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Implementation of Lean Manufacturing Principles in a Vertical Farming System to Reduce Dependency on Human Labour

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ABSTRACT

Based on the current trends and projections of population growth and average caloric intake per capita, the world is growing hungrier with every passing decade. Despite the advancements in agriculture techniques, the rising temperature, increasing frequency of natural disasters and changes in global precipitation concentration have negatively affected the yield of agriculture sectors around the world. Adding to the fact that there is a scarcity for labour in farms worldwide, the agriculture sector is facing an immense challenge to meet the growing demand for agriculture produce. With the largest consumers of said produce concentrated in the urban areas, a new revolution of growing and harvesting produce known as Urban Farming has gained popularity as a green and self-sustaining initiative. Among the common urban farming systems, a plant factory that combines water-based agriculture, vertical farming and controlled environment agriculture, boasting the highest yield and growth rate has the most potential to feed the ever-growing population of urban dwellers. However, plant factories are notorious for their high overhead cost due to the high-power consumption and dependency on human labour. This paper attempts to redesign the typical plant factory layout in order to reduce the need to move the growing trays and enable the implementation of low-cost, simple cartesian robotics. The prototype adopts the lean management principle *karakuri kaizen* to enable mechanical motion of the growing trays which reduces the amount of vertical and horizontal motion needed by a cartesian robot as well as maximizing the space used for the growing area of any typical plant factory layout. Experimental results show that 90% of 36 seedlings of cabbage have grown successfully within a 6-week period.

Key words : Plant Factory, Urban Farming, Vertical Farming, *Karakuri Kaizen*

1. INTRODUCTION

Agriculture sectors around the world are facing difficulties in maintaining their annual crop yields due to global climate change. A study investigating the effects of global warming on the average temperature and precipitation levels of farmlands across the globe concluded that the average rise in temperature and varying precipitation levels resulted in a decrease in consumable food calories of 0.4%, 0.5%and 0.7% for rice, wheatand maize respectively [1]. This study is backed by localized researches from Vietnam [2], Iran [3]and USA [4] where rice, maizeand other crop yields have been on the decline costing the agriculture sector millions of lost revenues which will continue to worsen into the future.

Besides facing an environmental challenge, the agriculture sector is also facing a social-economical obstacle, labour shortage. Studies conducted at North Eastern Karnataka farms concluded that the demand for labours exceeds the available supply for seven of the twelve months, especially during the sowing and weeding seasons [5]. A survey conducted in Chilean reported that 32.3% of the farmers identified labour shortage as a problem and tried to overcome the situation by offering higher wages, improve working conditions and mechanization [6]. The scarcity of labour in agriculture could be due to a number of external factors such as occupational changes, government policiesand low wages as indicated in the United States where agriculture wages peaked in 2009 and have been on a slow and steady decline [7].

With the global human population to projected to reach 11.2 billion people before the start of the next century [8] as well as their growing appetite as shown by the increase in average intake per capita from 2200 kcal/day in the 1960’s to 2800 kcal/day in 2009 [9], the agriculture industry will be placed in immense pressure to keep up with the demand for agriculture produce. To relieve this pressure, a new revolution known as Urban Farming (UF) was popularized as an alternative for a greener and self-sustainable approach to agriculture. Many countries such as Indonesia [10] and the Netherlands [11] are analysing the possibility and potential of implementing various UF systems such as rooftop farms, vertical surface farmsand indoor farms into their city developments. Adopting agriculture into city development comes with many positive environmental and economic effects such as reducing carbon emission of food transportation and storage, recycling of resources such as water and organic wasteand improvement in urban air quality [12, 13]. It is estimated that if one-third of an urban area incorporates a UF system, it could provide and meet the demands of all its local residence [14].

Of the several available UF systems, a plant factory holds the most potential to cater to the agriculture needs of its local urban residents. A plant factory is a combination of different modern agriculture techniques such as non-soil-based agriculture, vertical farmingand controlled environment farming to pack as much produce as possible in any given land area in a monitored and regulated growing environment (temperature, humidity, carbon dioxide concentration, pHand EC) to exponentially boost agriculture produce [15] **-** [17]. An optimized growing environment such as these is proved to improve the growth rates of produces housed within them [15]. The development of machine learning in the agriculture sector [16] which includes computer visions to monitor plant growth and detect any abnormalities will further boost the viability of plant factory systems [17, 18].

