Chapter 9
SAIBAIX: Production Process Management System

Shunsuke Sakaguchi

Abstract In order to increase commercial-use PFAL (plant factory with artificial lighting) profitability, it is essential to improve area productivity and RUE (resource-use efficiency). Described here are functions demanded of production process management systems aiming at the achievement of the same, as well as examples of adoption.

Keywords Production process management system · Plant growth · Index value · Productivity

9.1 Introduction

The major merit of a PFAL is the ability to increase the growth rate of plants by creating the ideal environment for plant growth. In doing so, a PFAL can achieve a productivity in terms of area (land) more than 100 times that of open ground (fields). Its second merit is the capacity for stable production of high-quality plants irrespective of the impact of weather conditions.

In order to realize a highly productive factory, as shown in Fig. 9.1, not only are actuators to appropriately control cultivation environment required but also cultivation equipment equipped with sensors to evaluate plant growth and CP (cost performance). However, in reality, in the great majority of PFALs operating in the red, there is a lack of the cultivation environment control performance required to increase productivity to levels that would put them in the black. This is the main reason why only around 25% of PFALs operate in the black in Japan (Kozai et al. 2015). There are many variables that have an impact on productivity, including cultivation environment conditions and damage to plants during work. Furthermore, these variables are themselves mutually interconnected. Accordingly, it is too complicated to understand all of those relationships with human intuition alone,

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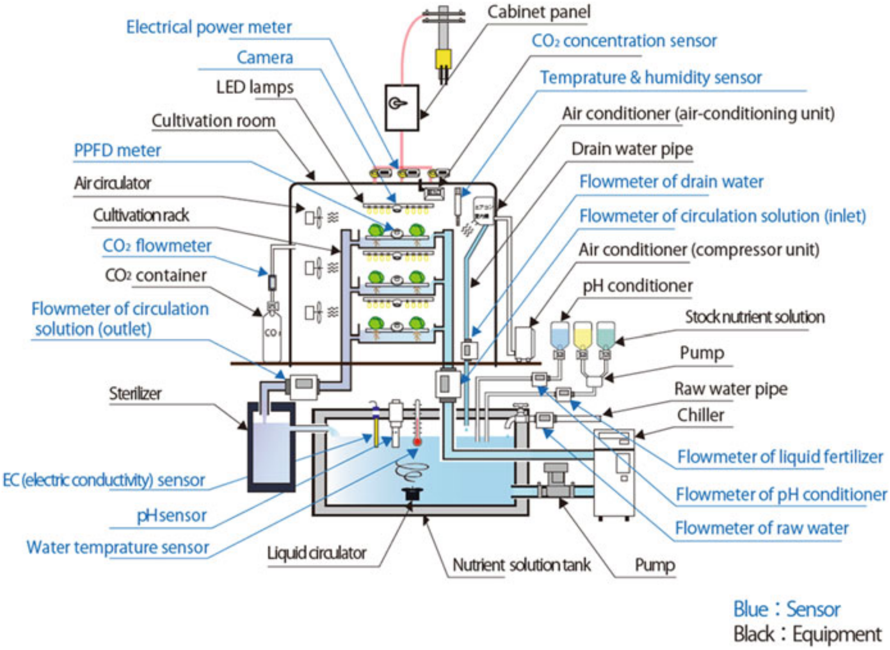


Fig. 9.1 Example of cultivation equipment including actuators and sensors. *PPFD* photosynthetic photon flux density

and it is for the abovementioned reasons that, in order to maximize the merits of PFALs, a production management system that can maximize PFAL productivity by quantitatively managing plant growth is essential.

9.2 System Description

A PFAL production management system requires plant growth, production process, and sales management functions. This is because PFAL profitability is greatly impacted by a PFAL's production output, product sales prices, and sales yield compared to its cultivation area, electric power consumption, and labor costs.

9.2.1 Management of Plant Growth

The first step in production management is a quantitative assessment of what is taking place inside the factory. The following are examples of what should be quantitatively assessed in a PFAL:

1. Cultivation environment state variables (air temperature, VPD (water vapor pressure deficit), CO_2 concentration, leaf-surface PPFD (photosynthetic photon flux density), nutrient solution ion concentration, etc.)
2. Plant growth rate and related rate variables (fresh weight increase rate, leaf surface-area increase rate, net photosynthesis rate, nutrient uptake rate, etc. Here, rate variables are variables including time units such as kg/sec and me/kg/sec).
3. Plant quality (size, shape, color, texture, presence/absence of physiological disorders, etc.).
4. Resource supply rate and RUE.

In particular, the creation of value in PFALs depends on the growth of the plants themselves, so circumstances in which plant growth rates are not managed cannot be described as productivity management. Furthermore, RUE is greatly impacted by plant growth rates, so there is a need for multifaceted measurement and evaluation of plant growth.

