Development of a grow–cell test facility for research into sustainable controlled–environment agriculture

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Abstract

The grow–cell belongs to a relatively new category of plant factory in the horticultural industry, for which the motivation is the maximization of production and the minimization of energy consumption. This article takes a systems design approach to identify the engineering requirements of a new grow–cell facility, with the prototype based on a 12 m× 2.4 m× 2.5 m shipping container. Research contributions are made in respect to: (i) the design of a novel conveyor–irrigation system for mechanical movement of plants; (ii) tuning of the artificial light source for plant growth; and (iii) investigations into the environmental conditions inside the grow-cell, including the temperature and humidity. In particular, the conveyor–irrigation and lighting systems are optimised in this article to make the proposed grow–cell more effective and sustainable. With regard to micro–climate, data are collected from a distributed sensor array to provide improved understanding of the heterogeneous conditions arising within the grow–cell, with a view to future optimisation. Preliminary growth trials demonstrate that *Begonia semperflorens* can be harvested to the satisfaction of a commercial grower. In future research, the prototype unit thus developed can be used to investigate production rates, plant quality and whole system operating costs.

Keywords: Agricultural engineering, Sustainable development, Energy

efficiency, Automation

1. Introduction

Controlled environment horticulture is a subject nested within the wider agenda of optimising the food system, in order to deal with forthcoming changes in population and climate (Food and Agriculture Organization of the United Nations: FAO (2002, 2015)). Today's established protected crop growth medium is the glasshouse (and related plastic covered systems), globally occupying an estimated 8000 km^2, in which intensive use of pesticides and excess water supply generally takes place (Wainwright et al., 2014). Hence, there is a considerable effort by stakeholders in the agricultural industry to optimise a range of sub-processes, with the aim to decrease harmful residues and energy inputs.

Such research includes investigations into the physical structure in which plants are grown, and the exploitation of modern technological know-how in order to deploy a higher level of system automation. For instance, significant work has been carried out by the industry to realise what are typically known as plant factories. These are multi-layer growing systems installed in thermally insulated, fixed or mobile buildings, and equipped with artificial light (Markham, 2014; Payne, 2014; FreightFarms, 2016; GreenTech, 2016; Hughes, 2015; Kozai et al., 2015; Oguntoyinbo et al., 2015; Ohara et al., 2015; Park and Nakamura, 2015; Sugano, 2015). Some immediately perceived benefits are: the flexibility to grow crops at any geographical location, reduced pesticide use and the decrease of food miles, all of which induce savings in terms of transportation costs, greenhouse gas (GHG) emissions and crop nutritional and economic value (Tsitsimpelis and Taylor, 2014). There is also scope for investigation of biological and horticultural issues, for example crop delivery date and flavour, by on–line regulation of the lights and micro-climatic.

Plant production by means of artificial climate and artificial or hybrid light dates back to the first quarter of the 20th century. Initially, the primary motivation was to facilitate research into plant responses for different environmental conditions, with illustrative early citations including Harvey (1922); Popp (1926); Davis and Hoagland (1928). However, thanks to recent technological advances relating to the performance and operating costs of LED lights, it is now possible to realise such facilities for industrial use, with the long term expectation being to outpace the use of greenhouses in terms of production and energy efficiency. A number of systems have been brought into the industrial domain over the past few years, particularly in Japan and the USA (see e.g. Markham, 2014; Freight-Farms, 2016; GreenTech, 2016), and interest is expected to further increase as big corporations are investing in the erection of indoor farms (Payne, 2014; Hughes, 2015). Nevertheless, there are numerous on-going research challenges relating to their design and operation. For example, their energy requirements, air movement, dehumidification, internal racking design, different ways to deploy artificial LED lighting, and the monitoring of crop reaction to these.

In principle, a holistic approach to the optimisation of all these will allow for the minimization of total GHG emissions and water consumption, and the concurrent maximization of year round production. Hence, for the research behind the present article, a systems design approach is used to identify the engineering requirements of a new grow–cell facility, with novel contributions made in three interconnected areas. These relate to the systems for mechanical movement and irrigation of the plants, the control of artificial light and an analysis of the environmental conditions inside the grow-cell, including temperature and humidity. The article also provides a selective overview of the literature in these areas, and in this manner aims to provide an introduction to the grow–cell concept and current limitations.

The prototype unit for this research is based on a 12 m$\times$ 2.4 m$\times$ 2.5 m freight container. As illustrated by Fig. 1, the interior is partitioned into two sections. The first, nearest to the entrance, occupies 2.5 m of the overall length and is used to facilitate control, monitoring equipment and power supply. The main area is further split in half via a motor controlled curtain, with one half presently left empty for access to plants by researchers. The plant growth process takes place in a multi–layer configuration, and light for photosynthesis is provided by

LED panels. In the commercial system, the entire container would be given over to plants in order to maximise production. In part for this reason, the growing trays are circulated by means of a novel conveyor system, in which single point irrigation is implemented. The conveyor allows for operator access to the plants and potentially provides for the automatic insertion, inspection and harvest of crops. It also ensures a more equal treatment of plants in terms of environmental variables, and adds to the circulating effect provided by the fans.

One aim of the present research is to optimise the conveyor–irrigation and lighting systems to make the prototype grow–cell more effective and sustainable. With regard to the conveyor, the specific objective is to design a mechanical system with low-power consumption that is adaptable for differently sized grow-cells, and different types of irrigation; and to evaluate the reliability and practical utility of this design in both a laboratory situation and for an illustrative plant growth trial. For the lighting system, the objective is to adapt readily available commercial units so that they are capable of varying the amount of photosynthetic photon flux density (PPFD), and to investigate their spectral characteristics. The subsequent aim is to use these results to optimise the balance between PPFD magnitude and energy consumption in advance of the growth trial.

The primary objective of the growth trial is to test the entire prototype grow–cell system in an illustrative practical situation and, more specifically, to demonstrate that *Begonia semperflorens* plantlets can be grown and harvested to the satisfaction of a commercial grower. During these experiments, micro–climate measurements are collected from sensors inside the grow–cell. Although not the focus of this article, previous research by the present third author has modelled such processes using a data–based mechanistic approach that generally leads to relatively straightforward, dominant mode models suitable for digital control system design (Price et al., 1999; Taylor et al., 2004; Stables and Taylor, 2006; Taylor et al., 2013). In this regard, typical practice (e.g. in greenhouses) is to use a small number of individual sensors at locations such as air inlets/outlets, and the middle point of a growing area, to serve as a representation of temperature conditions in the whole facility. By contrast, the present research utilises an array of 33 sensors along the entire length and height of the growing area. The initial objective is to use these data to gain an improved understanding of the heterogeneous conditions arising.