The University of Bronn conducted a study whereby they simulated the cost of a vertical farm feeding 15,000 of its local community [19]. The design of a 0.93 ha vertical farm that employs an aquaponic system is capable of producing one kg of consumable biomass (fish meat and vegetables) at the cost range of 3.50 €/kg to 4.00 €/kg, (4.55 USD/kg to 5.20 USD/kg) when compared to current market prices, which are 1.2 to 4 times more expensive. The study pinpointed that two of the highest variables that are contributing to the inflation of the prices are due to high power consumption and heavy reliance on human labour.

Improvements in the overall efficiency of a plant factory had grown over the years and the success of companies such as Aerofarm, Bowery Farmand Panasonic Plant Factory proves that plant factories can be economically viable. Espec Mic Corp's VegetaFarm in Japan produces 1000 heads of lettuce a day consistently and sustainably within an effective space of 1600 m^2 [20]. The change from fluorescent to LED lighting drastically decreased the implementation cost and power consumption of a plant factory, a study with a growth area of 1 x 3 in^2 area concluded that the cost of providing artificial lighting with LED and fluorescent lighting is 5 USD/year and 80 USD/year respectively. [21], however, the plant factory reliance on human labour remained true to all examples mentioned above [22].

Lean manufacturing practices such as *karakuri kaizen* attempts to reduce the amount of labour needed in a production line by reducing *muda* or wastages. *Karakuri kaizen* generally describes pure mechanical devices that improve work without relying on external power sources. The adoption of lean manufacturing practices has shown to improve productivity in most manufacturing processes, including the production of meat and dairy products [23, 24].

As the size and popularity of plant factories continue to grow the number of workers and the potential danger that they face due to the usage of a scissor's lifts will rise [25, 26]. This research attempts to innovate a new structural system that maintains the potential of plant factories while creating a safer working environment, reduces reliance on human labour as well as further improves the space utilization of a plant factory layout.

2. METHODOLOGY

The design requirements of the prototype model can be broken down into three major systems, which are structural, lighting and irrigation. The lighting and structural system are the beating heart of any plant factory as only with an appropriate implementation that the produce will grow. Therefore, several design configurations will be tested via simulation and experimental methods to ensure that all the seeding receives sufficient amounts of nutrient solution and illumination. The irrigation system will be based on a variation of the hydroponics family known as aeroponics, which delivers the nutrient solution in the form of a mist, directly to the root of the plants. As for the lighting system, 4 ft full spectrum LED grow lights will be used as the primary source of lighting for the produce.

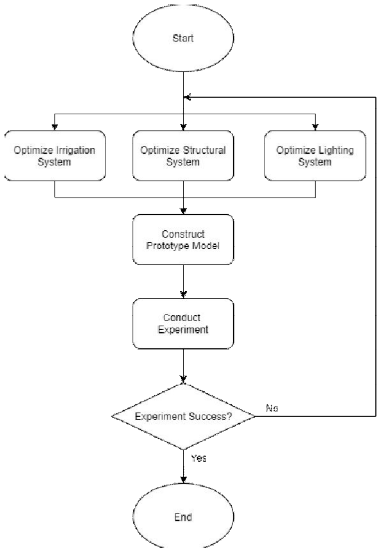


Figure 1: Methodology flowchart

Current structural systems of the plant factory are static and do not put any consideration into the implementation of robotics. Attempts to automate plant factories are being developed, however, current methods are extremely expensive and the low returns of agriculture produce do not justify its implementation cost. The structural system of the prototype model, which will be constructed with the pipe and joint system, will not only reduce the labour associated with the movement of the growing tray and improve the space usage efficiency of the plant factory layout, it will also enable the implementation of simple cartesian robotics to replace human labour.

