ENGN2226 Systems Engineering Analysis

Temperature Regulation in a Domestic Greenhouse

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1 Abstract

The temperatures in a domestic green house in Queanbeyan can vary between 15-54°C in summer and 0-36°C in winter. While automated temperature control systems, such as vents and fans, can be used to vary the temperature in a domestic greenhouse (Shamshiri & Wan Ismail, 2013), they only serve to respond to a set temperature level at the control sensor. This results in a temperature difference between the greenhouse floor and apex. Reducing this temperature difference would provide consistent growing conditions across the entire greenhouse. The potential to reduce this difference was investigated by measuring the temperature at three different heights within a greenhouse both with, and without an air recirculation system in operation. The results did not prove conclusive as the testing period was short, experienced significant changes in climatic conditions, and a control greenhouse was not available for comparison. Additional work is required to determine what rate of air recirculation is required, and whether the concept of air recirculation is viable for the domestic greenhouse environment.

2 Aim

The project proposal is to examine the idea of recirculating the air from the upper level of a greenhouse (the hotter air) to floor to provide a constant temperature level across all locations of the greenhouse. This project will examine the temperature differences and effects of recirculating the internal air mass.

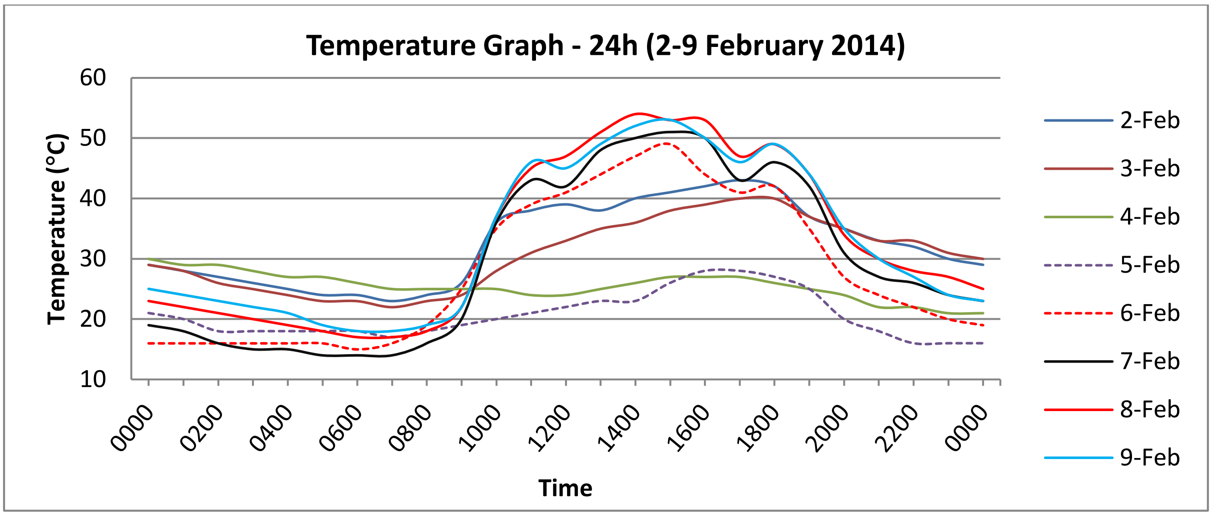
Image 1. *Sproutwell Greenhouse: Garden Pro 1800 Model Greenhouse* (Sproutwell Greenhouses, 2015).

3 Hypothesis

Previous data collected from within a domestic greenhouse showed temperatures ranging between 15-54°C in summer (and 0-36°C in winter)[1]. It is hypothesised that a constant temperature (or greatly reduced temperature difference) can be achieved by providing recirculation of air within the greenhouse. This will provide a more constant temperature level within the greenhouse for improved conditions.

With ceiling and floor vents, it is anticipated that there will be a temperature variation between the roof space of the greenhouse and the floor – resulting in a temperature difference between the plant roots and crown / plant head. Temperature is one of the main factors affecting seedling germination, and maintaining the optimum temperature for the seedling species will increase germination success (Durr, et al., 2015). By maintaining the optimum temperature throughout the greenhouse, a horticulturalist can maximise the number of seedlings being germinated and increase output and potentially revenue.

[1] The temperatures were recorded in Queanbeyan by the author in a 2m x 2.8m domestic greenhouse in 2014.



Graph 1. *Greenhouse temperatures recorded over the period 2-9 February 2014.*

4 To recirculate or Not to recirculate .... That is the Question!

Building on the a previous project theme of automated greenhouse environmental control, this project narrows the topic further to examine the level of temperature difference within the greenhouse space. The question of concern has three main parts:

- How much variation is there in temperature at different levels within a domestic greenhouse;
- Will forced air recirculation sufficiently reduce the temperature variation; and
- Is the proposed solution financially viable.