9.2.2 Management of Production Process

In a PFAL, what is desired is a shortening of the production lead time through an increased plant growth rate, along with a simultaneous reduction in the hands-on human workload that includes transplanting and harvesting. Not only does unnecessary automation of work alone not enable a shortening of the production process, there conversely is also the risk it may lower CP. Accordingly, a function that shortens the production process both effectively and efficiently is required.

9.2.3 Sales Management

Generally, in order to increase the profitability of a factory, even where productivity is stable, it is essential to link factory production control and inventory control in order to adjust production output in response to fluctuations in demand. Production factories in the manufacturing industry can adjust production by stopping production lines temporarily in response to fluctuations in demand.

However, with a PFAL, the production process cannot be stopped temporarily until seeds that have been sown are harvested as plants. Accordingly, mistakes in production adjustment mean product shortages or disposal, which in one way or another cause an operating loss. For that reason, in order to minimize harvest shortages or disposal, a function for the adjustment of factory growth management and sales management is required.

By applying these advanced techniques to PFAL production management, strict production management to rival that of the production factories in the manufacturing industry will be possible. Together with Toyoki Kozai (Professor Emeritus, Chiba University), PLANTX Corp. has developed SAIBAIX, which is a dedicated PFAL production management system and is providing the same for commercial-use PFALs. In the following sections, the above functions using SAIBAIX will be explained and interspersing examples analyzed.

9.3 Measurement of State and Rate Variables

In order to increase PFAL productivity, it is important to manage not only the setting values for the various main cultivation environment factors but also the plant growth rate. No matter how precisely setting values for state variables such as temperature, VPD, CO_2 concentration, and nutrient solution ion concentration are maintained in a cultivation room, if those setting values do not create conditions to increase the growth rate for plants, then productivity will not improve. The plant growth rate can be estimated online from rate variables such as the net photosynthetic rate, the nutrient solution ion uptake rate, and the water uptake rate (Kozai 2013; Kozai et al. 2015). Furthermore, using these rate variables enables the almost-real-time estimation of the RUE and CP for resources including electricity, CO_2, and water, which will be discussed below. Next, an example of estimating net photosynthetic rate and uptake rate will be shown.

Plants grow through photosynthesis, so the net photosynthetic rate is a rate variable that directly represents plant growth. A plant's net photosynthetic rate can be estimated from the CO_2 concentration and CO_2 supply volume (Kozai 2013). Figure 9.2 shows an example of the net photosynthetic rate in a cultivation room. The diagram shows the net photosynthetic rate for all plants being cultivated in the cultivation room. Monitoring the net photosynthetic rate enables noninvasive estimation of the growth rate. Furthermore, by constantly comparing the steady-state net photosynthetic rate and the current values, growth abnormalities can be detected online.

It is difficult to notice unforeseen changes in the cultivation environment such as a toxic-substance outbreak in the nutrient solution or a drop in PPFD due to equipment failure by just monitoring state variables alone. Plants respond quickly to such changes in environment, so additional monitoring of variables that indicate plant growth will enable the detection of growth abnormalities before any declines appear in harvest weights.

Functional plants such as mineral-rich vegetables or medicinal plants can be cultivated in PFALs. In order to cultivate these plants, it is necessary to manage not only plant growth but also the functional components of the plants. To that end, it is important to manage the nutrient solution ion uptake rate. Figure 9.3 shows the ion uptake rate when cultivating lettuce. The diagram is the ion uptake rate in a nutrient solution system controlled to maintain a uniform EC (electrical conductance). As described in Chapter 24, even if EC values are uniform, the balance of the ion concentration in the nutrient solution changes according to the uptake of fertilizer

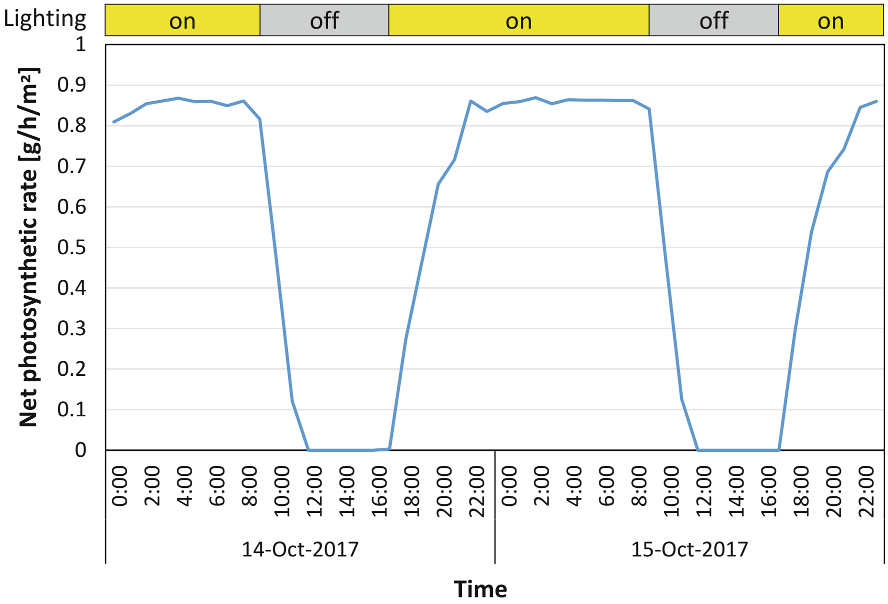


Fig. 9.2 Average net photosynthetic rate per unit area when cultivating lettuce. Bands at the top indicate ON/OFF for cultivation rack lighting