2.1. Optimization of Irrigation System

An aeroponics system is more water and power efficient when compared to other hydroponics methods. However, misters used in an aeroponics method have a minimum working pressure that must be met. Models with different irrigation arrangements and configurations were model in ANSYS and 2-D flow analysis was simulated to determine the pressure distribution of each model. The four models that were designed and studied are shown in **Figure 2**. Design 1 and Design 3 are counterparts of Design 2 and Design 4, respectively. The simulation aims to study the difference in pressure distribution if the main pipe that supplies the water into all four levels when it is split into two sub-channels, supplying water to two levels each. The initial condition of the experimental method was an input pressure of 750 kPa which was repeated on the simulated model.

Table 1: Simulated and experimental result of the irrigation system

Level	**Design 1**				**Design 2**				**Design 3**				**Design 4**			
	4	**3**	**2**	**1**	**4**	**3**	**2**	**1**	**4**	**3**	**2**	**1**	**4**	**3**	**2**	**1**
Simulated Pressure (kPa)	514	472	301	327	407	362	385	328	402	220	126	101	315	259	324	257
Experimental Pressure (kPa)	675	500	450	400	575	575	525	425	775	750	625	750	900	925	775	725
Average Simulated Pressure (kPa)	404				371				212				289			
Average Experimental Pressure (kPa)	506				525				725				831			
Simulated Pressure Distribution	0.32	0.29	0.19	0.20	0.27	0.24	0.26	0.22	0.47	0.26	0.15	0.12	0.27	0.22	0.28	0.22
Experimental Pressure Distribution	0.33	0.25	0.22	0.20	0.27	0.27	0.25	0.20	0.27	0.26	0.22	0.26	0.27	0.28	0.23	0.22
Simulated Standard Deviation	0.0652				0.0228				0.1608				0.0309			
Experimental Standard Deviation	0.0591				0.0337				0.0233				0.0290			

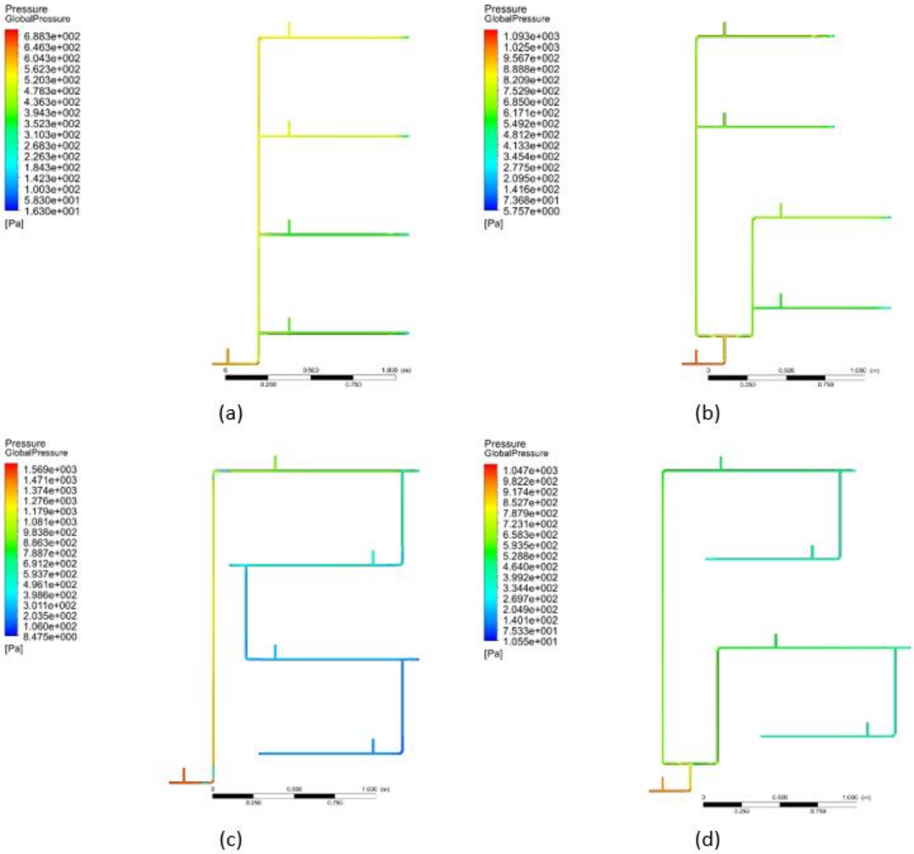


Figure 2: Pressure contour of simulated irrigation model (a) Design 1 (b) Design 2 (c) Design 3 (d) Design 4

Based on the results shown in **Table 1**, it is clear that by splitting the distribution channel into two subchannels consistently improved the distribution of pressure along with its system. Abnormalities in the data sets are the result of experimental errors such as leakages on the experimental setup as well as simulation setting and boundary conditions. Future improvements of both of these parameters may lower the percentage error between simulated and experimental results.