5 Data Capture and Analysis

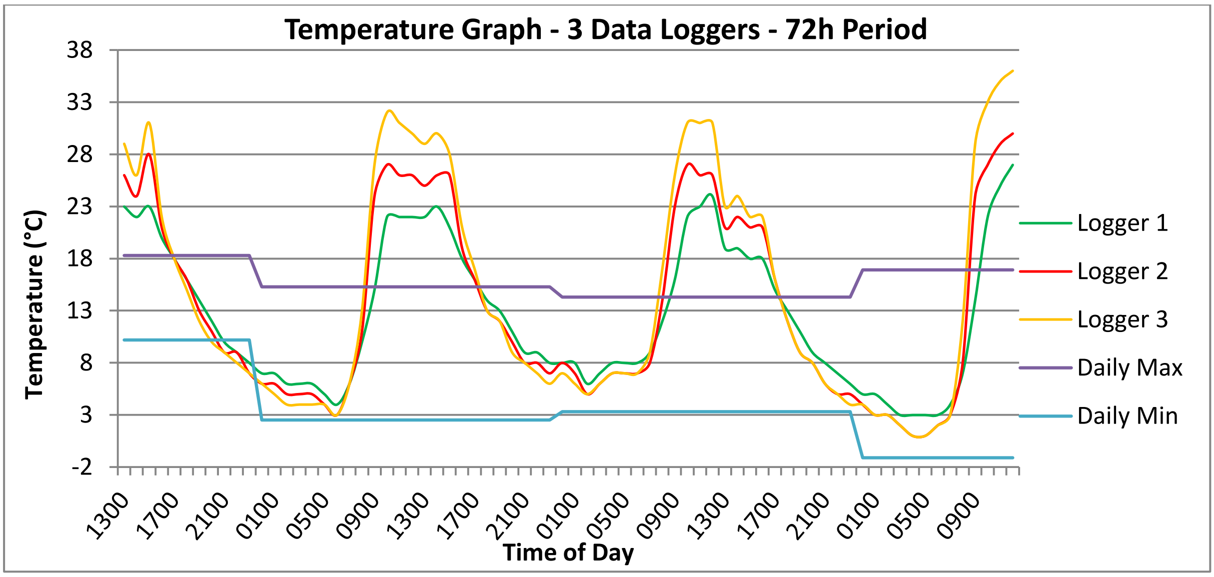
5.1 Data Capture

To answer the questions outline above, a procedure was developed to measure the greenhouse temperatures without forced air recirculation and then repeat the measurements with the introduction of forced air recirculation. Assessments were also undertaken to determine the materials and financial impact of the proposed forced air recirculation system.

The first step towards gathering the data was to design three temperature loggers which could reliably record temperatures at the same time and with the same accuracy. This was important to ensure that measurements were accurate, repeatable and taken simultaneously.

The design was based on a DS1820S one-wire integrated circuit which was driven by a 12F683 programmable integrated circuit (12F683 PIC). The design utilised the 12F683 PIC to trigger the temperature readings and store them in on-board memory. The information was then downloaded from the data logger using an RS232 interface and transferred to an Excel spreadsheet for graphing and analysis.

The three data loggers were fixed to the rear wall of the greenhouse and positioned so that the temperature reading element were not in direct sun light at any stage. The data loggers were provided identification numbers Logger 3, Logger 2 and Logger 1. Logger 3 was positioned at the apex of the roof, Logger 2 was located 1.5m off the ground (mid way between the apex and floor) and Logger 1 was located approx 5cm from the floor. Graph 2 shows the data captured using three data loggers located at three levels inside a domestic greenhouse without any form of forced air recirculation[2].



Graph 2. *Greenhouse temperatures recorded by three data loggers over a 72 hour period in September 2016.*

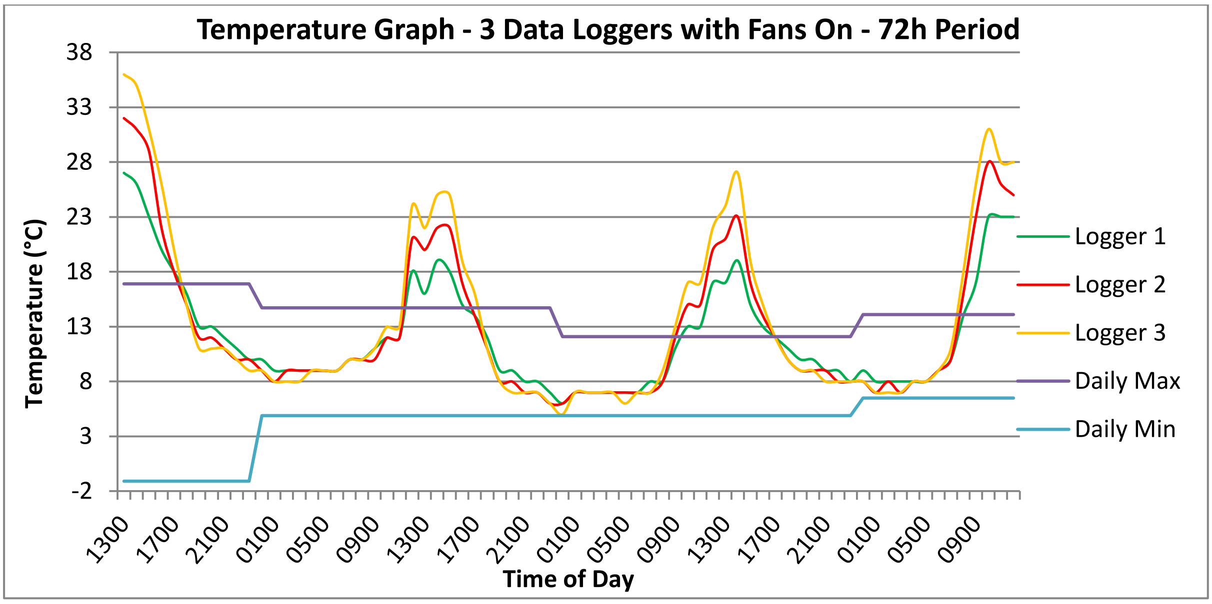
As was anticipated, Graph 2 demonstrates that the temperature level over a three metre height can vary by as much as 10°C (likely more in the middle of summer).

The process was repeated for a second 72 hour period, however, this time a forced air recirculation system was used. The system drew air from the apex area of the greenhouse at a rate of 12.4m^3/min and expelled it at the floor level. The volume of the greenhouse is approximately 11.875m^3 which results in the volume of air within the greenhouse being recirculated once every minute. Graph 3 shows the temperature levels of the three data loggers over the second 72 hour recording cycle[3].

The graph shows that the temperature variation was reduced when the forced air recirculation system was in operation. The time span over which the temperature difference was greater than 4°C[4] was also reduced when the forced air recirculation system was in operation.

