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Lean Principles in Vertical Farming: A Case Study

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Abstract

Vertical farming (VF) has been recognised as an important tool for managing future food security, yet economic viability poses a significant hurdle with the vast majority of farms closing within three years. The application of lean principles poses an opportunity to address inefficiencies, such as significant labour expenditure, but existing literature is yet to consider process improvement methodologies in VF. In this paper, an established framework for lean implementation is applied to an industry case study providing techniques for process improvement. This work is novel and crucial for workflow standardisation and higher profit margins in this emerging sector.

Keywords: vertical farming; lean manufacturing; operations management; process improvement; urban agriculture

1. Introduction

In this introduction, vertical farming (VF) and its challenges are presented, followed by a selection of an appropriate process improvement methodology and the research aims.

1.1. Vertical Farming

Vertical Farming (VF) is a method of food production that uses the vertical dimension to grow crops hydroponically, typically with indoor controlled-environment agriculture (CEA) technologies such as artificial grow lighting [1]. Over the past decade, VF has seen a surge in popularity [2, 3] and it is viewed by many as a method to engage with a plethora of global challenges facing food production such as the growing population, water scarcity and food safety [1, 4].

VF involves the management of highly complex systems and, despite the opportunity it presents, standard approaches to process management are yet to be adopted in the industry. Addressing this knowledge gap could resolve several issues currently facing the industry. Economic viability is one of the core obstacles facing this sector [5], as start-ups have struggled with (i) underestimated labour costs [6], (ii) lack of adequate VF knowledge and education [6] and (iii) inefficient workflow and inadequate ergonomic design considerations [6, 7]. In the largest survey conducted on CEA businesses globally in 2019 (n=316), human labour was identified as the largest challenge for growers [2]. Industry reports indicate labour is the single highest operating expense for even the most well capitalised vertical farms [2, 8], accounting for roughly 56% of a vertical farm's operational costs (n=45) [8]. Solutions to this key issue are likely to lie in the processes adopted for the management of the farm. Practitioners has begun to consider manufacturing methodologies but techniques have yet to be discussed in the literature.

Securing funding and scaling are other core issues experienced by the VF industry identified by the CEA Census [2]. Both issues, as emphasised by industry experts [9], can be addressed by considering good process flow. The increasingly manufacturing orientated nature of high-tech indoor farming allows the application of systematic methodologies, such as lean manufacturing principles. Moreover, the reduction in supply chain from the majority VF located near the point of consumption results in farms performing a wider spread of value-added activities (i.e. processing, packaging, marketing and delivery). This makes VF a good candidate for methods that optimise value-added systems.

1.2. Why Lean Manufacturing for Vertical Farming?

Applying process improvement methodologies to support the standardisation of processes in VF could support the industry in overcoming the aforementioned challenges. As VF achieves drastically reduced harvest times compared to traditional farms, it has potential to benefit from manufacturing methods. However, despite numerous VF practitioners stating the implications of considering such methodologies [9–12], the literature on the subject is scarce. The most significant writing is a book chapter called "Plant Production Process, Floor Plan and Layout of Plant Factories with Artificial Lighting (PFAL)" [13] (PFAL is the Japanese term for vertical farms). The chapter briefly discusses application of principles of motion economy at a relatively high-level, requiring further discussion for contextual recommendations. Without literature to develop on it was therefore necessary to consider which process improvement methodology could be most useful in a VF context.