The prototype model will adopt an irrigation configuration similar to that of Design 2 because of it's potential in providing high average pressure throughout the system and relatively small standard deviations.

TABLE 4.

Figure 3: Experimental setup for the investigation of light intensity distribution over various height levels

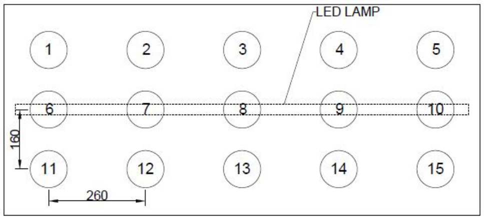


Figure 4: Indicated points of light intensity distribution experimental setup

The exponential increase in light intensity relative to the height is indicated in **Figure 5Error! Reference source not found.**. The rate of change of light intensity increases as the distance between the target and the light source decreases. Thus, the efficiency of the lighting system increases as the distance decreases. Thus, based on the values of selected points on **Table 2** and **Error! Reference source not found.**, the height of 200 mm provides the best balance of light intensity and available growing height and will be used for the prototyped model.

2.2. Optimizing the Lighting System

An experiment was conducted to investigate the distribution of light intensity of a T8 4 ft Full Spectrum LED Grow Light. Leafy greens such as kale, spinachand vegetables are categorized as low-light-level crop and only need a Daily Light Integral of 12 – 17 mol m $^{-2}$ day $^{-1}$ [27], which translate into 5000 to 10000 lux from a full spectrum white LED grow light that was used in this experiment. The aim of the experiment was to determine the appropriate height between the light source and the growing tray which will provide the produce with ideal light intensity. An experimental setup as shown in **Figure 3** with adjustable members to vary the distance between the light source and the lux meter at various pre-determined points. The results of the experiment were tabulated as shown in

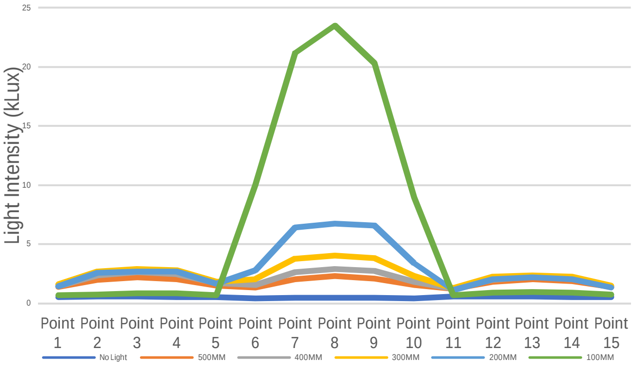


Figure 5: Distribution of light intensity over various points and heights

Table 2: Distribution of light intensity relative to the front plane[1]

	Light Intensity (kLux)				
	Point 6	**Point 7**	**Point 8**	**Point 9**	**Point 10**
100 mm	10.02	21.2	23.5	20.3	8.94
200 mm	2.79	6.42	6.72	6.58	3.4
300 mm	2.04	3.74	4.02	3.81	2.32
400 mm	1.57	2.63	2.91	2.71	1.84
500 mm	1.35	2.02	2.28	2.11	1.54

Table 3: Distribution of light intensity relative to side plane[2]

	Light Intensity (kLux)		
	Point 3	**Point 8**	**Point 12**
100 mm	0.85	23.5	0.89
200 mm	2.67	6.72	2.02
300 mm	2.92	4.02	2.27
400 mm	2.62	2.91	1.98
500 mm	2.21	2.28	1.79

[2] [2] The colour contour in the table indicates the distribution of light intensity

TABLE 4: Light intensity of indicated point in the experimental setup at various height levels