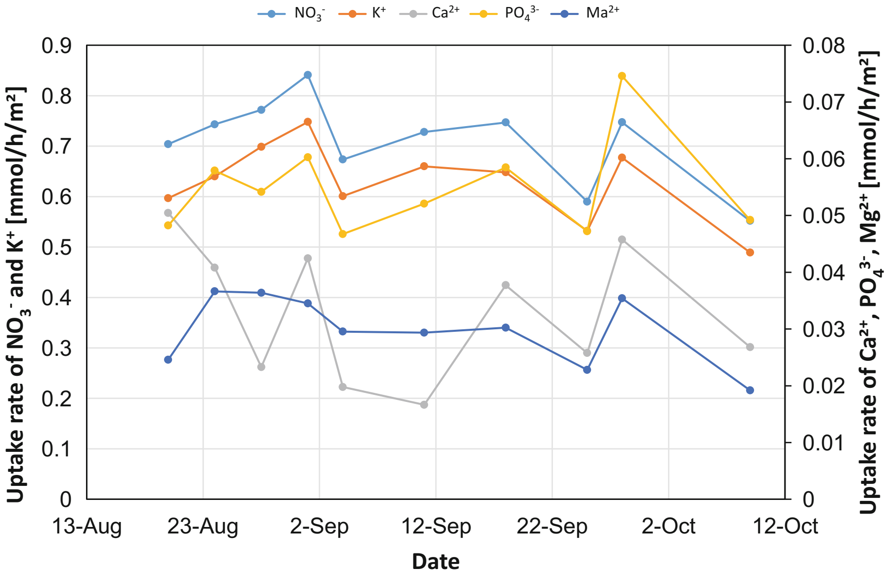


Fig. 9.3 Ion uptake rate per unit area when cultivating lettuce. Electrical conductance has been kept constant in this example. Fluctuations in uptake rate are considered to be caused by changes in solution ion concentration and fluctuations in plant bodyweight due to harvesting

components by the plants, and because of this, the ion uptake rate also changes. Clarifying this relationship between the ion uptake rate and the rate of change of components inside the plant bodies and appropriately adjusting the ion concentration allows plants to have the desired components.

Growth management of plants using the rate variables described above will not only simply enable early detection of abnormalities, it will also deliver operational advantages such as reductions in product development times, so that the importance will probably only increase in the future.

9.4 Online Estimation of Resource-Use Efficiency and Cost Performance

The first step in improving the profitability of a factory involves accurately ascertaining problems through a quantitative evaluation of productivity and CP. In general, production factories are always measuring and managing items related to productivity, such as component costs, manufacturing costs, yields, and manufacturing lead times. In the same way, in PFALs it is necessary to constantly manage the cost for resources, such as seeds, CO_2, water, and fertilizer, and electric energy costs, harvest yields, and plant growth rates. PFALs are different from open ground (fields), using only electric energy in a closed space, so the energy input/output relationship can be measured and evaluated almost in real time. RUE and CP of PFAL are defined in detail for each resource, such as lighting, CO_2, or fertilizer (Kozai 2013). SAIBAIX can manage such RUE and CP.

Figure 9.4 shows the monthly electricity consumption and electricity CP. Electric power costs are one of the largest cost factors for PFALs, and their reduction has a great effect. Of the electric energy, energy for lighting composes the largest percentage (Fig. 9.5). Accordingly, the amount of electricity consumption per month in Fig. 9.4 is mainly proportional to the factory's operating ratio, in other words, the percentage of lighting equipment turned on. In the figure, despite January 2015 having almost the same amount of electricity consumption as the previous month, the weight of the harvest has increased. This can be considered as being due to a temporary improvement in cultivation environment factors other than lighting, such as air temperature or nutrient solution. In this way, productivity can sometimes be increased without raising costs by improving the cultivation environment. Furthermore, where there exist plural conditions that deliver the same harvest weights, the condition(s) that increase CP can be selected. Additionally, methods to reduce electric power costs are introduced in Chapter 21 in Kozai et al. (2015).