To determine which methodology was most appropriate to consider first, several methodology selection frameworks were considered. These were used to compare Six Sigma, Lean, Total Quality Management, JIT and Agile as outlined as the key methodologies [14]**.** Some frameworks [15] demanded too much detailed data for selection. A rigorous selection process of this kind was not appropriate for a new industry where key metrics such as product output, capacity and power are not yet standardised. Two higher-level frameworks were then consulted [16, 17] which both suggest that new industries "in the absence of regular, consistent and standardised output" should consider lean manufacturing principles which emphasises reduction of waste of all kinds. For new industries, key product indicators are still being standardised and the chosen methodology must consider much more than the product output. In support of this suggestion, Garvin [18], states that if the operations in general rely on shop-floor employees as opposed to automation, methodologies that focus more on the reduction of waste as opposed to defects and product flow, should be used. The vertical farming industry in general is gradually introducing automation but most farms in the United Kingdom are currently predominantly operated by shop floor employees [19]. Finally, single cell operations or those with limited product variety, which currently represents most VF operations should aim to adopt lean principles [15]**.** Lean manufacturing was therefore chosen among other process improvement methodologies to explore first in context of vertical farming.

Lean manufacturing methods can improve process flow in manufacturing environments, reduce fatigue and eliminate unnecessary movements through highlighting processes that add value by reducing everything that does not add value to the customer. Through streamlining operations and implementing "poka-yoke" mechanisms, to avoid human mistakes [20], labour risks can be reduced and profitability of VF projects can be improved.

1.3. Aims and Objectives

In this paper, the authors demonstrate the application of lean manufacturing implementation in the context of VF in a practical manner. This is the first work in academic literature to apply manufacturing principles to the nascent sector.

Core lean principles are analysed and applied to a case-study farm in Liverpool, United Kingdom. This is representative of many VF companies because of the limited variety of equipment solutions. With this paper the authors aim to enhance lean transformation for VF companies through the examples provided. To fulfil the aim of this paper, two objectives were developed:

(1) To investigate lean manufacturing implementation methods
(2) To evaluate how lean principles can be applied within a VF context through a case-study for practical implementation

The structure of the paper is organised into five sections. After the introduction, the second section describes and illustrates the case-study and its existing operations. The third section is broken down into three lean manufacturing principles and how each can be applied to VF (with an example for the case study). The fourth section consolidates the considerations improvements in operations for the case-study. The final section concludes with the potential implication of implementing lean principles proposed, addressing the research objectives and providing recommendations for future research.

2. Case Study: Liverpool Crypt Farm

This study was done in collaboration with Farm Urban [21], utilising their 200 square-metre vertical farm located in Liverpool as a case study to provide empirical recommendations. Situational analysis was conducted to assess the organisational attributes such as personnel, facilities, location, products and services to discover opportunities to apply lean principles. Fig. 1 shows the initial state diagram for the existing layout and operations.

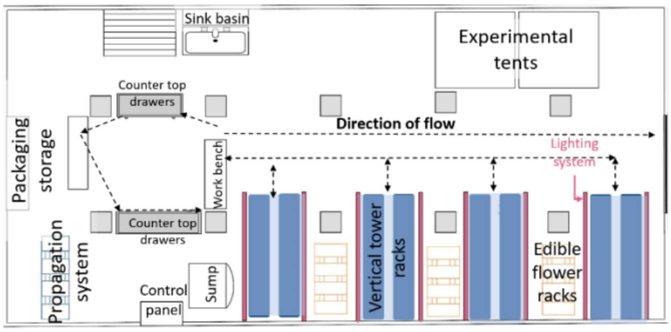

Fig. 1 Initial state diagram of Liverpool crypt farm layout

<u>Facilities and Location</u>: The farm is based in a basement in Liverpool city-centre. The farm has a production capacity of 200 kilograms of leafy green salads per week using mobile vertical tower growing systems (240, eight-foot towers), complimented with four-tier rack system for edible flowers. Nutrient dosing and climate control have been automated.

Personnel: The farm is run by four employees. An operations manager, a master grower and two farm hands.

Operations: The farm is in the comissioning phase and standard operating procedures (SOPs) are under development. Protocols are being managed weekly. Performance metrics and standardised quality checks have yet to be implemented.

Product and service: The sales model is fixed-price and subscription-based. The product offering is a cardboard box containing four live heads of lettuce and a sealed jar of edible flowers delivered by foot within a two-mile radius.