	No Light	500 mm	400 mm	300 mm	200 mm	100 mm
Point 1	0.54	1.36	1.44	1.58	1.41	0.67
Point 2	0.55	1.96	2.36	2.69	2.58	0.73
Point 3	0.55	2.21	2.62	2.92	2.67	0.85
Point 4	0.53	2.05	2.45	2.78	2.67	0.86
Point 5	0.51	1.49	1.72	1.79	1.63	0.68
Point 6	0.43	1.35	1.57	2.04	2.79	10.02
Point 7	0.46	2.02	2.63	3.74	6.42	21.2
Point 8	0.47	2.28	2.91	4.02	6.72	23.5
Point 9	0.46	2.11	2.71	3.81	6.58	20.3
Point 10	0.43	1.54	1.84	2.32	3.4	8.94
Point 11	0.55	1.2	1.24	1.29	1.1	0.66
Point 12	0.55	1.79	1.98	2.27	2.02	0.89
Point 13	0.56	2.04	2.22	2.36	2.18	0.93
Point 14	0.54	1.87	2.05	2.25	2.04	0.87
Point 15	0.51	1.38	1.45	1.51	1.33	0.74

2.3. Optimizing the Structural Design

To enable automated mechanical motion base on gravitational forces, the growing trays are placed on placon rollers which are secured at an angle. An experimental model as shown in **Figure 6** was set up to determine the coefficient of friction between the placon roller and the growing tray. With the coefficient of friction obtained, the minimum angle in which the growing tray will be able to travel down the placon rollers on its own will be obtained mathematically.

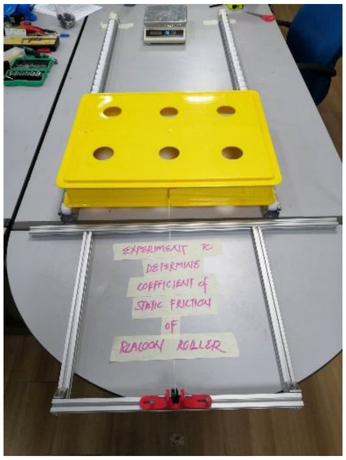


Figure 6: Experimental model to determine the coefficient of static friction between placon roller and growing tray

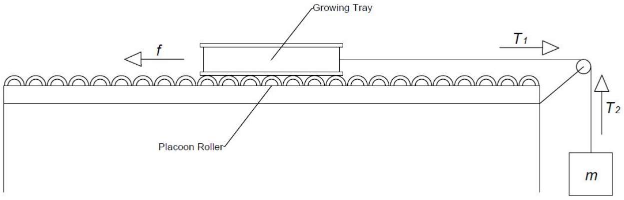


Figure 7: Free body diagram analysis of the experimental model

$$T_1 = T_2 \qquad (1)$$

$$f = mg$$
$$Mgf = mg$$
$$f = {}^{m}/_{M}$$

The force components *f*, T_1 and T_2, are represented as shown in **Figure 7**. The experiment's aim was to determine the minimum amount of mass needed the move the growing tray from a static condition. Mass was added in increments of 2 grams, based on the limitations of the digital measuring scale. The experiment determined that 26 grams of mass are needed to move a growing tray which weighs 746 grams, resulting in a static coefficient of friction of 0.0375. Based on **Figure 8**, the resultant gravitational forces and frictional forces experienced by mass M were calculated and tabulated into **Table 5**.