The article is organised as follows. Section 2 considers existing research in this area, and uses this to help define the key engineering requirements of the grow–cell prototype. Section 3 develops the conveyor–irrigation and lighting systems thus identified. Sections 4 and 5 present the experimental results and associated discussion respectively, followed by the conclusions in section 6.

2. Engineering Requirements

To address the practically orientated aims of the research behind this article, a prototype grow–cell is developed using a combination of both off–the–shelf and novel components. One essential requirement of the prototype, namely that it can be readily transported to different growers for evaluation purposes, is straightforwardly satisfied by procuring and adapting a standard freight container as the base unit (Fig. 1). To convert this container into a grow–cell facility, the immediate requirements relate to the environmental conditions inside the growing area, including both lighting and micro-climate, and the approach to hosting and feeding the plants. Although the proposed conveyor system proves central to all of these, the background and motivation for the micro-climate and lighting systems are first discussed below.

A plant's healthy development depends on its exposure to the required levels of light, water, temperature, humidity and carbon dioxide. For instance, temperature control is reported to have acute impact on plant growth and morphology, while humidity control is essential for dealing with plant transpiration (Vox et al., 2010). One can control an indoor plant growing environment within a certain range by handling the ventilation rate around it. Fresh air supply drives in essence the levels of temperature, humidity and carbon dioxide, which in turn influences the physiological development of the plants. Its causal relationship with micro-climatic variables is the reason it is regarded as the fundamental factor for many types of indoor environment (see e.g. Taylor et al., 2004; Brande, 2006; Chen, 2009, and the references therein).

However, the spatial distribution of environmental variables is not well addressed in many growing systems. In conventional greenhouses, the lack of light uniformity due to equipment around the plants, outside weather volatility, staff working around the growing environment and other disturbances, all contribute to a complex situation. By contrast, the grow–cell is intended to generate a relatively undisturbed environment. The thermal insulation makes it independent from external weather conditions whilst PPFD uniformity and unobstructed delivery above the plants is improved by the use of artificial lights.

2.1. Artificial Lighting

Artificial light has been used in greenhouses for many years, mainly to compensate for low sun duration in certain geographical locations, but also as a substitute for sunlight during night hours. High intensity discharge, incandescent and fluorescent have been the main sources of artificial light (Bourget, 2008). By contrast, interest in LED technology has only come to the fore relatively recently, with early research into agricultural applications including e.g. Bula et al. (1991); Barta et al. (1992). LEDs have the ability to emit light at specific wavelengths and can be instantly switched on and off. Furthermore, they produce a relatively low thermal radiation compared to other light sources (Barta et al., 1992; Sager and McFarlane, 1997; Bourget, 2008; Massa et al., 2008; Morrow, 2008), which means they can be placed very close to plants without causing damage, while excess heat may be removed by air extraction and/or utilising heat sinks.

As a result, there are numerous studies on plant growth under LED lights e.g. Hahn et al. (2000); Muthu et al. (2002); Nhut et al. (2003); Kim et al. (2004); Lin et al. (2013). Much research effort has focused on the effect of different ratios of red, blue and green colours (Kim et al., 2004; Lin et al., 2013) and on the control of the magnitude of light output to minimise energy consumption (Fujiwara and Sawada, 2006; Shimada and Taniguchi, 2011; Harun et al., 2013). Many studies address the potential energy savings by controlling the on–off frequency cycles of LEDs (Muthu et al., 2002; Shimada and Taniguchi, 2011; Almeida et al., 2014), while others use fewer lights by employing a system that moves them at a certain speed around the growing area (Blom and Zheng, 2009; Lee and Kim, 2012). Recently, Hendrawan et al. (2014) have developed an image processing system that scans the plant and controls the operational level of individual LEDs above it. However, in terms of increasing performance and reducing energy consumption, this type of technology is at a relatively early stage and the initial investment cost might be prohibitive for certain crop species, i.e. those that require high light energy levels.

More generally, resistance to the deployment of artificial light as the sole medium for photosynthesis relates primarily to the initial investment costs and on-going energy consumption. However, the former concern arises because LED technology has not yet reached maturity, whilst its cost is expected to decrease in the coming years. Furthermore, the long operational life of LEDs reduces their replacement and maintenance costs in comparison to other sources of light (Bourget, 2008). For these reasons, the approach chosen for the present research is based on a straightforward and relatively low cost, white colour LED system.

2.2. Mechanical Movement of Plants

In recent years, conveyor and robotic systems in greenhouses undertake tasks ranging from pre-harvest through to post-harvest management. For example, soil seeding, watering, transplanting, transportation to different environments, crop spacing and labelling are all typically automated in order to save time and costs. In the commercial version of the grow–cell, plants will occupy the whole container, allowing for maximum growing capacity: this is critical in regard to the efficiency of the system. This leaves no pathway for growers to physically access the plants. Hence, a conveyor system of some type is essential to achieve single point inspection. Furthermore, plant factories such as the present grow–cell can potentially generate a higher density of plant foliage at each layer than a conventional greenhouse. As noted above, if these plants are not exposed to sufficiently uniform micro-climatic conditions, significant differences in quality and yield can emerge in different parts of the building.

The concept of physically moving plants around the air space in order to compensate for imperfect mixing in the micro–climate has not been extensively researched, although there are some examples in the literature (e.g. Wallihan and Garber, 1971; Hardy and Blumenthal, 2008; Brien et al., 2013, among others). Went (1943) presents an example from the 1940s of automating growth that encompassed the mechanical movement of plants, while a modern example of a conveyor system employed for this purpose is the rotating vertical farm concept of SkyGreens (2016). Nonetheless, to date, the overwhelming majority of greenhouse system controllers do not take into consideration the spatial variability of the micro–climate, which is only partially compensated for by e.g. manually moving trays around on an *ad hoc* basis and by using mixing fans. A recent review (Duarte-Galvan et al., 2012) of control systems used in greenhouses, for example, summarises numerous approaches to address the non–linear nature of controlled environment farming; although the studies mentioned in this review discuss various advantages in terms of model analysis and/or control efficiency, comparatively little information is given about the feedback terms used by the control algorithm and hence the extent to which each study has taken into consideration the volume and spatial variability of the micro–climate. Of course, many authors do note the potential significance of spatial variation even when this is not explicitly addressed by the developed optimal control system (van Straten et al., 2011).

For high density systems in particular, spatial variability of environmental variables is not necessarily resolved by the use of mixing fans. This is illustrated in a recent study by the present authors in which 23 data loggers were installed in a controlled environment fodder crop facility, where the crop is grown using a conventional static multi–layer bench system (Tsitsimpelis and Taylor, 2014). Environmental data were recorded with one minute sampling rate for 11 days, with the airflow supplied by small orifices all around the ceiling. The fodder barn operators had reported undesirable variation in plant yield and quality.

