were visited to assess the individual systems and identify how the results of the work could be transferred to the benefit of the horticultural industry in the UK.

A full itinerary for the visit is provided in Appendix One.

3 Discussion – Objectives v Findings

3.1 What are the component models of IntelliGrow and Temperature Integration and what is the basis of their derivation? Are there any plans to further improve these models?

The component models for both IntelliGrow and Temperature Integration are based on published research that is widely available in the public domain. These models can be divided into two main areas:

- Plant Response Models
- Energy & Mass Balance Models

There are no plans in place by the research team at DIAS to further develop these models because it is considered that the current knowledge adequately describes the response of commercially produced species and greenhouses.

Further background to the models used is described below.

3.1.1 Plant Response Models

The models used in both Temperature Integration and IntelliGrow are well established theories describing the response of plants to temperature. These models describe how any element of plant response (height, flowering, respiration etc.) alters with temperature (Salisbury and Ross, 1985). In general the responses are limited by chemical reactions and so increase linearly over a certain temperature range and then either flatten off or actually begin to reduce as the conditions become sub-optimum.

Temperature Integration is essentially a way of assessing the thermal input into a crop. That is to say, it is possible to sum all the temperatures achieved and calculate the ‘thermal time’ that has been delivered to a crop. If it is known (for a given light receipt) either how much thermal time a given crop requires to get to flowering, or at a given temperature a crop will flower in a predictable time, then temperature integration becomes usable (Cockshull, 1993).

In practice plants tend to average the temperature over given periods of time. For some plants this may only be one or two days, but with most species this will extend to a period of over a week. This enables a grower to push a crop during favourable conditions and let it slow down during cooler periods. This process is the basis of both DIF and DROP, where the plants ability to average over 24 hours enables growers to manipulate the ‘form’ of a plant by controlling stretching or shortening. Temperature Integration further extends this process by logging the temperature history during production and shifting set points to allow the average temperature to be maintained and a schedule to be met.

IntelliGrow is primarily based on a model to optimise photosynthesis. It uses models of how leaf photosynthesis and respiration vary with irradiance. At any given temperature and CO_2 concentration, a plant increases both photosynthesis and respiration linearly until a plateau is reached. Changes in either temperature or CO_2 concentration cause this optimum to alter.

The IntelliGrow control algorithm therefore uses monitored light level to derive options for both temperature and CO_2 concentrations. The control computer then selects the highest possible net photosynthesis (or lowest possible negative balance against respiration) that is closest to the current glasshouse environment and thus easiest (i.e. lowest energy input) to achieve (Aaslyng et al, 1999).

3.1.2 Energy & Mass Balance Models

Figures 1 and 2 show a schematic representation of the heat flows during energy inflow (heating) and outflow (cooling).