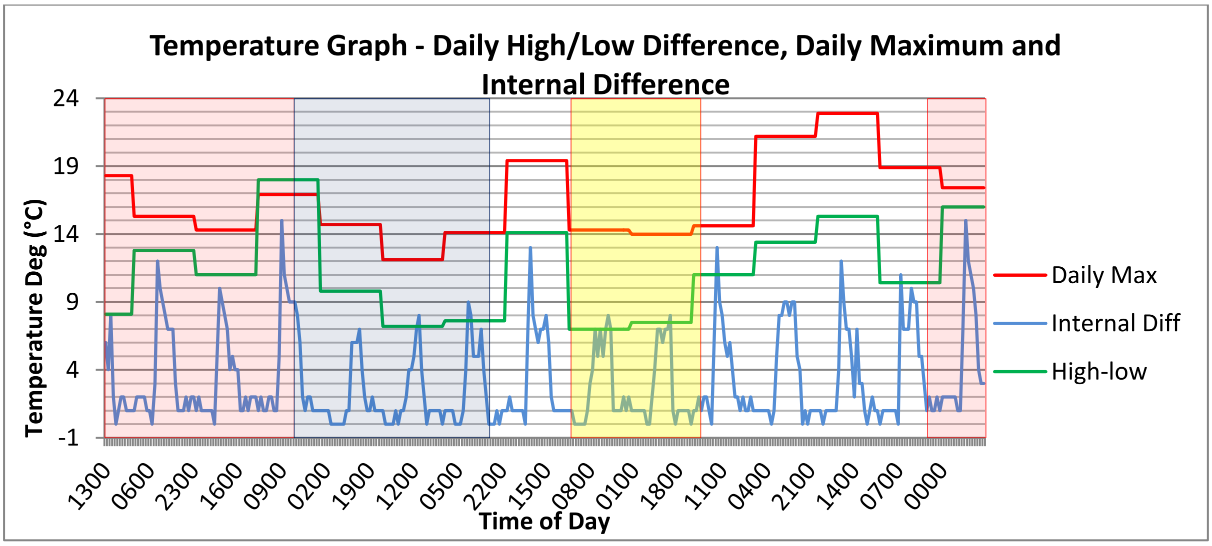
It should be noted that the data has only been collected over a 72 hour period for both test regimes and during that time the regional weather was not stable. During the second 72 hour test period, the daily maximum temperatures (Bureau of Meteorology, 2016) fell as much as 5°C below the previous test period. The daily maximum and minimum temperatures used in Graphs 2 and 3 were drawn from the Australian Government Bureau of Meteorology website (Bureau of Meteorology, 2016).

[2] Temperatures recorded in Queanbeyan by author in a 2m x 2.8m domestic greenhouse 25-28 Sep 2016.
[3] Temperatures recorded in Queanbeyan by author in a 2m x 2.8m domestic greenhouse 28 Sep – 1 Oct 2016.
[4] 4°C was identified as the variation at which the temperature difference increased rapidly in the morning and deceased slowly in the afternoon.



Graph 3. *Greenhouse temperatures recorded by three data loggers over a 72 hour period in September 2016 with forced air recirculation.*

Graph 4 shows the Daily Maximum temperature, the difference between the Daily High and Daily Low temperatures and the difference between the Internal greenhouse extremes over a 14 day period. This period starts with the initial 72 hour period (shaded in red) followed by the second 72 hour period (shaded in blue) and the remaining 8 days. The areas shaded in red also represent times when the recirculation system was not in operation. It can be seen that the Internal Difference temperature loosely follows the Daily Maximum temperature. A lower Internal Difference temperature is evident during the second 72 hour period, however, this was also the time when the Daily Maximum temperature was lower. A similar trend is shown (highlighted in yellow) when the Daily Maximum drops again. Of note is that the Internal Difference does not show a significant change from the Daily High / Low difference.



Graph 4. *Temperature Graph comparing Daily Maximum, Daily High/Dow Difference and Greenhouse Internal Difference temperatures over an 8 day period.*

5.2 Data Organisation

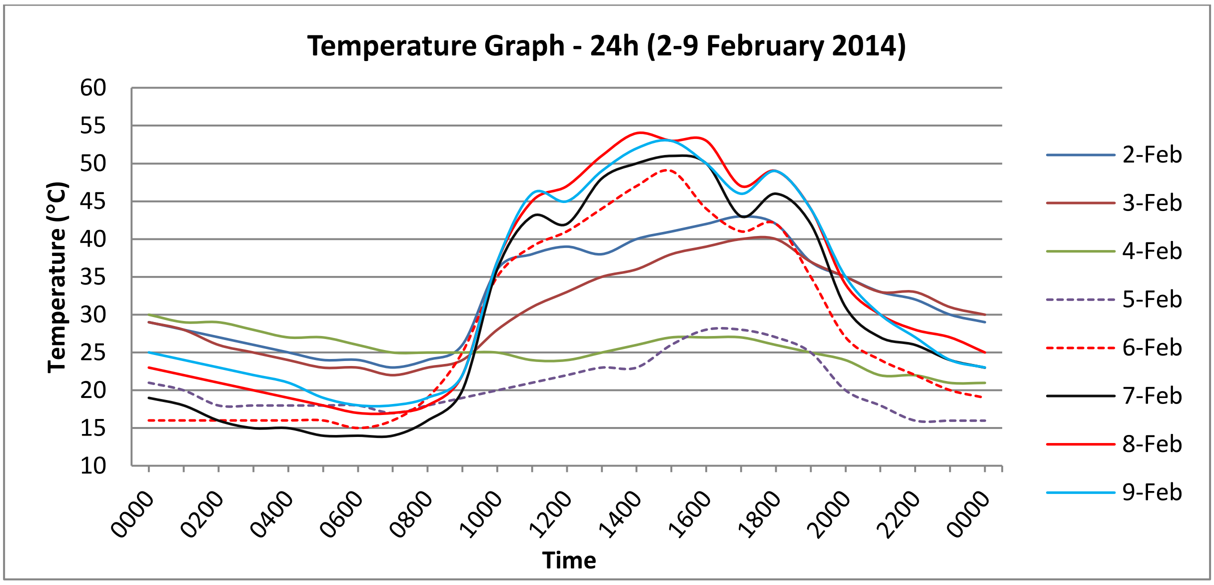
In order to manage the data (both system tests and actual data logging), an Excel spread sheet was used to store the data, manipulate the entries and conduct analysis. A total of three data loggers were used and these were given an identification number which was inscribed on the unit and used as the heading in the column where the data was recorded. This ensured that the information was systematically and consistently recorded.