To illustrate why this was occurring, the 24 hour readings displayed in Fig. 2 reveal the poor performance of the rather basic industrial on–off temperature controller utilised in this instance but also shows that, unsurprisingly, the top layer receives the highest rate of fresh air. In fact, for this particular barn, there is a relatively uniform distribution of temperature and humidity levels within each shelf but significant differences of up to 5 °C emerge between levels.

To conclude, the introduction of some type of conveyor system is regarded as essential for managing access to the plants but is also motivated by the observation of significant variation of key environmental variables.

3. Prototype System Design

As discussed in section 1, the prototype grow–cell is based on a standard freight container (Fig. 1). The container is thermally insulated with a foaming system and has an air-conditioning unit to maintain the required temperature and humidity set points: the cooling and heating capacity of the system is regulated by means of PID controllers acting upon the speed of the compressor. These standard algorithms were not modified for the trials reported in the present article. The default air supply configuration comprises a bottom air delivery system. In the adapted container, steel frames are installed to divert the air delivery along the growing area from the direction of the control room.

3.1. Conveyor

The combined conveyor–irrigation system developed by the present authors and industry partners addresses the requirements noted in section 2.2 above. The mechanical form of the conveyor (Fig. 3) is an assemblage than can be straightforwardly built and dismantled. It comprises a rounded rectangular circuit, with (for the purposes of the prototype) twenty multi–tray carriers and three motors. The top end of each tray carrier is mounted on the circuit by means of skate wheels, while its bottom end is slotted to a grooved circuit that keeps the body frame vertical to the circuit's trajectory (Fig. 4: i–ii). Two motors are employed above the rounded sides of the circuit in order to undertake the sweeping task, while another motor at the centre controls a two sided crank and slotted lever mechanism, which is employed to carry out horizontal movement of the trays (Fig. 4: iii–iv).

The levers of the mechanism are steel rods, the bottom sides of which have pegs attached that exert force on the tray carriers. These pegs function as a ratcheting mechanism, allowing each rod to transfer the tray carriers to the respective round side it pushes towards. All three motors are of an asynchronous type, enclosed and equipped with fan–cooled ventilation. They have cage rotors made of aluminium and are fitted with 100:1 ratio worm gear units in order to simultaneously decrease operating speed and increase output torque.

The circulation of the trays is controlled by a smart relay module (Schneider Electric, model: SR3B261BD). This alternating process (horizontal to sweeping motion) is carried out with respect to the signal output of five sensors. More specifically, two photoelectric sensors monitor the growing trays at the front end, while two proximity sensors and one reflective sensor are used to control the starting position of the sweep and main motors, respectively. The control panel is equipped with a graphical user interface module in order to display information and receive commands from the user.

The two photoelectric sensors that are mounted at each side of the front end of the unit determine the start and stop time for the three motors (Fig. 5). The tray carriers are placed in such a configuration that, at both ends, there is eventually a carrier waiting to be swept at one side and free space to receive it at the other side. At this state, the first photocell detects a carrier and the second photocell detects the absence of one. This subsequently activates the sweep motors to transfer the trays at both ends (Fig. 5: ii). Once the trays are swept across (Fig. 5: iii) and the sweep motor arms have returned to their starting position, horizontal motion takes place and the whole process is repeated. The time taken to complete one full circulation can be adjusted. The system is programmed to operate in three modes, namely Automatic, Manual and Stand–by. The latter is provided in order to stall the system at any time. In

Automatic mode, the operation is continuous and each full cycle occurs after a pre–set time delay. The delay timer can be modified from the control panel. In Manual mode, one full cycle occurs at the press of a button.

Several timers are employed in the program in order to monitor the system state and halt it in case of an abnormal signal combination and/or if the time exceeds a threshold for performing a given subtask. The latter time limit for each stage is specified by trial and error experimentation. The nature of the alarm is displayed on the interface module. Finally, an interlock switch is used to indicate whether the conveyor area is open to allow physical access (curtain open) or not. In this case the system will either not start or will halt immediately to prevent potential damage to people and/or equipment.

3.2. Irrigation

Single point irrigation is provided at the front end of the conveyor structure by five plastic pipes, which are laid out vertically at each layer. Batch control is employed in order to compensate for the water mains pressure variations and ensure consistent delivery of the same volume of water at each layer. During the irrigation phase, the irrigation system is activated each time a new set of trays completes a circulation around the end of the conveyor.

The system used for the growth trial operates as follows: the signal from the photocell that has just received the tray hanger (Fig. 5: iii) drives five counters/digital switches. These in turn switch on the solenoid valves and water is injected into the trays. At the water delivery point of each layer a flow-meter monitors the volume of water and yields an impulse output, the frequency of which is linear to the flow. Each of the five outputs is sent to the respective counter, which is pre-set with the desired set-point. Once the set-point is reached the counter switches off the respective solenoid valve. The water drains out of each tray into plastic gutters, which are placed at each layer over the length of the conveyor structure; and collected to a tank for purification and reuse. A main counter and time delay circuit are employed before this system in order to control the irrigation schedule. The frequency of this schedule is adjustable for crop specific water intake requirements (see later section 4).

3.3. Lighting

The lighting system comprises 200 thin surface panels, with unit dimensions 0.5 m × 0.3 m × 0.025 m. Twenty adjacent panels are mounted at each side of each layer of the conveyor system in the grow–cell. The distance between the growing trays and the light panels can be changed by adjusting the tray positions (Fig. 6). The basic commercial system obtained also has to be adapted so that it is capable of varying its PPFD output. This is necessary in order to ensure suitability for more than one plant species and to reduce energy consumption (see later section 4). Hence, the power is provided to the lights via twenty transformers, which are customised for variable DC voltage output that matches the operational range. These are installed in the control room along with the rest of the control and power equipment. Prior to the transformers, configurable time relays are installed in order to control the duration and frequency of the photo-periods for specific growth requirements.

3.4. Instrumentation

Finally, the prototype grow–cell is instrumented in order to obtain a better understanding of the micro-climate, with a particular focus here on temperature and Relative Humidity (RH) as exemplars of spatial variability. Fig. 7 shows the approximate location of the combined temperature/humidity USB sensors, which are mounted at the sides and just above the growing trays. An array of 30 equally spaced sensors are distributed within the growing area, each separated by a distance of 1.2 m lengthwise and 0.35 m in height. Three additional sensors are placed in the air supply, growing area inlet (sensor number 32 in Fig. 7) and outlet (sensor 33). The sensors have a storage capacity of up to 16382 readings, with a user selected sampling rate as fast as 1 sample per second. However, the sampling rate for the measurements presented in this article was set at 10 seconds to allow for a longer time series. Finally, their accuracy is ± 0.3 °C and ± 2 %RH. In addition, *ad hoc* airflow measurements were manually taken at various locations using a portable hot–wire air flow meter, which has a resolution of 0.01 ms^{-1}.