Figure 9.6 shows the daily amount of drainage water from heat pumps. One of the greatest advantages of PFALs is their high WUE (water use efficiency). So long as there are no large divergences from target ion concentrations or problems such as proliferations of disease-causing bacteria, then the nutrient solution can be continued to be used. Moisture transpired by plants is collected as drainage water from the

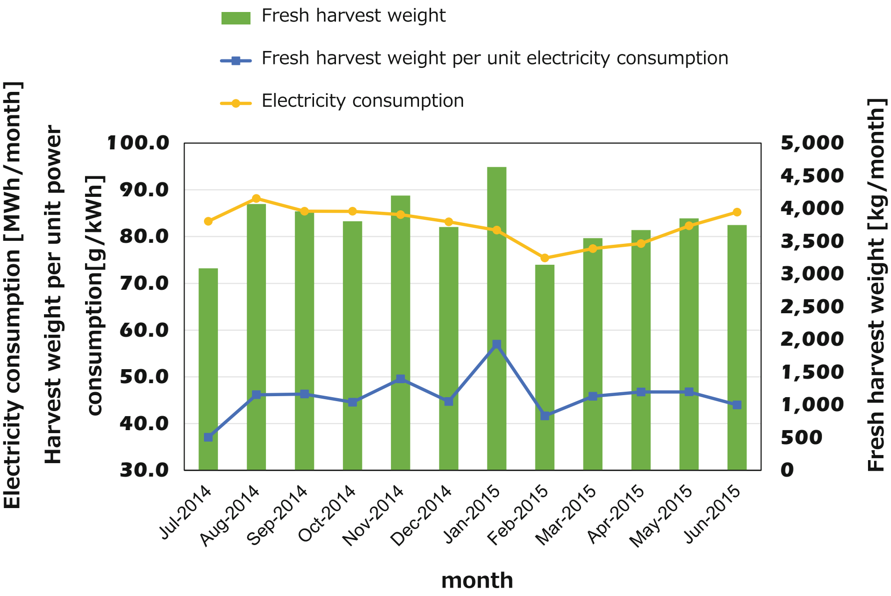


Fig. 9.4 Monthly production, electricity consumption, and electricity use efficiency (Courtesy of JA Touzai Shirakawa "Miryoku Manten Yasai no Ie")

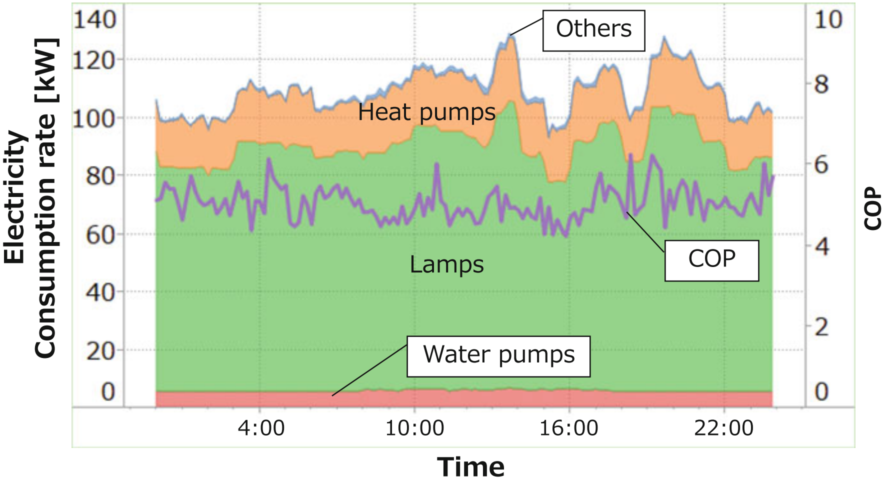


Fig. 9.5 Example of shift in electric power consumption over 1 day. The COP (coefficient of performance for air-cooling heat pumps) = (lighting power + pump power + other electric power)/ air-cooling heat pump power (Measured at JA Touzai Shirakawa "Miryoku Manten Yasai no Ie")

air-conditioners in the cultivation room, and when recycled, of the raw water supplied to the cultivation system, hardly any is lost, with the exception of the water included in the shipped plants. As a result, compared with a maximum of 2%

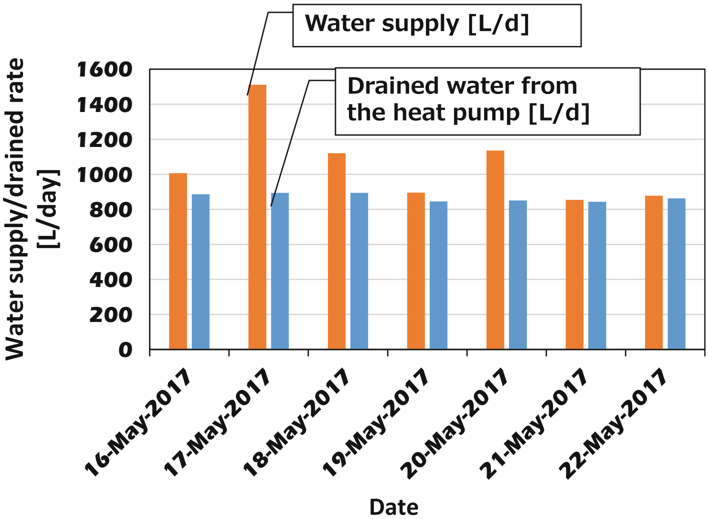


Fig. 9.6 Relationship between amount of water supplied for cultivation and amount of heat-pump drain water collected. The amount supplied changes depending on the presence/absence of work inside the cultivation chamber such as harvesting or cultivation solution renewal. The drain water collection rate for days with no work inside the cultivation chamber (May 21 and 22) was more than 98%. Drain water is not reused in this example, but when it is, the water supplied is roughly the same as the amount of water contained in the harvested plants. (Raise Co. Ltd., Chiba University Factory)