The data was downloaded via an RS232 link and captured using HyperTerminal Private Edition 7[5]. The information was then transferred to an Excel spreadsheet to undertake calculations for the temperature range, this involved converting the data from a number represented in text to a number format.

5.3 Error Consideration

In the case of this project, the population sample is extremely small – one greenhouse – and could be considered to be a sampling error; however the data in Graph 1[6] has been captured over a six month period and this provides a sound population of information for this specific greenhouse. While the same tests could be undertaken in a number of different greenhouses, it is a fair assumption that for a greenhouse without any form of air recirculation, the internal temperature readings would follow a similar trend as those from the tested greenhouse.

As can be seen from Graph 5, there are dips in the trend lines at 1200h, 1500h and 1700h. These were initially assessed as being non-sampling errors caused by the temperature recording equipment, or possibly due to overcast periods during the recording timeframe. Closer observation (at the actual times of the ‘glitches’) identified that at these times, a shadow from the greenhouse structure was cast across the temperature recording equipment, resulting in a lower reading.



Graph 5. *Greenhouse temperatures recorded over the period 2-9 February 2014.*

[5] Hyper Terminal is a terminal emulation program capable of connecting to systems through the internet via Telnet or SSH, by Dial-Up Modem, or directly connected by a RS232 serial cable and COM port.
[6] The temperatures were recorded in Queanbeyan by the author in a 2m x 2.8m domestic greenhouse in 2014.

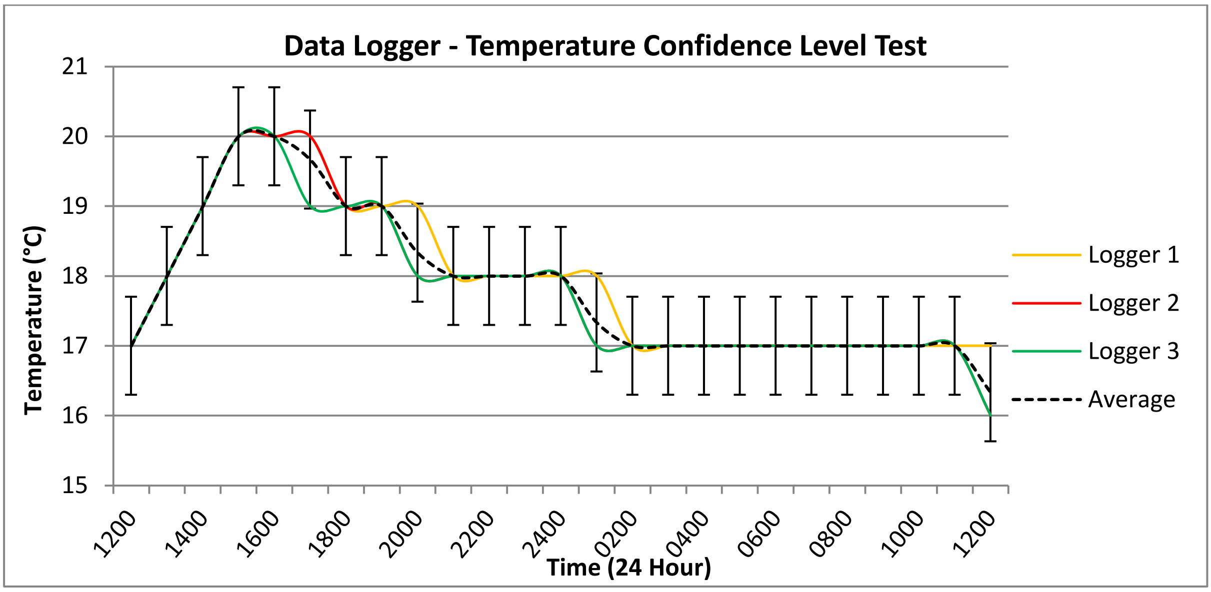
In order to mitigate the effects of the shadows cast by the structure, the temperature loggers were shielded from direct sunlight so that the readings were representative of the ambient air temperature and not affected by the direct sunlight. Graphs 2 and 3 show the temperature readings after the temperature loggers have been shielded. Of interest, even with shielding from the direct sunlight, the recorded temperatures in Graphs 2 and 3 still display dips in the trend lines at similar timings (albeit less pronounced). The dips still coincide with the greenhouse structure and for the purposes of this project do not affect the results as the dips for each of the trend lines follow the same deviation.

5.4 Prototype Development

Calculations were undertaken to determine the confidence levels relating to the test equipment. Two initial tests were run; these were designed to determine the confidence level in the temperature readings (namely accuracy) and the confidence level in the timings of the readings.

5.4.1 Temperature accuracy

The aim of the test was to determine what the level of confidence was for each of the data loggers to record the same temperature. Given that the temperature reading integrated circuit could record to a 0.5°C resolution and that the data loggers had been programmed to disregard the least significant bit of data (i.e. the 0.5°C), it was expected that the confidence level would be high.



Graph 6. *Data Logger temperature levels undisturbed and recorded over a 24 hour period.*

The three data loggers were placed in an undisturbed location for 24 hours and left to record temperatures. Results showed that over the 24 hour period, no two data loggers differed in temperature by more than 1°C. This resulted in a standard deviation of 0.4714 and provided a confidence level of 99% (see Graph 6).

5.4.2 Timing accuracy

The aim of the test was to determine what the level of confidence was for each of the data loggers to record a temperature reading at the same time.

Each of the data loggers were connected to a Saleae Logic analyser and left to run for a 12 hour period. The logic analyser recorded a signal every time the data loggers undertook a temperature reading. The results were then read from the data capture log and the time between each temperature reading was recorded.