4. Experimental Results & Optimisation

The present section describes results from both laboratory testing and the growth trial, and shows how these are used to improve operation of the prototype.

4.1. LED Characterisation

To investigate the LED panel characteristics beyond the manufacturers specifications, tests were carried out on selected lights in a laboratory environment. In the first instance, the spectral characteristics are determined using a light spectrometer (Uprtek AI-MK350D). The spectral output of a typical panel is visualised in Fig. 8, where it can be seen that most energy packets arrive from the blue wavelength band, with a peak at 448 nm. However, the phosphor coating that has been applied to the LEDs by the manufacturer, in order to yield a white colour output, results in some additional light arriving from the green and orange–red wavelengths.

Secondly, a broad wavelength photosynthetically active radiation (PAR) meter is utilised to measure the PPFD magnitude (μmols m^{-2} s^{-1}) over the operating range. The latter test was subsequently extended in order to assess the distribution of PPFD in the area directly below and adjacent to the light source, as well as to quantify the accumulation of PPFD when two light sources are placed next to each other. Note that the PAR meter utilised for this research only counts the moles of photons within the 400-700 nm band, hence any relatively little light arriving from the near infra-red region is not added to the cumulative PPFD. Fig. 9 shows one light panel fixed at 0.2 m above the centre of the measuring board, with the holes representing 104 measuring points below and adjacent to the sides of the light panel. These measurements were taken in a dark room without other light sources present and with a dark coloured measuring board in order to minimise its reflectivity.

Fig. 10 shows the spatial distribution of PPFD at a distance of 0.2 m below one panel and under different power supply levels. The area projected in each subplot has the same 0.5 m $\times$ 0.3 m dimensions as the light panel. The 40 measuring points pertinent to the panel were interpolated to yield the PPFD distributions. Fig. 10 shows that most of the energy is delivered at the centre of the illuminated area, as would be expected. Table 1 states the observed PPFD levels at the centre (maximum PPFD) and corner (minimum PPFD) of the board for each power input.

Related to these results, Fig. 11 shows that a power supply set to 73% of the standard (maximum) setting, yields a light output only slightly lowered (96%) from the maximum PPFD, indicating considerable scope for energy savings by suitable tuning of the system. In fact, it is clear these light panels operate most efficiently within the 50% to 73% power supply band, which can deliver a PPFD level between 120 to 210 μmols m^{-2} s^{-1}. Here, the 50% limit is based on discussions with growers (this lower bound is considered sufficient for *Begonia semperflorens*) whilst the 73% is the inflexion point in Fig. 11. All twenty transformer units require 15 kW to provide maximum power supply to the lights but at 67% power supply, for example, this drops to 11 kW. For plants that do not require high PPFD levels, it is possible to reduce the power requirements even further.

Although most of the light energy is delivered directly below the panel, some light is naturally dispersed towards adjacent sides. In general, the magnitude of this dispersion depends on the distance of the light from the illuminated area and the angle at which the individual LEDs are manufactured to emit. In this case, the PPFD ramps down to approximately 2 μmols m^{-2} s^{-1} at 0.3 m adjacent to each side of the panel. Extrapolating from these results, it is observed that for each power supply level, the overall PPFD is increased by 11% on account of the cumulative effect of the dispersed light when light panels are arranged next to each other (i.e. 20 panels over 6 m length).

4.2. Preliminary LED Growth Test

A laboratory based test using these lights was conducted for non–stop Tuberous begonias or *Begonia tuberhybrida*, a type of begonia grown for propagation by the third party company that also ran the full scale growth trial. This growth stage takes 13 weeks in their greenhouse environment, whilst it took 50% less time to grow them to the same stage under the LED lights. Fig. 12 shows the difference between 4 week begonia plantlets under the LEDs (middle tray) and those grown in the greenhouse. This type of experiment suggests that the energy consumption of LED lights can potentially be compensated for by increased production rates. However, this is an illustrative result only, used to test the LEDs before proceeding to the growth trial, and clearly further research under controlled conditions is required before generalised conclusions can be made.

4.3. Conveyor–Irrigation Tuning

To sweep one set of trays around the end of the conveyor racking takes at least 45 s. Experimentation in the laboratory determines this is effectively the fastest speed that can be achieved without risking mechanical problems, i.e. the pegs and sweep motor arms exert just enough force to move the trays. Hence, this setting was selected for practical use and no problems were encountered during the growth trial, when the conveyor system was in continuous operation for nearly 8 weeks. By contrast, the frequency of circulations is intended to be adjusted according to the light and dark periods, irrigation schedule and other pre–programmed tasks, such as inspection and harvesting.

For instance, in regard to inspecting the crops, a delay of 30 s between circulations is found to be sufficient, whereas placing or removing the trays requires at least 60 s. For practical operation, such schedules are decided by trial and error adjustment in consultation with the grower. The batch control approach to irrigation is determined to require 120 s between circulations. This is in order to deliver water within a reasonable time-frame, in such a manner that all the plants get sufficiently wet.

Outside the time frame of an irrigation cycle, a much slower circulation rate is generally employed. During the light period, for example, any adjustments to the frequency are dependent on the distance of the lights from the plants, the PPFD levels used, and the temperature and humidity gradients arising in the grow–cell. Together, these determine the drying rate. For the growth trial, the lights are on 16 hours a day, from 12 am to 4 pm, to take advantage of lower costs during the night, whilst the distance between the trays and LEDs is 0.2 m. For these specific conditions, a frequency of four circulations per hour is found to yield a relatively uniform soil drying rate as required by the grower.

4.4. Interpolated Temperature Data

Fig. 13 and Fig. 14 are based on measurements taken following completion of the racking and conveyor system but before the installation of plants. In order to visualise temperature distributions in the grow–cell arising from the LEDs, Fig. 13 is based on the average steady state temperatures for each sensor, with the data interpolated using MATLAB in order to yield the contour surface shown. These data were logged from 6 pm to 8 am with the lighting period commencing at 6:30 pm for eight hours. The supply air temperature set-point for the air-conditioning unit was 12.5 °C and the RH 65%.

During the photo-period the maximum temperature gradient within the airspace reaches 4.2 °C. The coolest area is closest to the inlet whilst the warmest is above 1 m and between 4 m to 5 m horizontally along the growing area. The effect of the exhaust fan at the outlet is visible in the two lower shelves where heat is extracted quicker than from the upper layers. By contrast, during dark periods, the effect on the temperature distribution due to the circulation of the airflow is insignificant, with the temperature throughout the grow–cell remaining within $\pm$ 0.5 °C of the set-point at all times (Fig. 13: lower plot).