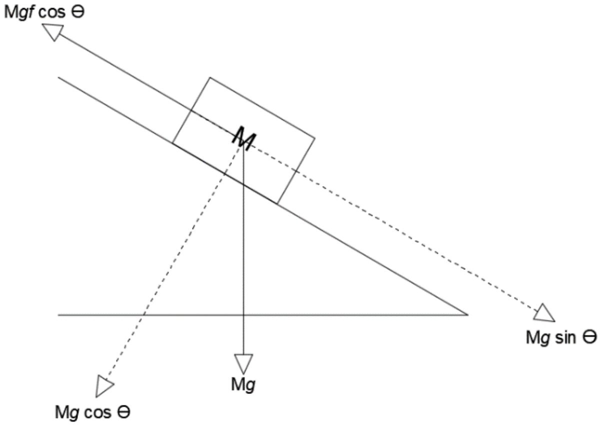


Figure 8: Free body diagram of the prototype model

Table 5: Force analysis of the prototype model at various angles

angle (degree)	angle (radian)	M	*f*	Mg cos Ɵ	Mg sin Ɵ
0.25	0.0044	0.746	0.0375	0.27	0.03
0.50	0.0087			0.27	0.06
0.75	0.0131			0.27	0.10
1.00	0.0175			0.27	0.13
1.25	0.0218			0.27	0.16
1.50	0.0262			0.27	0.19
1.75	0.0305			0.27	0.22
2.00	0.0349			0.27	0.26
2.25	0.0393			0.27	0.29
2.50	0.0436			0.27	0.32
2.75	0.0480			0.27	0.35
3.00	0.0524			0.27	0.38
3.25	0.0567			0.27	0.41
3.50	0.0611			0.27	0.45
3.75	0.0654			0.27	0.48
4.00	0.0698			0.27	0.51
4.25	0.0742			0.27	0.54
4.50	0.0785			0.27	0.57
4.75	0.0829			0.27	0.61
5.00	0.0873			0.27	0.64

The result of the experiment concluded that a minimum angle of 2.25˚ is required to enable automated mechanical motion. Other factors such as the length and height of the prototype model and the volume of stagnant water in the collection basin are both affected by the tilt angle of the prototype model. Due to the space mentioned above, the prototype model will be assembled with a tilt angle of 6.8˚.

2.4. Construction of Prototype Model

A prototype model was developed with SolidWorks after readily available parts are modeled based on the dimensions given by the manufacturers. Based on Section 2, the prototype model must fulfill the three aforementioned design specifications which are, a tilt angle of 6.8˚, a height of 200 mm between the light source and the surface of the growing trayand an irrigation system similar to that of Design 2 of **Figure 2Error! Reference source not found.**. The result of the modeling and construction of the prototype are shown below.

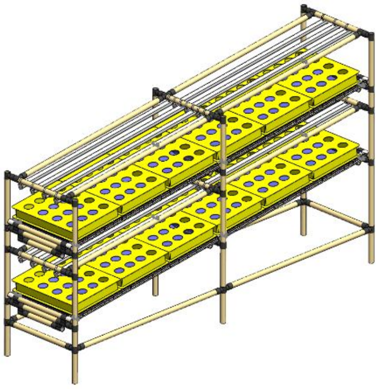


Figure 9: Prototype model

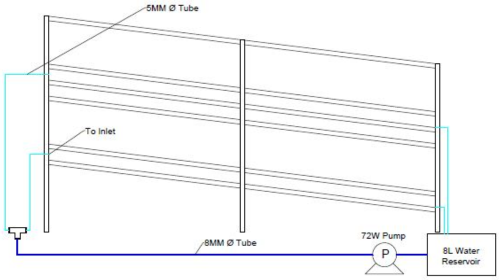


Figure 10: Irrigation configuration of the prototype model

Figure 11: Seedlings growing in the prototype model

3. RESULTS AND DISCUSSION

The prototype model was tested for its viability to grow to produce over a duration of four weeks. The seeds were germinated in a germination chamber for two weeks before being moved into the prototype model. Throughout the six weeks of data collection, the pH and EC (Electrical Conductivity, measured in ppm) value of the nutrient solution were monitored and regulated manually with pH reducer and A+B Nutrient solution. The amount of water, pH reducerand A+B Nutrient solution were measured and recorded throughout the experimentation period.

Table 6: Resources used in the germination station

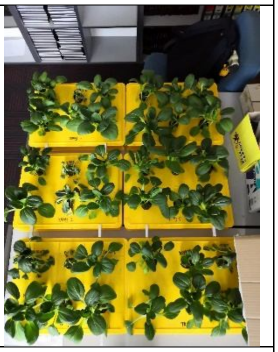
Date	pH Level	EC Levels	Resources Used		
			Water (ml)	pH Down (drop)	AB Solution A + B (ml)
1/11/2019	6.28	561	5000		50 + 50
5/11/2019	6.75	458		1	
6/11/2019	6.23	458			
7/11/2019	6.28	453			
8/11/2019	5.91	445			
10/11/2019	5.79	490	1000		10 + 10
11/11/2019	5.88	353			
14/11/2019	5.71	371			
19/11/2019	5.75	473			
Total Resourced Used			6000	1	60 + 60