3. Lean Principles Applied to VF

Womack and Jones defined five process-orientated lean principles to eliminate the wastes providing a framework for lean implementation [22]. These principles are *Identify Value*, *Map the Value Stream*, *Create Flow*, *Establish Pull* and *Seek Perfection* [22]. In order to meet the scope of the paper we emphasise the exploration into three principles: *Identify Value*, *Map the Value Stream* and *Create Flow*. We excluded *Seek Perfection* as this principle relies on the implementation of previous principles for further improvement. *Establish Pull* has been excluded because, at this stage, consumer buying habits in the industry are unclear and building an improvement approach around inconsistent product demand is likely to result in inaccuracies, although there are examples of companies incorporating this concept [23]. Each principle is introduced alongside the relevant context in VF and explored.

3.1. Identify Value

Value represents the actual and latent needs of the customer that the business is fulfilling. A clear value proposition that defines a problem being solved for the customer is vital for commercial success. Identifying value is the first step in ensuring manufacturing processes are optimised for fulfilling customer needs. In this section, the process adopted by Pattanaik and Sharma [24] for identifying value for lean processes is applied. It is first necessary to consult potential and existing customers in order to define value from their perspective [24]. There are many techniques to determine what customers find valuable, such as surveys, interviews, demographic information and web analytics [24]. In the context of Farm Urban and VF, key questions for identifying value are as follows:

(1) What crop do the customers want?
(2) How much do they want?
(3) How do they want it delivered?
(4) How much do they want to pay?

Each question covers a key aspect of the value-adding process, ensuring value is identified in the context of all key activities. This information is then used to identify how the existing offering can be optimised to meet customer needs.

For example, in the context of vertical farming, once a price point has been established (q. 4), this information can allow the crop selection to be optimised to ensure profitability. The use of metrics to address performance measures, targeted improvement and team recognition is inherent in lean [25]. Crops and practices that earn money should be tracked, and that which drain resources can then be the target of reduction and elimination. An easy way to do this is to track the value per harvest for each crop or the value per tray/tower. This is calculated by the number of crop per tower, the selling price and then deducting the associated costs of inputs: energy consumption, fertiliser, seeds, labour and maintenance.

Initial identification of value should lead continuous improvement in processes according to customer value [26]. If the customers are not retained, it is essential to determine the reason for cancellation. For example, it could be uncovered that the cardboard boxes are too large and are not valued by the majority of customers, in which case the box becomes representative of waste and over-processing and should become a target for reduction and experimentation. The identification of value and the optimisation of value is summarised in Fig. 2.

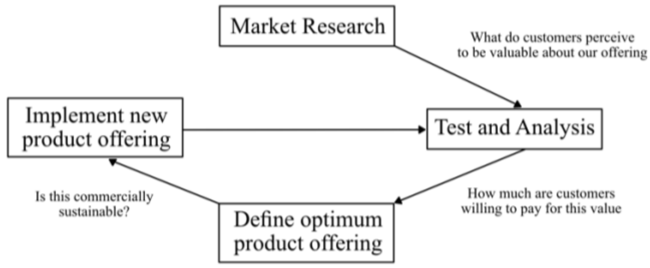

Fig. 2 Identifying and optimising value in a vertical farming context

3.2. Map the Value Stream

Having described the process for identification of value, value stream mapping (VSM) is the next step in waste reduction [22]. This method is used to investigate processes by identifying value-added and non-value-added activities in the form of a diagram to understand how value flows through an organisation. While it is difficult to remove all non-value adding activities, increasing time spent on value-adding activities, is one approach to increasing efficiency according to customer value [26]. The output of a VSM exercise is map outlining the process steps of each of the business: production, research and development, marketing, etc. These maps are vastly cross functional and vary in complexity [24]. To create a VSM this series of steps should be followed with the help of an experienced lean practitioner [27]:

(1) Identify a slice of the product
(2) Bring together an experienced team
(3) Decide the problem (lower price or increase in quality?)
(4) Bound the process (limit the scope to an area which will have the largest impact)
(5) Map the bounded process and define the steps
(6) Collect and note process data
(7) Create a timeline of the process with data–
(8) Assess the VSM current map and identify bottlenecks
(9) Design a future map that aligns with the company's vision
(10) Implement future map and use it to communicate changes

VSM has been applied to the case-study to analyse harvesting, packaging and delivery functions of farm operations. This has been captured in Fig. 3 as a simplified value-added flow chart. The exercise highlighted the inconsistency in time per activity due to a lack of standardisation as well as a clear need to reduce the number of quality checks and capture process data through timing activities. There were two bottlenecks identified outlined in red in Fig. 3: arranging packaging supplies and repeating batch quantities. This can be improved by introducing metrics and 'visual controls' such as signage for acceptable product quality. By combining identification of value and VSM, insights can be gleaned from this customer focused approach.

3.3. Create Flow

Flow is a core concept in lean manufacturing, as any type of waiting is a form of waste. Creating flow of value involves a smooth delivery from the moment an order is received to the moment the product is delivered to the customer. Bottlenecks are the main impediment to developing smooth flow and managers should seek to understand how work progresses, where tasks get stuck and understanding the causes for these obstacles.

Two key lean methods for reducing bottlenecks and their impact are the first-in-first-out principle [28] and one-piece flow [29]. In this section, each of these methods are considered in the context of the case study.

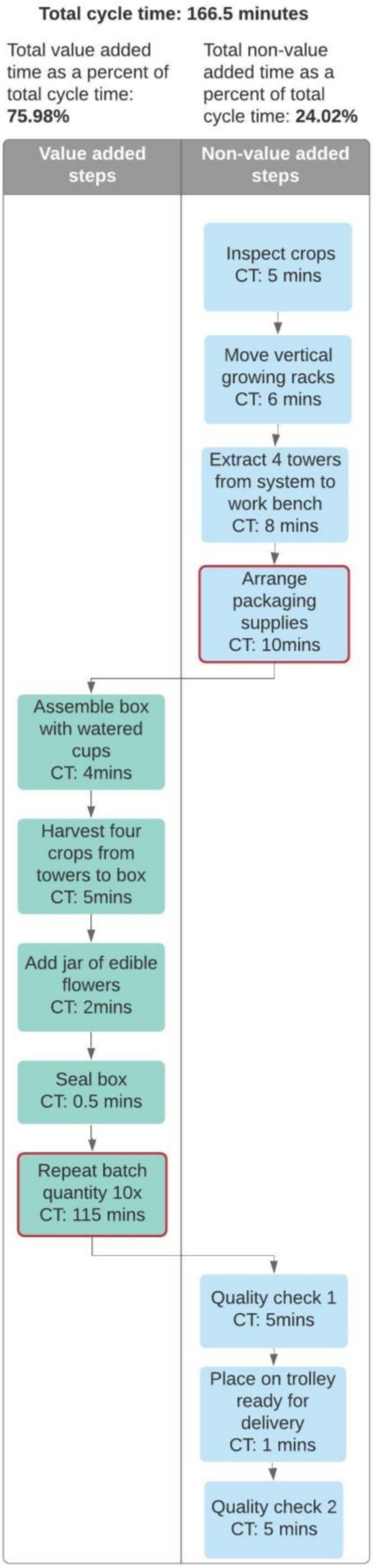

Fig. 3 a value-added flow chart for harvesting and packaging processes of the case study farm's operations

One-piece flow means products flow from workstation to workstation without waiting. The maximum product waiting in a work station is one, and according to Liker [30], this is the only production method which reduces all types of waste. The 'work cell' is a common way of implementing one-piece flow, whereby workstations are moved close together to minimise transport between them [29]. A U-shaped cell reduces the operator's movements substantially whilst allowing access for multiple workers. A farm should maximise the number of workers able to access a layout simultaneously whilst maintaining speed and ease of access to ensure efficiency. Fig. 4 illustrates a U-cell configuration applied to the case-study for the packaging and transplanting area in Fig. 1.