For a different experiment, Fig. 14 shows the transient response of the temperature distribution with a 10 minute interval between plots. From the moment the lights are switched on and for the following 10 minutes, the temperature distribution is relatively uniform (Fig. 14 i–ii). However, over the following 1.5

hours the temperature gradient range becomes increasingly obvious. At the 50th minute (Fig. 14 vi) it can be seen that the areas around the inlet have reached their steady state level for these heating and ventilation settings. By contrast, it takes the area towards the outlet over one hour and ten minutes after the lights have been switched on to reach steady state (Fig. 14 viii).

These results confirm that the current air–conditioning controller does not have the capacity to fully compensate for the heat generated by the lights and that some regions suffer from a lack of adequate fresh air supply. The latter is investigated using the hot–wire air flow meter, which shows that air typically enters the supply location with a velocity of 10 m s^{-1} but is dispersed into the growing area with an average velocity of 1.7 m s^{-1}. There is very little variation in airflow between the trays at different heights. Similar conditions occur during the growth trial due to the relatively small size of the plantlets. The exhaust fan draws air at a velocity of 7 m s^{-1} and enhances the air velocity towards the outlet slightly, particularly for the lower levels, explaining the cooler temperatures in this region.

These results are stimulating further research into the heating and ventilation controllers, as discussed in section 5. Nonetheless, it is evident from the growth trial considered below, that the mechanical movement of the plants by means of the conveyor system has helped to minimise the impact of these temperature (and humidity) variations along the length of the growing chamber.

4.5. Growth Trial

The preliminary growth trials reported here took place during February 2015. Throughout this growing period, the external temperature ranged from 1 °C up to 7 °C, with a total sunshine of approximately 75 hours. The third party company that tested the pilot grow–cell is a nursery which grows edible and ornamental plants. The three species of particular interest to this nursery in the context of the grow–cell are: tuberous and semperflorens type begonias (non-stop), and Impatiens divine, all of which are potted in plugs and produced up to a young age for the commercial trade. Semperflorens are chosen for the trials. These first trials are undertaken using only one layer of trays in order to reduce costs and initially prove that the concept works to the required standards of the nursery.

The begonia seeds are sown in 240 cell seed propagation trays, pre-filled with soil. Two of these trays fit into each grow–cell tray, making a total of 9600 seeds for the layer under trial. During irrigation, the grow–cell trays are filled to the top and then drained. In this manner, the plants' soil is kept moist throughout. Furthermore, plastic pieces of piping are mounted between the grow–cell and seed trays in order to air-prune the plants. This technique keeps an air flow going in order to help the plants develop healthy roots limited within their individual cells. Throughout the growth period the plants were irrigated every 30 hours, receiving a blend feed of Natrium, Phosphorus and Potassium.

The temperature setpoint was 22 °C, with the RH 95% during the germination period and gradually lowered to RH 65% over the course of the trial, as is normal practice for this nursery. The average steady state temperature and humidity distribution during the lighting periods are illustrated by Fig. 15. Here, it can be seen that the begonia growing layer with the lights switched on yields temperature levels up to 24 °C, while the lower layers without plants are closer to the set-point of 22 °C. Similarly for humidity readings, the begonia growing layer shows a reduction in RH to 85% compared to the lower levels (without plants) for which the RH remains close to the set-point. Here, the temperature and humidity changes during photo-periods are due to the heat energy emitted by the LEDs, while the plants themselves have a negligible effect on the two variables due to their relatively small size.

Two weeks following germination, the vegetative stage of the seedlings were characterised by qualitatively faster development than equivalent plants grown in the greenhouse. By the 5th week, the trials were officially complete, two weeks ahead of the scheduled (greenhouse) production. Naturally, generalised conclusions about the relative performance of the grow–cell cannot be made from this illustrative feasibility trial. Nonetheless, in consideration of the intended aim, it successfully demonstrates that *Begonia semperflorens* can be grown to the satisfaction of the nursery, with Fig. 16 showing the ready plantlets.

5. Discussion

The research shows that a relatively low–cost and readily available option for the base unit, namely a freight container, can be successfully adapted for growing plants. Such containers also immediately satisfy one of the longer term modular grow–cell concepts, i.e. they facilitate stacking of multiple containers. The commercial, economic and environmental implications of using existing buildings/containers against bespoke designs are clearly beyond the scope of the present article, and require further research. Important features such as heat storage and dehumidification for water storage and recycling were not available in these trials. In fact, the objective here was to use a standard freight container as a means of quickly advancing the research to the stage of a practical prototype, so that the other issues highlighted below can be investigated.

The heating, ventilation and air-conditioning unit used during the trials has not been specifically designed for growing plants and lacks sufficiently active control action. Whilst not surprising, these results provide further motivation for research into bespoke sizing of the air-conditioning unit and improved control system design. The direct correlation between the ventilation rate at different points in the growing area and the resulting temperature distribution, as noted in section 4.4, suggests that a multi–zone controller would be beneficial, and this is the subject of on–going research by the authors (Tsitsimpelis and Taylor, 2015).

The straightforward mechanical design for the racking and conveyor can be adapted to fit differently sized containers, and offers a generic framework for future development. Pre-harvesting and post-harvesting automation can be fitted adjacent to the grow–cell in order to manage insertion, extraction and handling of the crop e.g. the conveyor system could be connected to a separate building. Furthermore, such automation will be essential when stacking multiple containers. The incorporation of the conveyor system also achieves a more uniform average micro-climate for the crop as a whole. In section 4.3, the ability to change the time taken to complete a full circulation was exploited to optimise the drying rate of the trays. Although this proved successful in relation to the growth trial, there is considerable scope in this context for future research into biological factors, for example with respect to plant quality and mass.

Naturally, the light conditions also have a significant impact on such matters. Mixed wavelength output is suitable for numerous plant species, mostly for propagation, and the presently installed system targets low and medium irradiance plants such as begonias. The prototype grow–cell encompasses the capacity to add and replace lights according to the target crop species. More generally, LEDs allow for previously unachievable agricultural applications, such as merging different wavelength outputs (see e.g. Fig. 8) to obtain the maximum photosynthetic utilisation by plants and the deployment of time–varying light outputs depending on the growth stage of the crop.

Section 4.1 shows how the PPFD output can be improved to find a satisfactory balance between costs and performance. Extrapolating from the shaded area in Fig. 11 and applying a 16 hour diurnal photo-period, it is feasible to save between 29 to 139 kWh per day. Such power consumption calculations are clearly a function of the particular LED units procured for the prototype. Nonetheless, the generic concept is that the output can be straightforwardly varied for different species, and the spatial distribution and associated operational costs of the lighting system have to be considered on this basis. Further energy savings can be made by reducing the distance between the plants and light panels. For example, at a distance of 0.1 m, the PPFD output increases by up to 50% in comparison to the 0.2 m utilised for the growth trial. Indeed, one benefit of LEDs is that low heat output allows for the lights to be placed very near the plant canopy and the heat generated can be utilised as a complementary heating source (potentially useful depending on the climatic region and time of year).