for the WUE for a greenhouse, the WUE for a PFAL can be kept at a level of 80% and sometimes more than 90% (Kozai 2013).

In this way, by monitoring and improving RUE and CP, productivity can quickly be improved and continuously maintained at high levels.

9.5 Noninvasive (Camera Image) Measurement of Plants

The structure, color, texture, presence/absence of physiological disorders (e.g.,, yellowed leaves, tipburn), etc., for produced plants are important information when evaluating product values. Even today in the agricultural sphere, much of this visual information is subjectively evaluated by humans. However, not only is there individual difference in evaluations by humans, in terms of cost and feasibility; it is also not realistic to carry out 100 % inspections of large-scale PFALs. For this reason, the development of a quantitative evaluation method using image data is essential. The automation of evaluation will be the key to maintaining high-quality and stable production, which is the greatest strength of PFALs.

The below are examples of main evaluation items using images:

1. Seed submersion state when planting
2. Germination rate

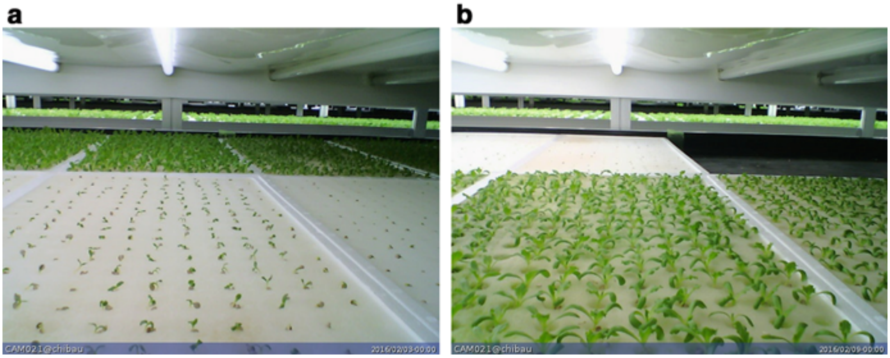


Fig. 9.7 Growing lettuce seedlings. (**a**) 4th day after seed sowing. (**b**) 10th day after seed sowing. (Raise Co. Ltd., Chiba University Factory)

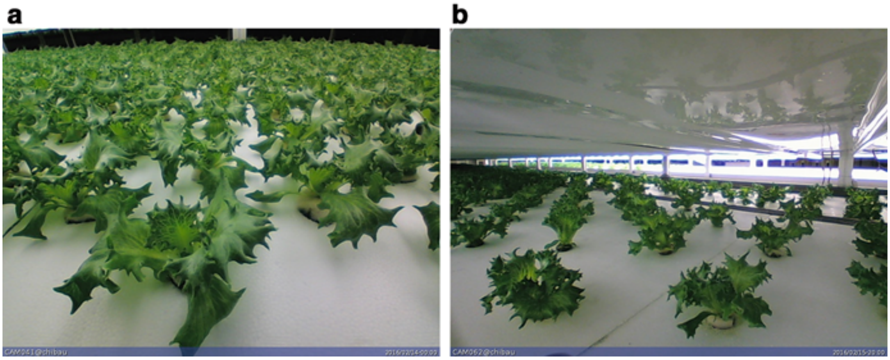


Fig. 9.8 Images of lettuce seedlings before and after transplanting. (**a**) Before transplanting (23rd day after seed sowing. 144 heads/m^2). (**b**) After transplanting (24th day after seed sowing. 33 heads/m^2). (Raise Co. Ltd., Chiba University Factory)

3. Seedling growth state (leaf unfolding/separation, leaf area, number of leaves, etc.) (Fig. 9.7)
4. State before/after transplanting (planting density, seedling damage, seedling collapse, etc.) (Fig. 9.8)
5. Growth rate
6. Condition at harvest (size, color, texture, presence/absence of physiological disorders, etc.)
7. 3D structure of plant (height, thickness of leaves, number of leaves, leaf area)

In particular, as shown in Chapters 2 and 26, plant 3D structure information will only increase in importance in the future because of phenotyping. The application of image data analysis in PFALs has only just begun but will probably see rapid implementation moving forward together with progress in AI (artificial intelligence) technology and phenotyping technology.