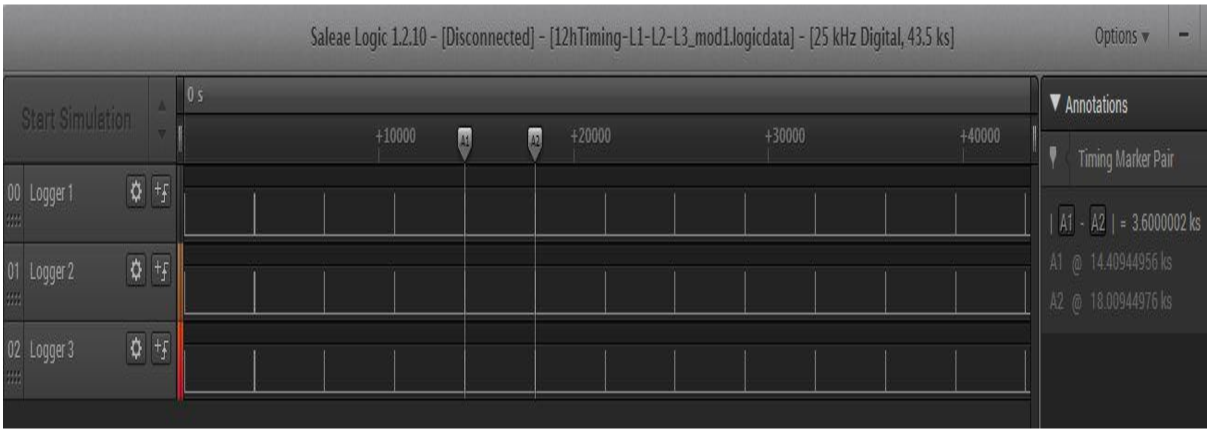
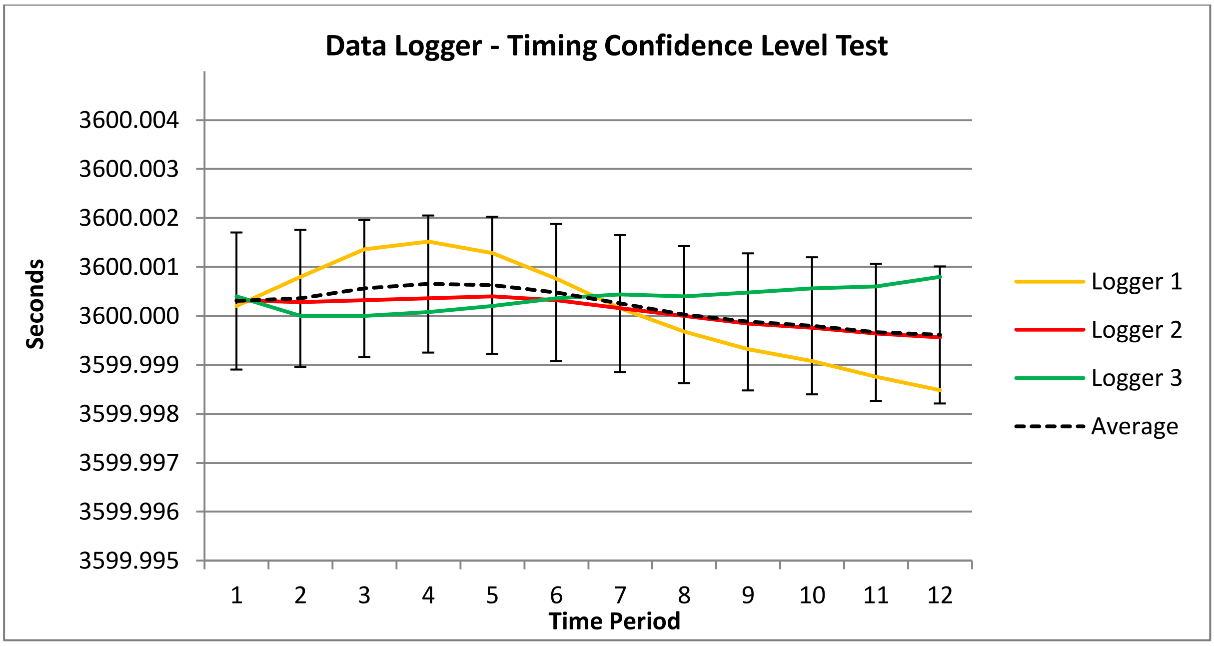


Image 2. *Saleae Logic Analyser timing data from 12 hour test of data loggers.*

Initially the trial utilised the on-board RC oscillator hardware, however this was found to be inaccurate (losing up to 18 seconds in an hour) – clearly this would not be acceptable over an extended timeframe. The PIC code was modified to utilise an external crystal for timing and tested again. The results improved with the greatest variation being 234ms per hour. Code for each of the individual logger was further modified to achieve a maximum standard deviation of 0.95ms per hour over an additional 12 hour test.



Graph 7. *Data Logger timing accuracy (against 3600sec) recorded over a 12 hour period.*

Graph 7 shows the timing variations with a standard deviation of 1.4ms which results in a confidence level of 99%.

The results of the tests show that there is a 99% confidence level that the data will be recorded to within 0.94°C and that all recordings will be taken within 2.8ms of each other.

5.5 Ethical Concerns

While the project has no engagement with humans or animals, it does rely on data collected from a small sample size. As such the data, while useful for exploring the concept and developing a prototype, cannot be held as representative for all types of greenhouses and should be guarded so as not to be mis-interpreted or used without context (IDEO, 2015).

As was outlined previously, the tests were conducted over a short timeframe and without a control environment for comparison. To release any of the raw data without this context could lead to misleading conclusions.

6 Risk Mitigation

As part of the design process, the prototype was assessed from a safety perspective and four main risks were identified:

- **Noise.** When in operation, the fans produce a noise level which needs to be assessed against the national standard.
- **Power.** The system utilises a power supply and therefore needs to be assessed for electrical hazards.
- **Wiring.** The wiring of the system could present a trip hazard.
- **Fixing.** The recirculation structure needs to be appropriately fixed and situated so as not to be a hazard to movement inside the greenhouse.

Table 1 in Annex A shows the Risk Matrix before any treatment or mitigation has been undertaken.