Table 7: Resources used in the growing station

Date	pH Level	EC Levels	Resources Used		
			Water (ml)	pH Down (drop)	AB Solution A + B (ml)
19/11/2019	6.14		8000		160 + 160
20/11/2019	6.36	1280			
21/11/2019	6.49	1310			
22/11/2019	6.01	1230	5000		100 + 100
25/11/2019	6.01	1400	5000		100 + 100
26/11/2019	6.36	1470			
2/12/2019	6.56	1360			
3/12/2019	6.59	1400			
4/12/2019	6.26	1300	6000		120 + 120
5/12/2019	6.32	1350			
6/12/2019	6.36	1280			
9/12/2019	6.42	1280			
10/12/2019	6.45	1350			
Total Resourced Used			24000		480 + 480

To monitor the growth of the produce, the weight of the produce was measured once a week to track any change in weight. Pictures were also taken to visually compare any difference in growth.

Table 8: Growth progress of experimental result

	
Week 1	Week 2
	
Week 3	Week 4
	
Week 5	Week 6

The inconsistency in the growth of the seedling weight is due to the fact that the weight being measured is the wet weight of the produce and not its dry weight. The water content of the plant and the rockwool, especially the rockwool, absorbs a significant amount of water that was supplied thus the weight significantly varies depending on the time when the measurements were taken. Further studies that focus on the growing effectiveness of the prototype will need to include various other physical parameters such as the number of leaves, the length of root and the height of the crop for a better indication of growth health.

However, it must be noted that some produce did not grow as well as intended, some of the more extreme examples such as A4 and B4 only had a final weight of 12 g and 14 g, respectively. An investigation into the matter revealed that the misters underneath those two plants were clogged and supplied very little nutrient solution to the produce. Further investigations revealed that most of the misters were clogged. The small orifice used in the misters is susceptible to be clogged from organic debris or clumped up dust particles. An addition of a filtration device into the irrigation system in future iterations will improve the prototype’s ability to consistently and uniformly distribute the nutrient-rich solution to all of the produce.

Table 9: Mass of produce over four weeks

Tray	ID	Fresh Weight of Seedlings (g)			
		19/11	27/19	4/12	10/12
	A1	38	44	32	58
	A2	38	40	26	38
	A3	36	14	16	22
	A4	40	12	16	12
	A5	38	38	30	58
	A6	36	34	34	44
2	**B1**	36	38	26	42
	B2	32	28	24	36
	B3	36	40	38	24
	B4	36	30	22	14
	B5	36	38	26	40
	B6	40	16	18	32
3	**C1**	38	54	34	48
	C2	38	42	24	36
	C3	34	32	26	32
	C4	34	36	12	10
	C5	38	44	46	66
	C6	34	46	46	34
4	**D1**	40	22	30	52
	D2	36	20	26	22
	D3	38	20	16	26
	D4	38	22	18	38
	D5	36	40	36	52
	D6	40	34	36	44
5	**E1**	42	40	28	46
	E2	36	44	34	50
	E3	32	14	26	30
	E4	34	30	20	52
	E5	32	36	30	44
	E6	34	36	16	30
6	**F1**	36	42	36	48
	F2	30	32	20	20
	F3	38	30	26	42
	F4	38	20	12	20
	F5	36	36	30	36
	F6	38	14	22	32

4. CONCLUSION

The concept of a vertical farm that is influenced by the Japanese lean manufacturing principles *karakuri kaizen* was developed and tested to determine its viability. The lighting and irrigation system were optimized to ensure that produce can be successfully grown on the prototype model. It was determined through experimental methods that the ideal distance between the growing tray and the light source is between 200 mm to 250 mm. Furthermore, by splitting the main irrigation source into two sub-channels, it has resulted in a better distribution of pressure thought the system. Plus, with some future optimization, the consistency of the produce growth may improve. Besides, the addition of simple cartesian robotics that can control the movement of the growing trays, building an economically viable automated plant factory can be deemed potentially achievable.

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