9.6 Visualization for Production Process Management

Generally, to efficiently perform production in a “factory,” it is necessary to (1) increase production quantity, (2) improve quality, and (3) shorten process times (Nakao et al. 2002). As described above, PFAL productivity is mainly determined by the growth of plants themselves. However, at the same time, the PFAL production process includes many processes involving human participation, such as transplanting, harvesting, packaging, and shipping handling. Not only do these ancillary processes represent roughly 1/4 of production costs, there is much work handling the plants themselves, so this directly impacts plant growth and product prices. Accordingly, if these processes are not carried out appropriately and efficiently, it is difficult to improve profitability.

In order to reduce individual difference in quality and speed in work carried out by humans, it is necessary to establish clear procedures and evaluation criteria for each process and enable anybody to carry out work that satisfies a fixed standard. An example of a method to realize this is DPD (decision-based process design) (Nakao et al. 2002). DPD is a technique that uses the so-called tacit-knowledge decision-making processes of workers to improve processes. Specifically, first, the decision-making processes tacitly undertaken by a highly skilled worker in each process are analyzed in detail. Then, the know-how which has become clear in that is further optimized before being standardized. Then, by incorporating that standardized know-how into process structure instead of individual knowledge or skill, a fixed standard of work quality is guaranteed. This method has been applied in the production factories of more than 100 companies, including mold manufacturing factories in the manufacturing industry. Depending on the situation, results have seen lead time reduced by 95% or more.

After using DPD process analysis methods to analyze the processes in commercial large-scale PFALs, they were segmented into roughly 200 steps, including processes relating to cultivation covering seed sowing to harvest, processes relating to packaging and shipping, and processes for materials replenishment and equipment maintenance (Fig. 9.9). As a result of work-process optimization based on the DPD analysis, the workload per harvest weight had been reduced by more than half.

The near future will probably see the realization of highly productive PFALs due to the overall systematization of production processes, including worker work designation functions, individual plant traceability functions, and linking with various kinds of automated machines.

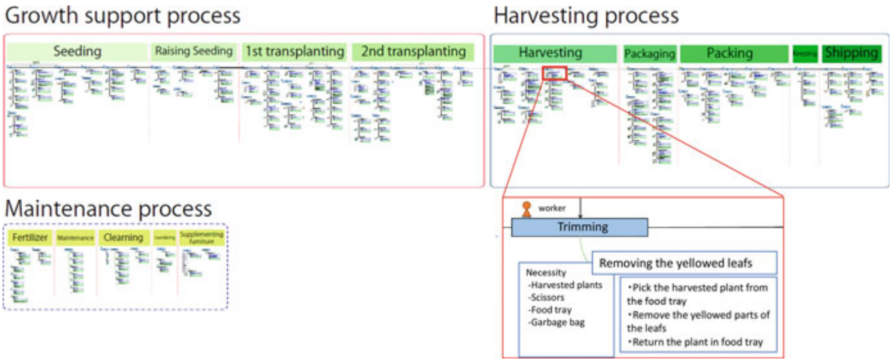


Fig. 9.9 Process chart for large-scale commercial-use PFAL, from seed sowing to shipping. The enlarged diagram at the top-right shows part of the harvest process. The entire process is comprised of roughly 200 processes, from seedlings to shipping. (Created based on the production process of a PFAL of Raise Co. Ltd. at Chiba University) (Jointly prepared with Stone Soup Inc.)

9.7 Modeling, Multivariate Analysis, and Big Data Mining

As described above, in PFALs it is now possible to obtain many datasets, including cultivation environment information, plant growth information, the operational status of workers and automated machines, and resource and energy use efficiency. Until now, data relating to the causal relationship between environment and growth in agricultural cultivation was mostly only obtainable few times a year at best. However, trials are continually underway in PFALs, so new data will accumulate every day. In order to extract and effectively use desired information from such vast data, sophisticated data analysis techniques will be necessary. Fortunately, in recent years there has been remarkable practical progress in data analysis techniques. With the spread of things like open-source machine learning software frameworks, there continue to be large-scale reductions in the costs involved in their introduction.

Figure 9.10 shows the results of an estimate of harvest weight from air temperature and water temperature using multivariate analysis. As shown in the diagram, it can be understood that rough trends can be estimated even from estimates that use simple methods and only a few variables. A factory operating in a steady state will be able to take fast countermeasures against any plant growth rate abnormalities by constantly monitoring differences between steady-state and current values in variables that indicate plant growth, such as the net photosynthetic rate described earlier. Similarly, with respect to plant components, leaf texture, etc., by analyzing the relationship between variables relating to cultivation environment and plant growth using nonlinear mathematical models and machine learning methods, the production of plants with desired characteristics will probably be possible.