6.1.1 Noise

As would be expected, the fans produce an audible level of noise when turned on. This presents a risk to workers in the vicinity and may lead to damage to or loss of hearing. Under the National Standard for Occupational Noise (Commonwealth of Australia, 2000), the maximum level of an average daily exposure to noise is 85dBA.

The fan under consideration (CAT.NO: YX2500) generates a noise level of 27dBA (Jaycar Electronics, 2016), and from previous calculations it was assessed that a total of four fans would recirculate the air in less than 1 minute. Given a maximum quoted noise level of 27dBA per fan (Jaycar Electronics, 2016), the net noise level for four fans is 33.02dBA. When compared with the daily acceptable rate of 85 dBA, it can be seen that the noise produced by the project proposal falls well below the maximum acceptable noise level. By choosing the correct fan, the risk is eliminated.

6.1.2 Power

With the system relying on power to drive the sensors, controller and fans, there is risk that the system could develop a fault and present an electrical hazard. This risk is mitigated by ensuring that all sub-elements of the system operate at low voltage (5 Vdc) and are housed in appropriate containers / structures to prevent exposure of bare wires and protection from the elements. The only item which will need to be slightly exposed is the fan; however, this element is housed inside a plastic pipe which provides additional mitigation.

6.1.3 Wiring

The wiring presents two possible risks; electrical hazards due to bare wiring, and trip hazards due to poor installation. Both of these hazards can be mitigated by using approved installation methods for the environment. This could include routing the wiring through conduit pipes fixed to the structure to remove any exposure to the operator and ensure the wiring is contained.

6.1.4 Recirculation Pipe Fixing

The recirculation pipes present a risk to head injury should an operator inadvertently walk into one. This can be mitigated by using hazard marking colours and ensuring that the pipes are appropriately fixed to the structure and away from traffic areas.

Table 2 in Annex A shows the Risk Matrix after treatment or mitigation has been undertaken. As can be seen, with the mitigation / corrective works, all risks are reduced to an acceptable level.

7 Project Timings

In considering the course of the analysis and solution development, a number of specific stages were identified. These included:

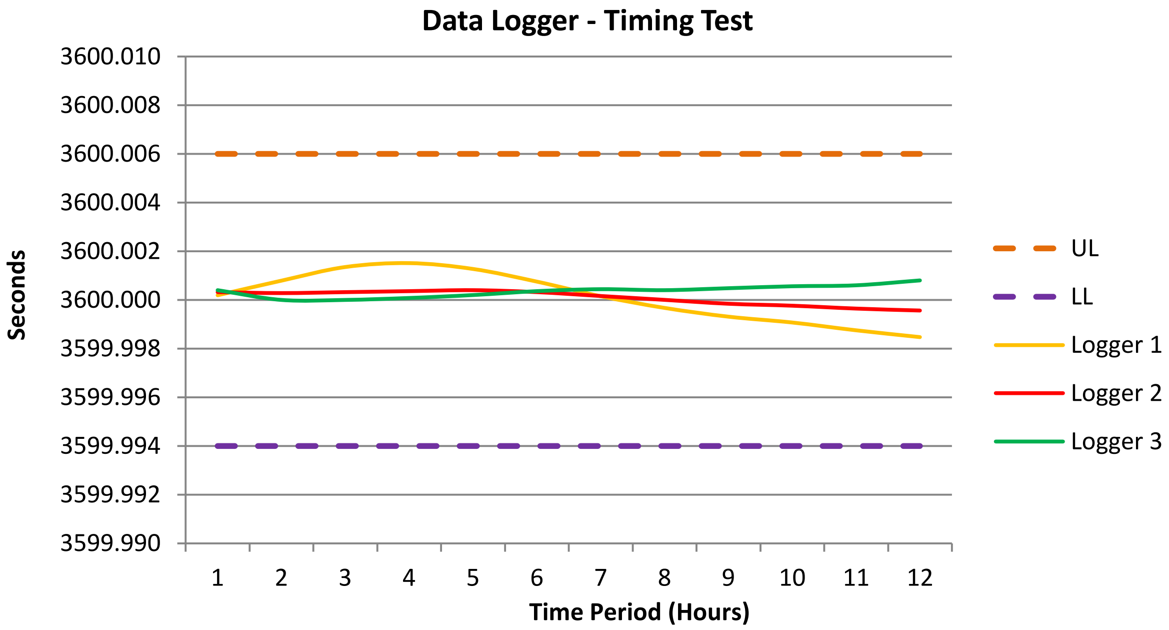
- Research into temperature variation
- Idea generation
- Costing
- Design and testing of equipment
- Data collection (pre-prototype)
- Prototype design
- Prototype manufacture
- Prototype testing and modification
- Data collection (post prototype)
- Final assessment

All of the stages were examined for duration and sequence and incorporated into a Gantt chart to describe the interdependencies and timeframe for the project. The Gantt chart is shown in Annex B (Graph 8). As can be seen from the Gantt chart, this project has a very linear structure, and has only one opportunity to “crash” the project. This is in the prototype design stage where resources can be reallocated as long as a working prototype is delivered before the final Data Collection activity commences.

Given that the results for the project are assessed as inconclusive, the Gantt chart in Annex B has been expanded to include timings for additional research, design, testing over an increased timeframe and analysis.

8 Control Systems

Process control methodology was used to confirm the accuracy of the data loggers with regards to measuring temperature at the same time. Given that the recirculation fans are rated at moving 3.1m^3/min, then a total of four fans will recirculate 12.4m^3/min which equates to 0.00021m^3/ms. With this flow rate, 0.01% of the greenhouse air would be moved in 6ms. For the design application, this was considered suitable for the upper limit (UL) and lower limit (LL) for the data logger timing accuracy. As can be seen in Graph 9, the timing accuracy for the data loggers fell within the upper and lower bounds.