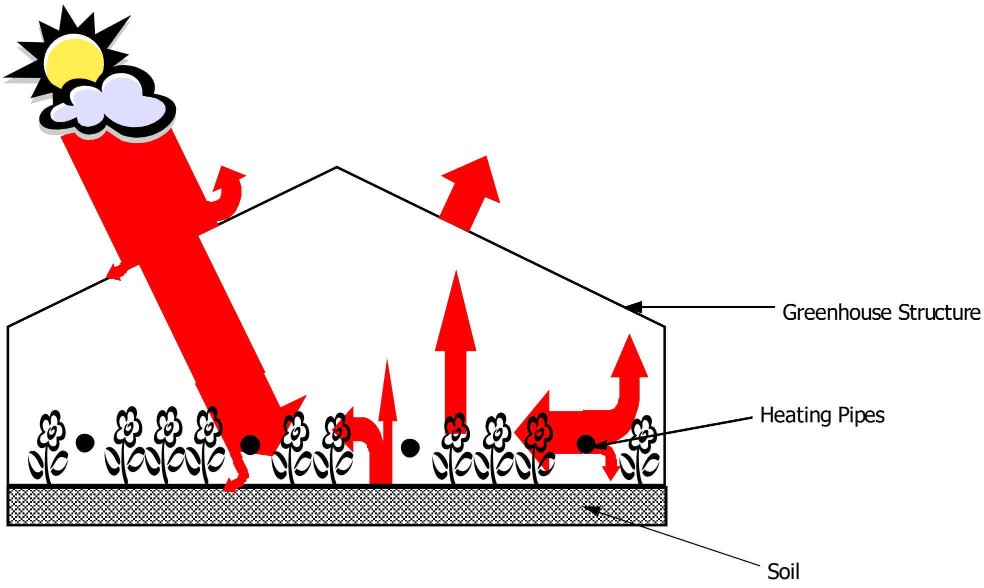

Figure One: Energy Flows During Heating

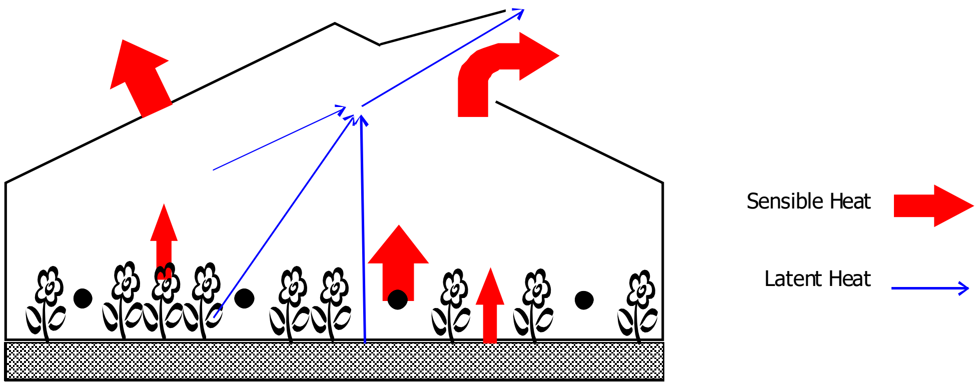

Figure Two: Energy Flows During Cooling

In its most simple form, the energy balance model for a greenhouse is described by equation 3.1 below.

$$Q = U\,A\,(T_i - T_o) - \alpha R_s \quad \text{------------------------} \quad (3.1)$$

Where:

Q	=	Energy supply requirement
U	=	Heat transfer coefficient of greenhouse
A	=	Ratio of greenhouse area to ground area
T_i	=	Internal temperature
T_o	=	External temperature
α	=	Proportion of solar radiation converted to sensible heat
R_s	=	Solar radiation

Examination of this expression reveals the methods available for reducing the energy inputs to a greenhouse. These include:

1. Improving the heat transfer coefficient
2. Reducing the area of greenhouse envelope
3. Reducing the differential between internal and external temperatures
4. Maximising the use of solar radiation

Other than through the use of thermal screens, options 1&2 are clearly not cost effective or practical propositions for existing facilities and/or current commercial greenhouse designs. Improved control systems therefore focus on points 3&4. Both Temperature Integration & IntelliGrow use a strategy that allows the control set point to drop at times of high energy demand (e.g. low ambient temperature with high external wind speed). This is however compensated for by allowing the internal temperature to rise when the solar radiation and/or ambient temperature is high, or the wind speed is low. This strategy also maximises the sensible heat input from solar radiation, rather than rejecting it to atmosphere through ventilation of the greenhouse.

Various workers (Joliet et al 1991, Van Bavel et al 1985, Bot 1983) have significantly developed the simple model and their work provides the basis of the algorithms used for decision support in the practical application of both IntelliGrow and Temperature Integration.

3.2 What are the key principles of new climate control systems and how do they differ from the equipment currently used by UK growers?

As detailed in section 3.1 above, both Temperature Integration and IntelliGrow use common key principles. These are:

- Greenhouse environmental conditions are allowed to change within pre-determined limits depending upon the prevailing ambient conditions (e.g. temperature, wind-speed, light levels).
- 'Set points' are allowed to change throughout the day and are determined by the control system to maximise plant growth and / or economic gain.
- To compensate for periods of increased temperature (which typically occur during the day), the temperature minimum set point (which normally occurs overnight) is reduced.
- Energy efficiency is improved by maximising naturally available resources (e.g. solar gain) whilst attempting to run the greenhouse at a reduced average temperature. The target rate of change of temperature is also relaxed to ensure that changes take place over a longer time-scale.

The key difference from systems currently in widespread use in the UK is that the new systems move away from the concept of fixed set points with relatively tight tolerances for control. Both systems apply the principle that plants can accommodate dynamic changes.

3.3 What experiments and commercial trials are being conducted with the systems in Denmark and Holland? What is the level of energy saving that is being achieved and how is it being measured?

Wide ranges of experimental work and trials have been carried out in both Denmark and Holland. This includes work at research centres and commercial uptake by growers in both countries.

The most reliable data is available from the research trials. This is because information and data has been collected in a thorough manner using well designed experimental protocols. In addition accurate and reliable instrumentation has been used to quantify the responses obtained.

Semi commercial & grower trials of the systems have produced enthusiastic supporters of the technology. Performance indicators are somewhat undependable however as they tend to be based on subjective and commercial indicators which are not based on reliable data.

Maximum energy savings of 40% are being achieved in the trials at DIAS. These are not true indicators of what can be realised on a year round basis as they were achieved over a period of a few weeks during the heating season.

3.4 Are there any potential problems such as humidity control, airflow, condensation, disease (e.g. Botrytis) and what are the implications for biological control when applying the system under UK conditions?