6. Conclusions

This article has described the development of a prototype grow–cell for horticulture, namely a sealed building with artificial lights and a controlled environment. A selective review of research in cognate topics has been used to develop the engineering requirements for the prototype. The subsequent research focus has been on the development of a conveyor system for moving the plant trays around, and the arrangements for single point irrigation/feed and LED lighting. The article discusses the design, testing and optimisation of these subsystems in advance of plant growth trials. Based on these results, recommendations have been made for how the prototype should be adapted for particular requirements. For example, the timing sequences of the new conveyor system are adjustable for differently sized grow-cells and different types of irrigation. With regard to the lights, the LED units used in the prototype have been optimised to obtain a satisfactory balance between PPFD output and energy consumption.

Data have been collected to help visualise the heterogeneous micro–climatic conditions arising inside the grow–cell. These results suggest that improvements in the environmental control system are required. Hence, experimental data from the prototype and other systems are presently being utilised by the authors to develop new thermal models and control algorithms (Tsitsimpelis and Taylor, 2015). A multi–zone controller that acted on the heating and ventilation devices in a manner such that the design requirement for each thermal 'zone' of the grow–cell is achieved, could potentially allow for improved growth regimes to be applied, and this will be investigated in future research.

Nonetheless, despite such limitations in the present air-conditioning system, it should be stressed that the prototype is already being used to successfully grow and harvest crops, including *Begonia semperflorens* as reported in the article (Fig. 16). Indeed, the aim is to use the prototype for practically orientated research and development, in which a range of horticultural, economic and environmental issues can be systematically investigated e.g. energy consumption and whole system running costs. There is also considerable scope for future quantitative research into the relative mass and quality (e.g. leaf size, root conditions etc.) of plants grown in different environments.

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Voltage (%)	Min (μmols m^{-2} s^{-1})	Max (μmols m^{-2} s^{-1})
40.0	33.4	113.0
46.5	38.0	128.0
53.0	42.7	144.4
60.0	48.5	163.8
67.0	56.0	189.0
100.0	64.2	217.0

Table 1: Minimum and maximum PPFD measurements associated with Fig. 10. The first five rows represent 1 V increments in the voltage, expressed as a percentage (i.e. 40% through to 67%). The final row is for the standard (maximum) power.

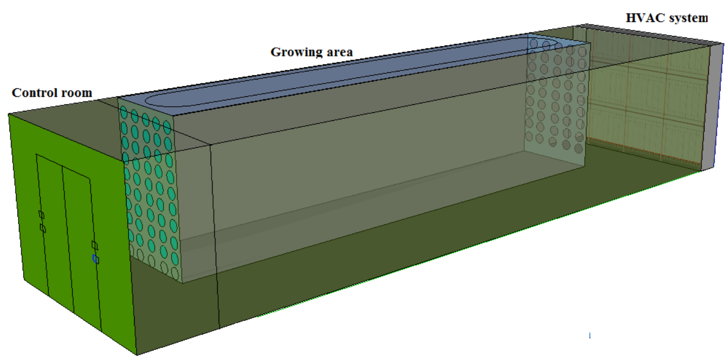

Figure 1: Grow–cell prototype drawing showing the basic layout of the modified freight container (12 m × 2.4 m × 2.5 m).

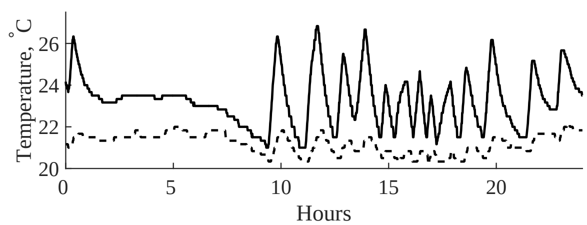

Figure 2: Illustration of thermal stratification, showing the mean temperature of the top (solid trace) and bottom (dashed) growing shelves of a fodder barn plotted against time in hours (Tsitsimpelis and Taylor, 2014). The sensors yield quantized measurements at one minute samples and the readings from three sensors are averaged.

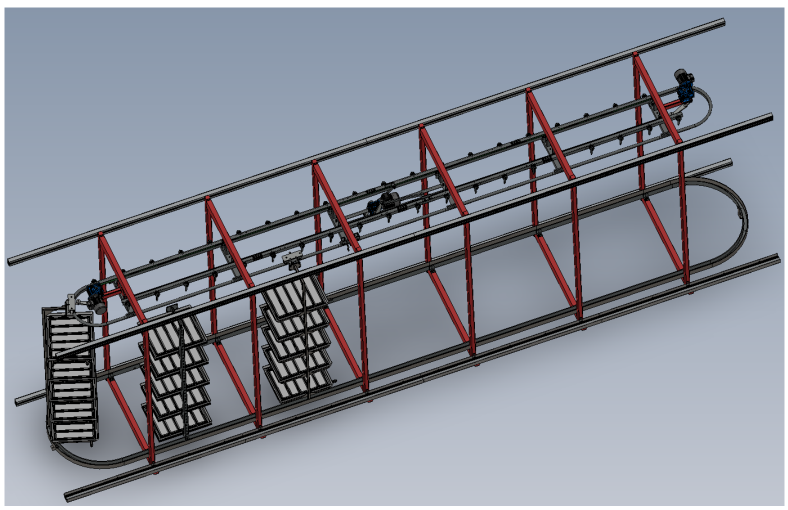

Figure 3: Conveyor and racking design schematic diagram.

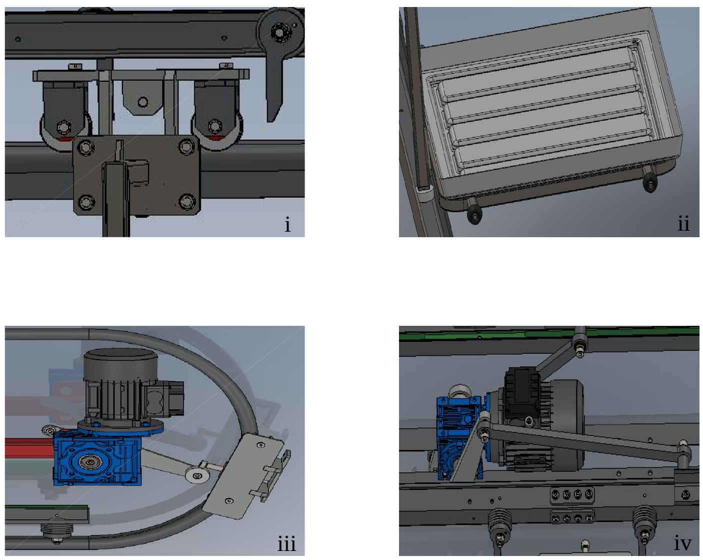

Figure 4: Conveyor structure detail showing (i) skate wheels attached to the main circuit, (ii) grooved circuit to keep the body frame vertical, (iii) sweep motion motor and (iv) horizontal motion motor.