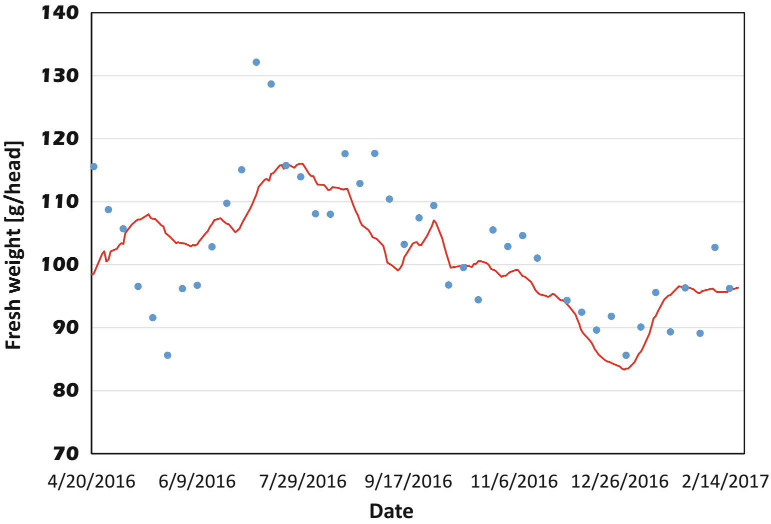


Fig. 9.10 Estimation result of harvest fresh weight using air temperature and water temperature. The red line shows estimated values, while the dots show actual measured values. Environmental factors are considered to have a large impact where large estimation errors are present. (Raise Co. Ltd., Chiba University Factory)

9.8 Commercial Application Examples

SAIBAX has been introduced in Japan's major large-scale commercial-use PFAL and an educational small-scale PFAL (Japan's first example of introduction for educational use). This paragraph will introduce examples of SAIBAIX use as well as its effects.

In 2014, JA Touzai Shirakawa became Japan's first agricultural cooperative to commence operation of a PFAL. SAIBAIX was temporarily installed in the PFAL, and a trial optimizing air-conditioning operation to homogenize cultivation environment conditions was carried out. In the trial, the operating devices of the 10-plus air-conditioning units installed inside the factory were adjusted to take into account the airflow inside the cultivation room. As a result, not only was there a large-scale reduction in the electricity consumption for air-conditioning, but the average air temperature inside the cultivation room also moved closer to the set value while air temperature distribution simultaneously improved. (For details, refer to Kozai et al. (2015), Chapter 22.)

Established in 2015, Raise (Raise Co. Ltd.) commenced operation of a large-scale PFAL inside Chiba University (Fig. 9.11). This PFAL was operated in 2012 by MIRAI as the world's first commercial-use large-scale PFAL and enables harvesting of 3000 lettuces per day. Raise took over the facility and equipment from MIRAI and recommenced operation. Before commencing operation, SAIBAIX was installed, and there was a continual effort to improve productivity. As a result, only 4 months

Fig. 9.11 Large-scale commercial-use PFAL and SAIBAX dashboard (LCD display on left side of photo). Cultivation trials using LED lighting equipment from various manufacturers are being carried out in the cultivation chamber. (Chiba University Kashiwa no Ha Campus, Japan)

after the recommencement of operations, the average harvest yield was doubled for the same number of cultivation days compared to before introduction of the system (Fig. 9.12). These results show the effectiveness of SAIBAIX. Specifically, they show that, even in the same production facility, there is the potential to increase productivity by improving cultivation environment conditions.

SAIBAIX for educational purposes was introduced when the educational small-scale PFAL was established at a Junior High School in Chiba prefecture, Japan (Figs. 9.13 and 9.14). It displays a variety of measured values, including the PFAL's internal/external air temperature, humidity, VPD, PPFD, CO_2 concentration, water temperature, EC, pH, electricity consumption, and plant growth videos, and enables learning of what those values mean. Not only does SAIBAIX allow students to understand PFAL mechanisms, it provides the opportunity for them to become interested in a wild range of science and technology fields, including plant physiology, chemistry, and electrical engineering, and in doing so contributes to the nurturing of the human resources who will be responsible for the next generation.

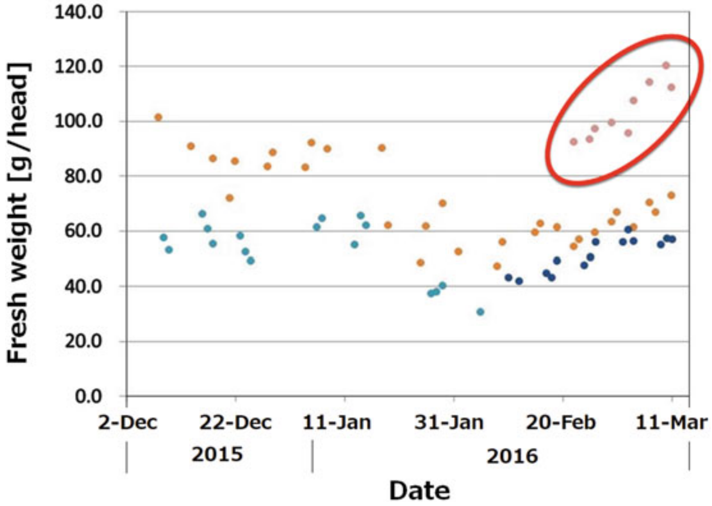


Fig. 9.12 Example of productivity improvement in a large-scale commercial-use PFAL. Different color dots show different cultivation conditions. Product is Frill Lettuce. As shown by the dots in the red circle, harvest weight has more than doubled due to cultivation conditions. (Raise Co. Ltd., Chiba University Factory)