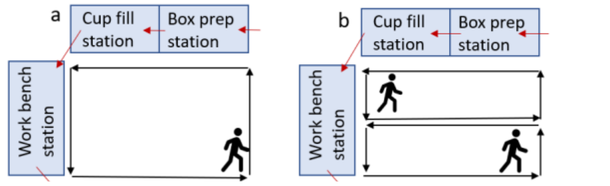

Fig. 4 a) a U-cell with one operator b) a U-cell with two operators. Red arrows visualise the flow of product in the cell and the black arrows visualise the operator's movements ending at the quality assessment (QA) station

First-in-first-out (FIFO) is another method to create flow and manage inventory, by keeping inventories small and waiting times low. FIFO is the principle and practice of production by sequencing to ensure the first part to enter a process or location is also the first part to exit [28]. This has been used in all sorts of applications and is suited for managing perishable products within a short crop-cycle. In the context of VF, seedlings would be transplanted (pushed) into a vertical farming system. Knowing the crop type can be extremely beneficial in order to get the most out of this method, enabling the layout of a farm to be optimised for the various growth stages of a plant's lifecycle (see Fig. 5).

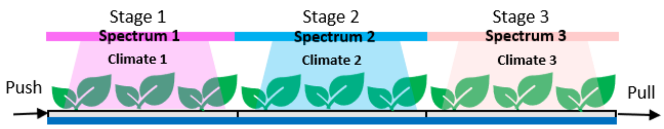

Fig. 5 A diagram applying the FIFO principle to a VF system, where crops flow from one end through a sequence of optimised growth environments

A system with FIFO in mind would take a batch of seedlings through a sequence of environments optimised for plant phase development: germination, vegetation, flowering and production of secondary methabolites. It is then pulled out at the end, ready for harvest and delivery. There are many vertical farming systems available yet very few take advantage of this relevant and simple principle. Intravision's "Gravity Flow System" is one example of an automated system that utilises FIFO [31]. To make the most of FIFO method the ideal growing conditions or "crop recipes" are required. If conditions are not known, lean principles alone are unable to optimise this process, and artificial intelligence (AI) techniques have demonstrated its capacity in VF to optimise the input parameters for each crop. FIFO can and should also be applied to stock to reduce inventory risks.

4. Lean Development at the Case Study Farm

Identify Value, *Map the Value Stream* and *Create Flow*, have been considered for the case study. This has led to changes in processes and management which are described below.

Firstly, the identification of value is underway by collecting customer feedback and experimenting with various product offerings. The business is also beginning to collect economic data to determine the value per harvest of a rack to reveal crops that drain resources.

Secondly, the understanding of the value-stream has led to efforts to collect process data, map the whole value-stream and mitigate bottlenecks by avoiding batch processing. The value-stream mapping process revealed a significant bottleneck in the harvesting/packaging processes, primarily due to a lack of flow in resources, layout and infrequent quality checks resulting in rejected batches. The authors recommend to reorganise resources near to their point of use and implement clear visual controls to reduce frequency of quality checks. Data that is recorded digitally for traceability using spreadsheets is another bottleneck in operational flow and could be made efficient using a tailored enterprise resource planning tools. Visual controls are now being used to prompt corrective action according to the SOPs and to aid quality checks. Examples include: markings for placement/orientation of equipment during transplanting and harvesting of towers, as well as maximum and minimum indicators for draining and filling the sump tank. These initial changes have proven effective to mistake-proof processes, and now the farm will begin to integrate further visual controls for all of their SOPs. The process data, such as time taken per step, will be tracked by staff using stopwatches and added to SOP documentation with the goal to track continuous improvement. This process data will be used for a thorough value-stream analysis as the farm investigates further application of lean principles.