Graph 9. *Data Logger timing accuracy (against 3600sec) recorded over a 12 hour period.*

The control system for this design incorporates the three simple aspects of sensing, computation and actuation. The Controller is responsible for receiving the recorded temperature values and determining the difference between the maximum and the minimum values. If the result is greater than 4°C[7] then the fans are turned on to recirculate the air. The data loggers provide the feedback to the Controller for appropriate control of the actuators (or fans in this case). The closed loop system results in sensing and adjustments being made on an hourly basis. If necessary, the loop timing could be reduced to cater for periods of fluctuation. This control system could be replace by a simple timer which turned fans on at 0800h and off at 1700h, however, it would not be able to cater to external temperature variations and seasonal changes, hence the preferred option of including a control system.

[7] This value has been chosen with reference to the temperature recordings seen in Graph 2. Choosing a value of 4°C will result in the fans being turned off over evening and cool periods. This could be modified in code or with a manual system, but would impact on the payback period assessment.

9 Materials, Energy and Lifecycle

The total embodied energy (EE) for the design is approximately 690MJ/kg (see Table 3) with the majority of the EE being associated with the PVC piping and the plastic coating for the wiring. Both of these are required for the ducting of air and connectivity within the system so cannot be removed. The copper EE value is based on recycled material and so no additional savings could be achieved, however, a change in the ducting (away from high pressure rated PVC) towards a thinner walled plastic could reduce the overall weight and therefore the EE.

Item	Quantity	Weight (ea)	Total (kg)	Embodied Energy (MJ/kg)	Total EE (MJ/kg)
Fan (plastic)	4	0.008	0.032	80.5	2.6
PVC Pipe	9	0.44	3.960	67.5	267.3
PVC 90 Elbow	4	0.158	0.632	67.5	42.7
PVC 45 Elbow	4	0.061	0.244	67.5	16.5
PVC Join	4	0.045	0.180	67.5	12.2
Acrylic	4	0.0031	0.012	70.5	0.9
Wiring (copper)	15.6	0.004	0.062	16.5	1.0
Wiring (plastic)	15.6	0.248	3.869	89.72	347.1
				Total	690.2

Table 3. *Embodied Energy of prototype components* (Hammond & Jones, 2011).

9.1 Life-cycle Costing

The manufacturer of a fan under consideration indicates the fan has a life of 100 000 hours (Jaycar Electronics, 2016). The temperature variations shown in Graph 3 indicate that the fans will need to run for the full 24 hour period to maintain a reduced temperature difference. Over a period of 1 year this equates to ~8800 hours or an 11.5 year operational life.

When considering the operational life of the recirculation system with regards to the existing structure, the supplier of the Sproutwell Greenhouses provides a 10 year limited warranty against the polycarbonate panels (Sproutwell Greenhouses, 2015). It would therefore be expected that the life of the recirculation system would be comparable with the original greenhouse purchase and once installed would not require maintenance or replacement before other parts of the original purchase. The costing for the project is outlined in Table 4.

Item	Quantity	Cost per unit ($)	Total ($)
Fan	4	12.35[8]	49.4
PVC Pipe	9	6.75[9]	60.75
PVC 88 Elbow	4	1.78[8]	7.12
PVC 45 Elbow	4	2.60[8]	10.40
PVC Join	4	2.95[8]	11.80
Acrylic	1	13.95[10]	13.95
Wiring	15.6	0.50[11]	7.80
Data Loggers and Control	3	12.50[12]	37.50
		Total	$198.72

Table 4. *Component costs* (Jaycar Electronics, 2016) (Bunnings Warehouse, 2016) (RS Australia, 2016).

[8] http://www.jaycar.com.au/5vdc-30mm-thin-2-wire-fan/p/YX2500
[9] https://www.bunnings.com.au
[10] http://www.jaycar.com.au/clear-acrylic-sheet/p/HM9509
[11] http://www.jaycar.com.au/light-duty-fig-8-speaker-cable/p/WB1702
[12] http://au.rs-online.com

9.2 Payback Period

The design has an initial one-off cost ($200) with the only on-going costs relating to electricity consumption. As this system is an extension of an earlier project which considered temperature regulation and utilise a green energy supply, the power related on-going costs may be covered by the previous system. Of note, however, is that each of the fans draws approx 85mA at 5 Vdc which equates to 1.7W and from the temperature variations at Graph 3 would only need to be run for approximately five hours each day. Using a flat electricity rate of 18.282c/kWh (Origin Energy, 2016), this equates to an annual electricity bill of $570.

The cost was $200 with components purchased at local hardware stores, however, this could be reduced if the design was to be mass produced.

See Annex C (Graph 10) for the Payback Period Graph. For the system to be efficient, the greenhouse would need to produce a minimum of $590 per year for 10 years as this is the manufacturer's time period warranty for the polycarbonate panels (Sproutwell Greenhouses, 2015). Increased maintenance or replacement costs would be expected after this time which would impact on the payback period.

From the information in Table 4, and given a 10 year life of type for the greenhouse, this results in a material cost of $20/year. While the upfront cost may seem excessive, over the lifetime of the project the increase could be considered an acceptable cost. What has not been assessed is the resulting output of the proposed temperature management, i.e. does the greenhouse produce in excess of $5900 of output over the lifetime of the product (10 years). This may be less than expected as the domestic greenhouse is not generally used with an income in mind. The requirement for such a controlled environment is more likely for a reduced market, however, at an overall cost of $590/year, it may still be an attractive option for a gardening enthusiast.

9.3 Energy Transfer

In order to better understand the potential for savings in energy, a Sankey diagram was produced to map the flow of energy through the system during operation. There are two main states for the system;

- On, where the fans have power supplied; and
- Idle, where the fans have no power supplied and are off.

In both of these states, the system goes through a low power period where a timer provides a one hour delay, and then takes a temperature measurement and performs a temperature difference calculation before repeating the delay cycle. If the difference between the maximum and minimum temperatures is greater than 4°C, the system transitions from an Idle state to an On state.