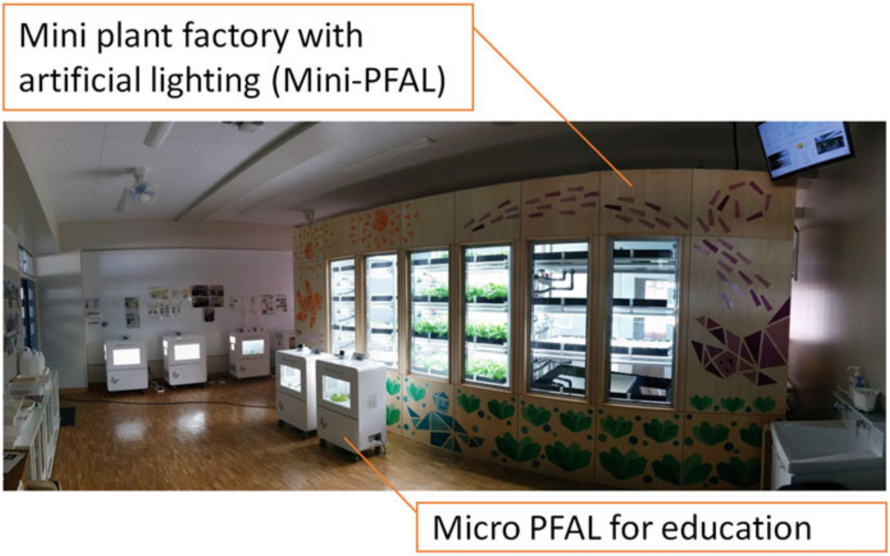
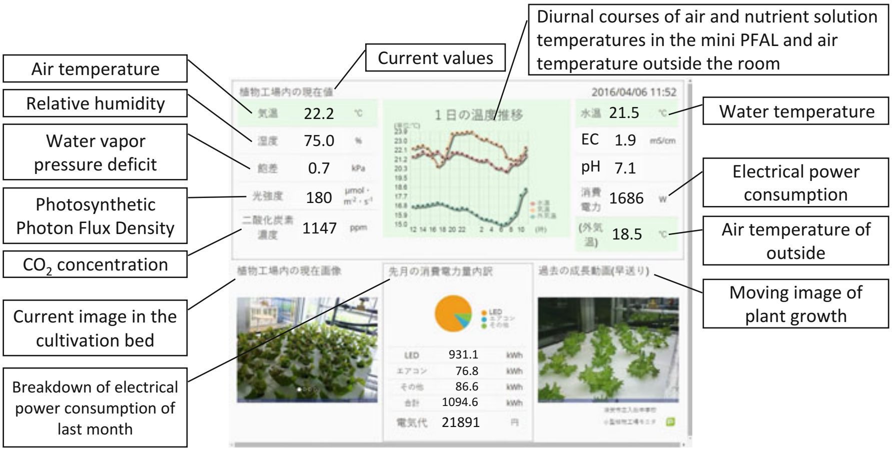


Fig. 9.13 A small-scale educational PFAL and SAIBAX dashboard (Top-right LCD display) in a junior high school. (Chiba prefecture, Japan. Photo taken by the author)



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気温	22.2	℃
湿度	75.0	%
飽差	0.7	kPa
光強度	180	μmol · $m^{-2} \cdot s^{-1}$
二酸化炭素濃度	1147	ppm
水温	21.5	℃
EC	1.9	mS/cm
pH	7.1	
消費電力	1686	W
(外気温)	18.5	℃

先月の消費電力量内訳

LED	931.1	kWh
エアコン	76.8	kWh
その他	86.6	kWh
合計	1094.6	kWh
電気代	21891	円

Fig. 9.14 Example of SAIBAX display at a junior high school

9.9 Concluding Remarks

Production management systems that can manage the growth of plants are essential in order to increase the profitability of commercial-use PFALs. A diverse range of advanced functions is sought in production management systems, including functions to monitor cultivation environment conditions, but also functions to monitor productivity and RUE, functions to optimize production processes, and ordering management based on harvest predictions. This chapter described a production management system equipped with such features and also examples of its application. In the future, together with advances in things like genetic engineering, phenomics research, and AI technology, production management systems will evolve even further and will probably become indispensable in the cultivation of plants with desired shapes and functional components.

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