Lastly, the creation of flow has been incorporated by amending the packaging and transplanting area of the farm to be aligned with the U-cell layout in Fig. 4. Suggested changes for shop-floor layout have been illustrated in Fig. 6, adjusting positioning of racking systems to integrate the FIFO principle. Currently, this is not possible to implement due to fixed equipment, but this provides consideration for future developments with a fixed crop selection. The two racks kept in this formation allow for one or two crops to cycle through the growing climates. The U-cell layout has also been rearranged and moved closer to the entrance for the farm to avoid unnecessary movement into the growing area and to enable quicker delivery and lower risk of contamination.

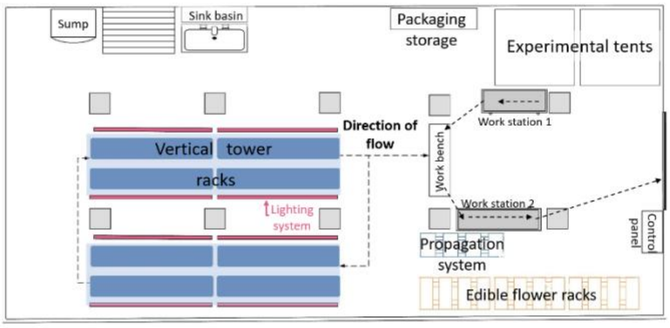

Fig. 6 The post-improvement state diagram of case study cultivation area layout

5. Conclusions and Future Works

Vertical farming (VF) benefits from unprecedented control and rapid crop cycles that enable the implementation of manufacturing methodologies. While industry practitioners express the value that manufacturing methodologies could offer the industry [6], there is no available guidance or literature. After consideration of different process improvement methodologies for VF, the authors determined lean principles a way to engage with labour challenges reported in the sector [2, 6]. This paper is the first of its kind to provide guidelines for implementing lean manufacturing principles in a VF context.

The authors have explored three lean manufacturing principles as described by Womack and Jones [22] and how they may be integrated into VF through the industry case study, Farm Urban [21]. The authors demonstrate the opportunity for significant improvements with minor adjustments to the farm, such as measuring time between value-adding activities to identify bottlenecks and reduction of non-value adding activities. Techniques have been explored to reduce: i) excess storage, ii) batch processes, iii) inefficient workflow and iv) crop cycle times. By applying FIFO principle, production scheduling can be made easier with quicker harvest cycles due to optimised growth parameters.

The complex and biological nature of growing crops requires “crop growing recipes” that lean optimisation methods alone are unable to optimise. This phase can be discretised into different grow-stages (as seen in Fig. 5), however artificial intelligence (AI) techniques to optimise phenome, environment and resource inputs [32] should be exploited if a farm wishes to rotate different crops. This is well recognised by practitioners, and is utilised to add-value through data-driven “crop growth recipes” [32]. Therefore, the authors suggest a hybrid approach of lean and AI for value-added system optimisation for VF processes with a flexible product offering.

As the VF industry seeks the path to profitability, key players utilising AI and automation to scale will find good process design and standardisation tools provided by lean manufacturing techniques. This can prime a business for scaling, proven by its track record particularly in the automotive industry [22].

This exploratory paper lays the groundwork for further lean principles to be considered. Exploring principles such as *Establish Pull* and *Seek Perfection* could provide guidelines for vertical farms to avoid over production, improve customer experience and consequently boost profits. In addition, several other manufacturing methodologies such as Kanban and Just-in-Time are likely to hold similar opportunities to the application of lean principles, and therefore should be explored in parallel. Work is currently underway to collect process data and integrate further lean manufacturing techniques to the case study farm to develop best practice guidelines and mathematical models which can be used for other farms. The authors hope the novel nature of this work in the sector will facilitate the adoption of process improvement methodologies, providing an agenda for further research by exposing voids in the knowledge base.

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