Yes the potential for problems linked to all of the above areas were identified.

It was felt that the research studies in Denmark were not representative of commercial practices (in either the UK or Denmark) and therefore did not provide a good indication of the likely commercial risks.

On the other hand commercial experience with the systems gave a more reliable indication of how the problems could be overcome in practice. In many cases the sites using the systems demonstrated that the internal greenhouse environment could be improved through careful manipulation of environmental control parameters.

It was observed that both the trial facilities and commercial nurseries visited had significant levels of condensation on the greenhouse cladding. When questioned, both researchers and commercial growers indicated that condensation levels were such that regular glass cleaning was very important. As a result recommendations of cleaning glass twice per year using a power washer were given.

No problems were identified with the application of biological control systems.

3.5 Are the energy saving facilities available on commercial climate control computers being widely used by the growers of ornamental crops in Holland and Denmark? If they are, then can their experiences provide UK growers with guidance on the likely energy savings and the effects on crop quality and scheduling.

In Denmark, the evidence presented indicated that energy saving control strategies were not in widespread use by commercial growers. There was however significant interest in applying the underlying principles of IntelliGrow and the extension service were currently very active in work programmes to increase commercial uptake. The nurseries visited in Denmark were producing specialist crops that were not typical of species grown in the UK (e.g Brunfelsia, Alemanda, Hianthus & Sagina).

Growers in Denmark highlighted that to successfully apply IntelliGrow on a commercial basis required the strategy to be used only during the vegetative growth phase of a cropping cycle. Using IntelliGrow during the propagation and flowering phases was likely to lead to both scheduling and quality problems.

Information gathered in Holland presented a more confused picture. One commercial control manufacturer indicated that it had in excess of 250 customers who were using temperature integration control strategies on a regular basis. However another supplier indicated that, although the facilities were available on their system, commercial uptake was limited. This therefore gave somewhat conflicting evidence. It is thought that a degree of resistance to the full uptake of Temperature Integration exists. This is due to the conservative nature of growers and their reluctance to upset an established production system just to make energy savings. The shifting economics of energy inputs is changing this view however.

Despite the fact that the crops grown on the nurseries visited were not typical of those produced in the UK, it was obvious that those using the technology were benefiting from improved energy efficiency whilst not compromising on crop quality or scheduling. In some cases, because the businesses now had a better understanding of the operation of their environmental control systems, improvements in product quality were resulting.

This is best illustrated by the quote of one grower who said:

'Never have I earned so much money in so few hours'

Indicative savings were 15% of heating energy inputs per annum. This level of savings is likely to be replicated under UK climatic conditions and production systems.

3.6 Who owns the IPR for the IntelliGrow system? What is the potential for exploitation by commercial climate control companies (e.g. Priva, VanVliet, Hoogendoorn etc) and how can UK growers adopt the new strategies into their existing climate control computer systems. Can IntelliGrow or Temperature Integration be integrated into the systems currently being used by UK growers and what would it take to do so?

Temperature Integration is now being fully exploited by most of the leading commercial climate control companies and is offered as a feature on the current range of systems.

There are no immediate plans by DIAS to commercially exploit the **IntelliGrow** system by working exclusively with a climate control manufacturer. DIAS feel that the underlying principles of the system are of greatest value and would like the concepts to be widely applied by a broad cross section of growers. It is felt that this can be best achieved by allowing manufacturers and growers alike free access to the concepts that make up the IntelliGrow system.

From the information obtained, a large number of UK growers can adopt the basic principles of dynamic climate control with the control systems currently in use. This move can be made relatively quickly and with little capital expenditure. Adopting the strategies does however require a greater understanding of the operation of climate control systems, their capabilities and the consequences of introducing a broader tolerance band for set points.

Growers using the most modern designs of climate controls are likely to be able to fully adopt Temperature Integration immediately.

4 Conclusions

1. The developments observed during the visit showed that significant improvements in energy efficiency can be achieved through the use of advanced controls in greenhouses. It was also concluded that growers in the UK could benefit significantly from using the technology.

2. Likely problems with crop scheduling and increased disease problems were identified. Nevertheless discussions with growers using the techniques revealed that such problems could be overcome in practice if the systems were applied sensibly at selective periods during the plant production cycle. Using the advanced strategies during the propagation and flowering phases was found to be inappropriate. However restricting the use of the strategies to the vegetative growth phases gave satisfactory results. It should be noted however that the crops viewed on the visit were restricted to specialist crops and were not typical of those produced in the UK.

3. Because the system can only be used at selective times, the energy saving potential in practice does not reach the maximum levels of 40% that are claimed by researchers at DIAS.