Figure 5: Conveyor structure operation for anti–clockwise rotation: (i) system ready for sweeping hangers, (ii) during sweep motion and (iii) system ready for horizontal motion.

Figure 6: LED lights and empty plant growth trays.

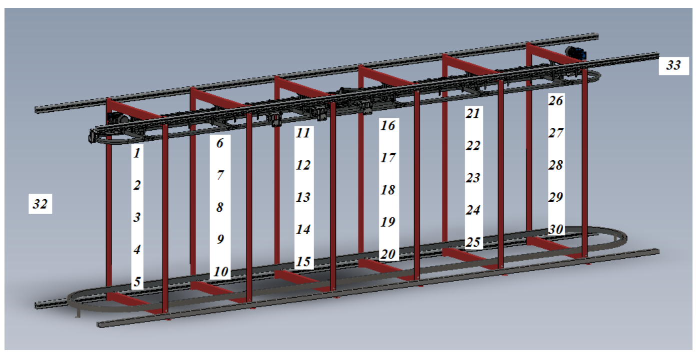

Figure 7: Sensor locations in the grow–cell. Note that sensor 31 (not shown) is located at the air intake of the unit.

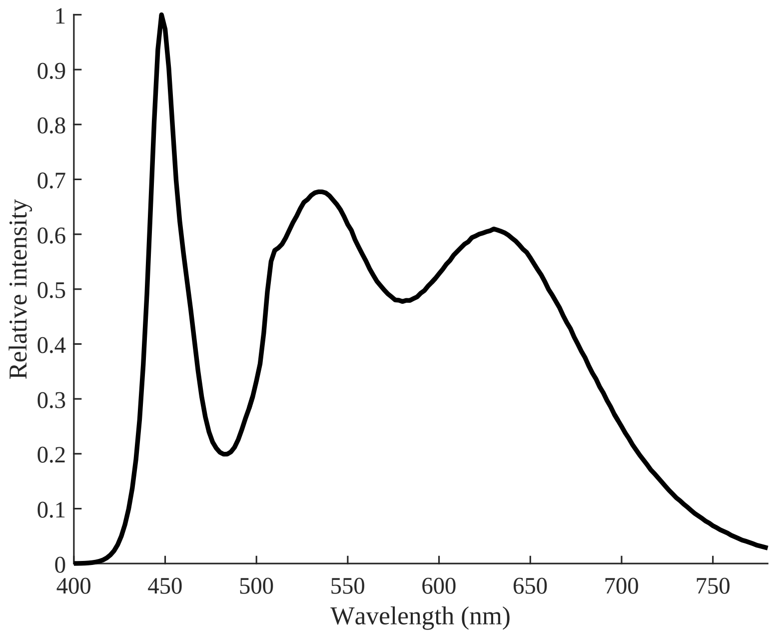

Figure 8: Spectral output of lights installed in the grow–cell.

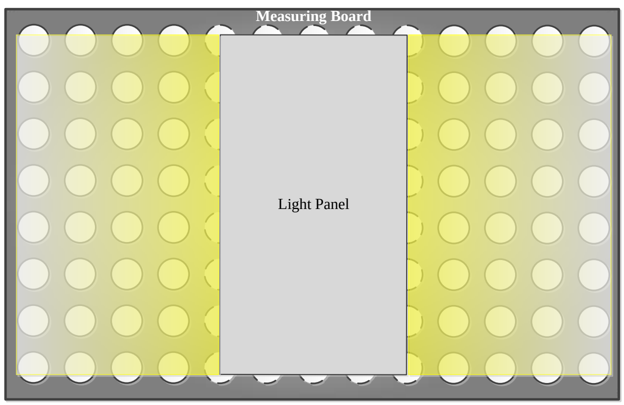

Figure 9: Schematic diagram of the 0.9 m× 0.5 m board for measuring PPFD magnitude, with one light panel and 104 measurement points.

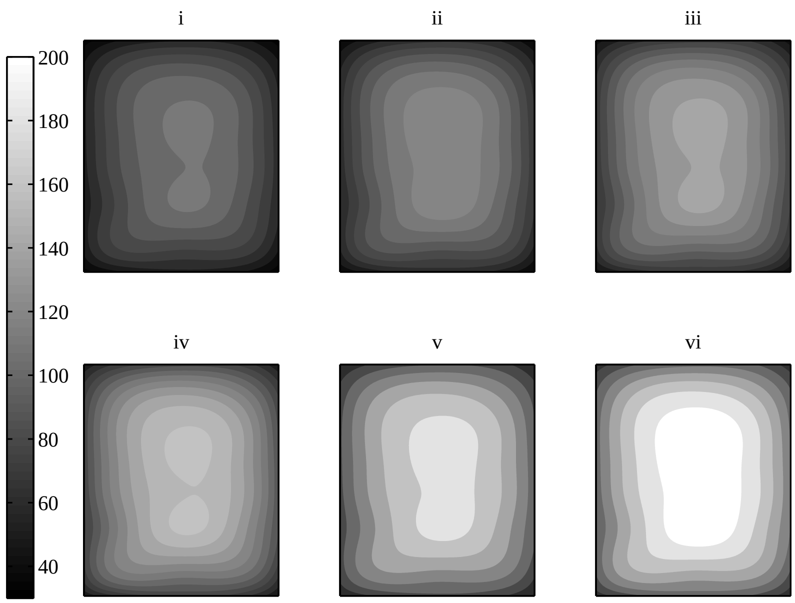

Figure 10: Spatial distribution of PPFD (legend: μmols m^{-2} s^{-1}) at a distance of 0.2 m. Subplots i through to vi are for voltage levels of 40%, 46.5%, 53%, 60%, 67% and 100% of the variable power supply. Each subplot indicates the PPFD over the 0.5 m (vertical axis) by 0.3 m (horizontal) light panel.

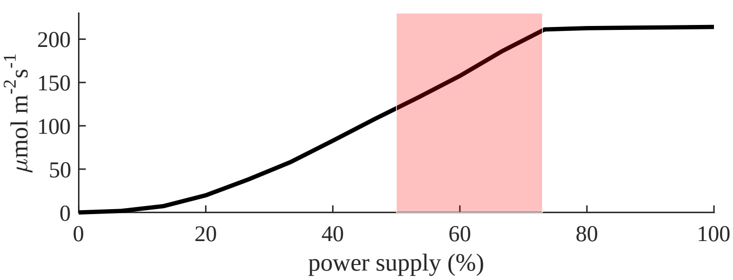

Figure 11: PPFD plotted against supply voltage expressed as a percentage of the maximum, highlighting the most energy efficient intensities (shaded).