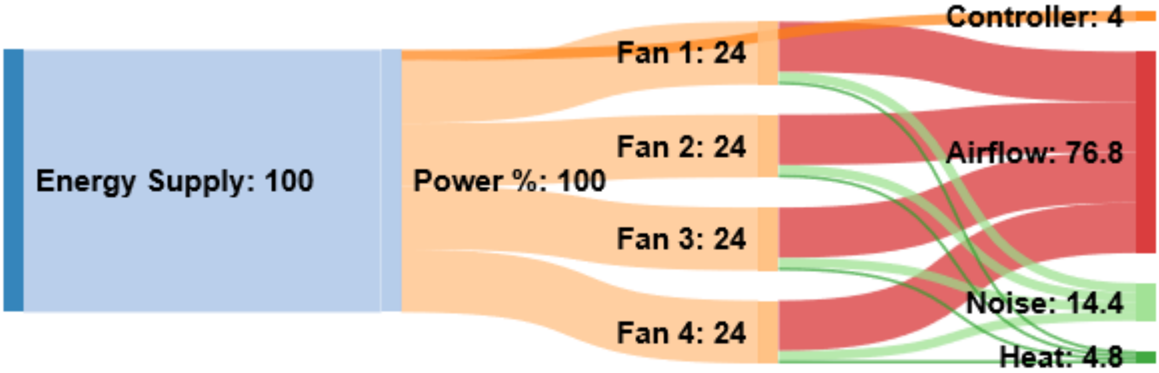


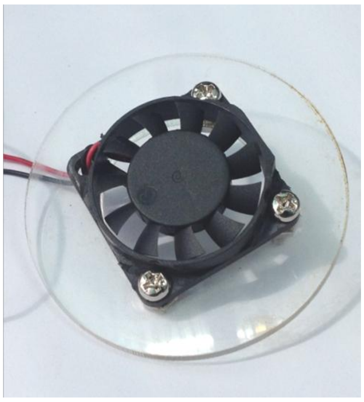
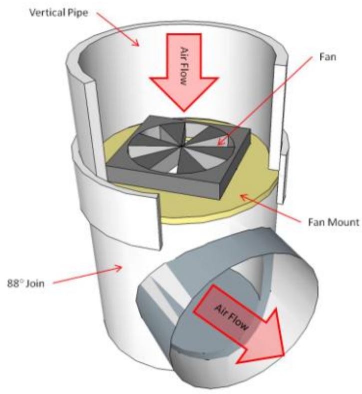
Image 3. *Sankey Diagram showing energy flow.*

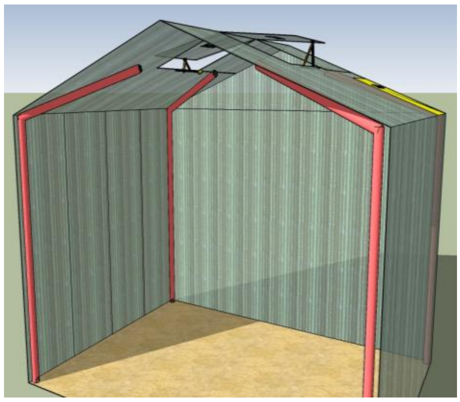
The Sankey Diagram (Image 3) shows the flow of power within the system during the On state and highlights areas for potential savings. It was noted that the fans produce a level of noise when in the On state. Future work could be directed at looking towards quieter fans which may present an energy savings. These potential savings would possibly reduce the annual operating costs. Note that while measurements were undertaken to determine the power consumption of the Controller and Fans, the division of energy across airflow, noise and heat was by rough estimation of 80%, 15% and 5% respectively.

10 Design Solution

The proposed solution was developed with two main considerations; cost and environmental impact. As the focus is on a domestic greenhouse which most likely does not generate an income, the cost of the solution needs to be as low as possible to make it viable and marketable. From an environmental impact perspective, the solution needs to be able to integrate into the urban environment without causing issues, and in this case, noise pollution is a factor. The fans chosen for the project produced a noise level well below the daily maximum acceptable level and achieved the aim of removing any risk associated with hearing damage and interference with neighbouring properties.

The proposed solution involved four ducting systems to recirculate the air within the greenhouse over a one minute period. The ducting system was designed using 50mm PVC piping and 30mm diameter 5Vdc brushless fans. The fans were mounted on acrylic forms which had been laser cut to 56mm external diameter with a 30mm internal hole to match the fan diameter. The 56mm external diameter enabled the fan mounting to be located at the join between the 88 deg coupling and the 50mm vertical pipe (Images 4, 5 and 6). This also removed the requirement for any special bracket design to hold the fan mounting in place.



Images 4, 5 and 6. *Recirculation fan mount design, fan location and layout of recirculation system.*

11 Conclusion

As can be seen from Graphs 2 and 3, while there was a slight reduction in the maximum temperature differences between the two test periods, it was not a significant reduction. This was further supported through testing the hypothesis using the collected data. To support the graphical evidence, the maximum temperature differences were recorded for both test periods and the mean, standard deviation and test statistic were calculated. Using the ANU online Surfstat (Australian National University, 2016), a probability of 0.685 was achieved. This indicated that the null hypothesis cannot be rejected[13].

This suggests that the current prototype does not recirculate the air in a sufficient manner to reduce the temperature difference.

12 Future Work

In reviewing the project and results, a number of areas were identified for consideration:

- **Trial Period.** The initial trial periods were very short additionally, both tests were undertaken under difference weather conditions (with different daily maximum and minimum temperatures). Consideration should be given to extending the data capture period.
- **Control structure.** Conducting both tests concurrently in separate and collocated greenhouses would provide more accurate data and alleviate issues with differing climatic conditions. This would, however, have a financial implication to payback period calculations.
- **Recirculation Rate.** Given the outcomes of the current project, consideration should be given to an increased recirculation rate – possibly less than 10 seconds for the volume of the greenhouse. However, this would likely increase the project costs through increased fan numbers or fans with a greater capacity and would affect issues such as noise, lifecycle and payback period.

[13] **Null Hypothesis:** That regardless of air recirculation, the temperature difference within a domestic greenhouse will remain constant. **Alternate Hypothesis:** With air recirculation, the temperature difference within a domestic greenhouse will reduce.

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