4. The levels of savings likely to be achieved in practice are:

- Immediate savings of the order of 8 to 10% could be made if growers examine the use of existing controls equipment in more detail and adjust the control set points and strategies to incorporate the underlying principles of Temperature Integration or IntelliGrow.

- In the medium term, savings could be increased to in excess of 15%. In the majority of cases however this would require many growers to upgrade their climate control systems to include Temperature Integration facilities with predictive capabilities and weather forecasting. This would therefore require some capital investments in new control equipment.

- In the longer term savings of over 20% may be achieved if the limits of application are determined. Achieving these levels would present significant risks with regard to crop scheduling and disease however and more R&D into the response of plants under the imposed conditions would be required.

5 Recommendations for Future Work

5.1 Technology Transfer

This work has strongly identified that immediate benefit could be obtained by a large number of UK growers if they could better understand and utilise the technology examined. This would however require a work programme with the following 2 elements.

- **Training –** Many growers have little understanding of the operation and capabilities of the climate control equipment installed in their greenhouses. As a result the majority of growers treat the equipment as a ‘black box’ which performs the functions of a sophisticated thermostat. In addition the consequences of adjusting environmental control parameters is not understood by many. This leads to a situation where the growers are not fully exploiting the capabilities of the equipment currently at their disposal.

  This situation could be addressed by providing training for growers and their employees. Various ‘stakeholders’ should be involved in the provision of this training including energy and plant science specialists, training organisations and control equipment manufacturers.

- **Demonstration –** As indicated above, growers are currently very conservative in their use of environmental control equipment and are reluctant to move away from the ‘tried and tested’. It is therefore likely that they will be reluctant to adopt the new approaches, as they will fear that any resulting problems may lead to a reduction in crop value.

  Demonstration work should therefore be carried out which illustrates the value of the technology to commercial growers. This work should be designed so that it shows that advantages can be achieved (both in terms of energy saving and improved production) without compromising plant quality.

5.2 Development Work

To fully exploit the potential of the technology will require more information on the limits to which the systems can be applied. It is unlikely that further work in Holland and Denmark will provide this data, largely because the crops and production systems that are common in these countries differ from those used in the UK. In the medium term therefore work will be require to establish plant responses and establish the practical limits for applying the techniques.

5.3 Strategic Research

All of the current work that is currently ‘near market’ concentrates on the manipulation of the internal atmosphere within the greenhouse to provide ‘optimum’ conditions for the crop. In most cases air temperature is used as the primary control variable.

It is now being widely recognised that this may not be the most effective method of manipulating plant response, and that parameters such as tissue temperature should be used. Both DIAS and the commercial manufacturers consulted during this study are all developing the use of infrared temperature measurement equipment to integrate with existing designs of climate controls. In addition recent MAFF funded research being carried out by Langton et al at HRI has initiated investigations into the changes in tissue temperature, which are brought about by variations in climatic conditions.

It is likely that a greater understanding of these parameters will extend the boundaries of concepts such as Temperature Integration and IntelliGrow and increase the potential for energy savings. For this reason it is important that strategic research is initiated which leads to a greater understand of plant response to the manipulation of the wide range climatic variables including CO_2, light, temperature and relative humidity.

Of particular importance are the response of crops to light and a greater understanding of threshold levels and the concept of light integration. Further information in this area would allow previous work relating to temperature and CO_2 response to be brought together such that energy inputs could be optimised.

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Appendix One – Visit Itinerary

Monday 26th February 2001	Travel to Danish Instititute of Agricultural Sciences, Aarslev, Denmark. Meet with Carl-Otto Ottosen, Head of Research Group for Floriculture & Eva Rosenquist.
Tuesday 27th February 2001	Visit Danish growers using IntelliGrow system in a commercial basis. Address details are: • Soren Ploug-Sorenson, Hojagergaard APS, Assens Vej 293, DK5642, Millinge. – Grower of Brunfelsia and Alemanda in greenhouse of total area $8500m^2$ • Bjorn Rasmussen, Finn Plougheld, Gartneriet Lundegard, Espestok 54, Korup, DK52 10 Odense. - Grower of Hianthus, Sagina & Twiggy in greenhouse of total area $6000m^2$
Wednesday 28th February 2001	Travel from Denmark to Holland
Thursday 1st March 2001	Meeting with Hoogendoorn Automation, Vlaardingen , The Netherlands. Discussions with Peter van Duin (Sales Director) and Ted van den Akker. Taken on conducted tour of 3 nurseries including cut Gerbera, Pot Plants and cut Roses.
Friday 2nd March	Meeting with Priva Hortimation BV, De Leer, The Netherlands. Discussions with Andre de Raadt (Product Manager) and Chris Addis (managing Director, Priva UK). Taken on conducted tour of Bunnick Plants, Bleiswijh.