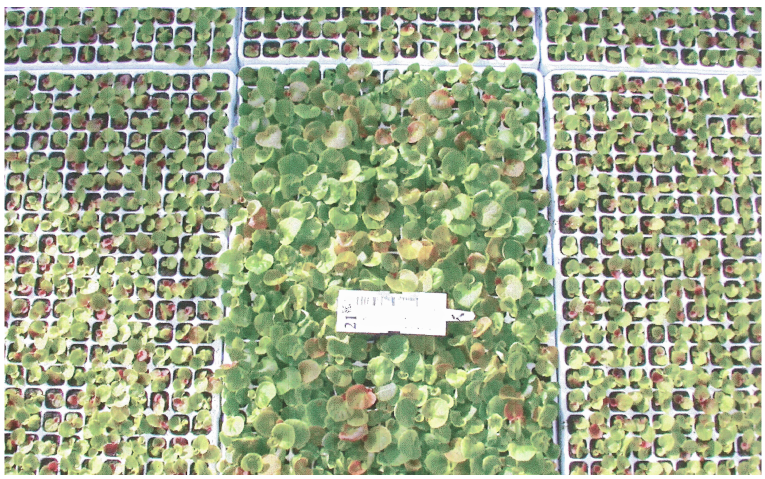

Figure 12: Four weeks old Tuberous begonia plants grown under white LEDs (middle tray) and in a greenhouse (the other trays).

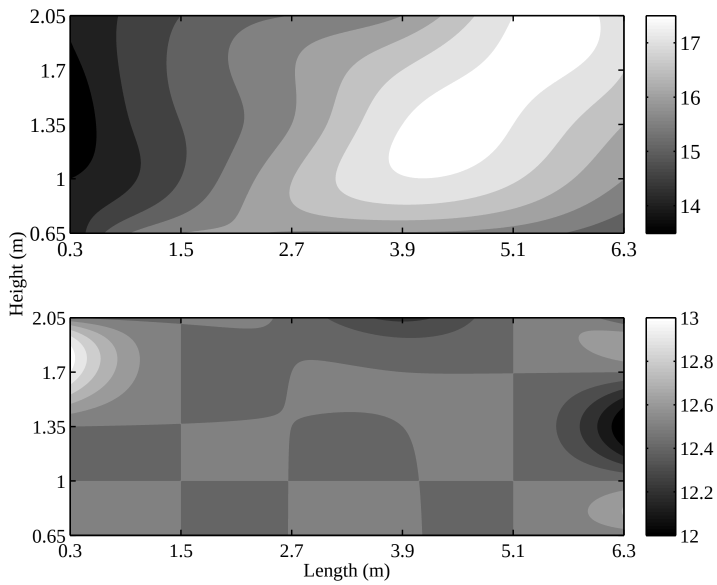

Figure 13: Steady state temperature distribution with lights switched on (upper subplot) and off (lower). The legend shows the temperature (°C). The horizontal axis for each subplot represents the temperature variation in a longitudinal plane along the length of the grow–cell, i.e. distance (m) from the inlet end. The vertical axis for each subplot represents the temperature variation vertically, i.e. height (m). Figures generated using spline interpolation from 30 point measurements in MATLAB.

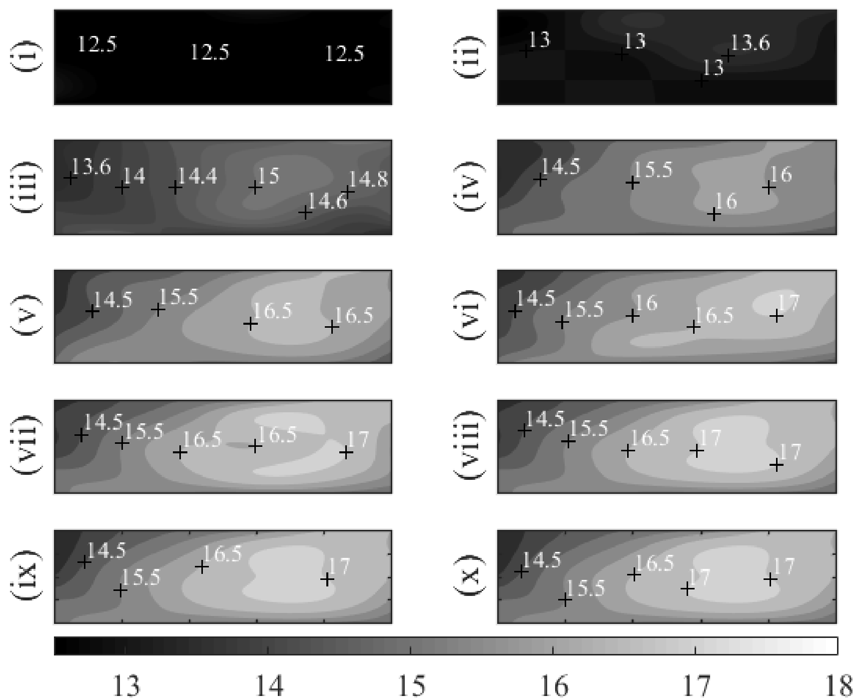

Figure 14: Transient response of temperature distribution in the growing area shown at 10 minute intervals from the moment the lights are switched on (i) through to 1.5 hours later (x). The legend shows the temperature (°C). The height and length axis (not shown) for each subplot are identical to those in Fig. 13. Numerical values are illustrative temperature point measurements, °C.

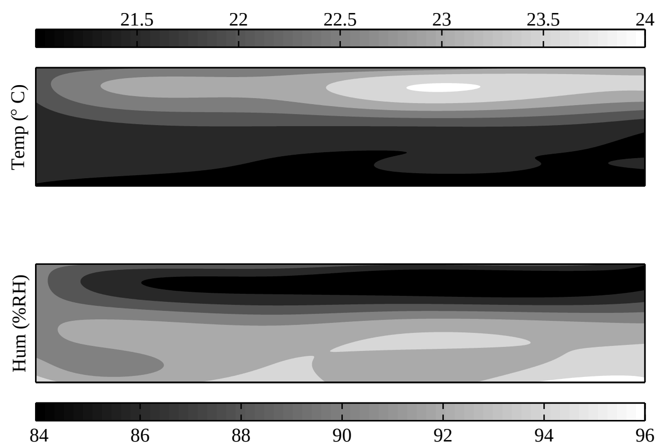

Figure 15: Steady state temperature (upper subplot) and humidity (lower) spatial distribution during photo-period. The legends show the temperature (°C) and humidity (% RH). The height and length axis (not shown) for each subplot are identical to those in Fig. 13. Illustrative example based on the first ten days of data.

Figure 16: Finished *Begonia semperflorens* plants in the grow–cell just before harvest.