Lean manufacturing for indoor agriculture

Managing throughput and capacity with aquaponics vs hydroponics

Within the world of indoor agriculture, aquaponics is a niche player compared to its cousin, hydroponics. If you're a traditional greenhouse operator or just a hobbyist, there are reasons to choose hydroponics over aquaponics. Information on aquaponics is buried in academic literature while hydroponic handbooks abound. Aquaponic operators need to devote valuable farming real estate to fish and fertilizer production while hydroponic operators don't. More directly, fish feed is more expensive than hydroponic fertilizer.

As one of the few tech-focused, commercially-driven aquaponic companies in the world, we have a strong opinion: the future of large-scale indoor farming lies with aquaponics, not hydroponics. The reason has to do with the increasingly manufacturing-oriented nature of indoor farming.

Whereas traditional farms' primary concern is weather, indoor farms can control the climate. Instead of weather, indoor farms need to worry about capacity and throughput—the two problems that vex every manufacturer. In this post, we'll explain how aquaponics is better equipped than hydroponics to manage capacity and throughput, drawing parallels to Toyota vs GM.

The capacity vs. quality trade-off in hydroponics. Hydroponic produce is infamous for tasting like water. It looks great, it feels great, but the taste just isn't there. High-end restaurants—a bellwether of food trends—have historically avoided hydroponic produce as a result.

The reason traditional hydroponic produce tastes bland is that traditional hydroponic growers fertilize all of their crops using the same chemical nutrient solution, despite the fact that different crops (e.g. arugula, basil, or kale) require different fertilizer formulations (e.g. pH and nutrient ratios). Given the number of variables to be controlled, most hydroponic growers choose to reduce complexity by resorting to the lowest common denominator—a single nutrient solution that is sufficient for all their crops but isn't optimal for any of them.

That's changing with the new generation of hydroponic growers like Gotham Greens and Aerofarms, who are able to achieve better quality and higher yield by using unique nutrient "recipes" tailored for each crop. With higher quality, this new breed of hydroponic grower is seeing wider adoption of their product, from chefs to high-end grocers, like Whole Foods Market.

There's a trade-off though—in order to deliver each crop its custom hydroponic nutrient recipe, separate fertigation systems (fertilization + irrigation) are required, and each fertigation system has finite capacity. Here's an oversimplified explanation of the issue for precision hydroponic growers.

Let's say you're setting up a facility to sell 200 cases per week on average across two SKUs, spinach and arugula. Your anchor customer wants 80–120 cases per SKU per week, depending on the week. So, what do you do? You set up two fertigation systems, each with a peak capacity of 120 cases. You grow at full capacity (240 cases per week), and any product that your anchor customer (200 cases per week) doesn't buy gets sold at a discount to a distributor, donated, or thrown away.

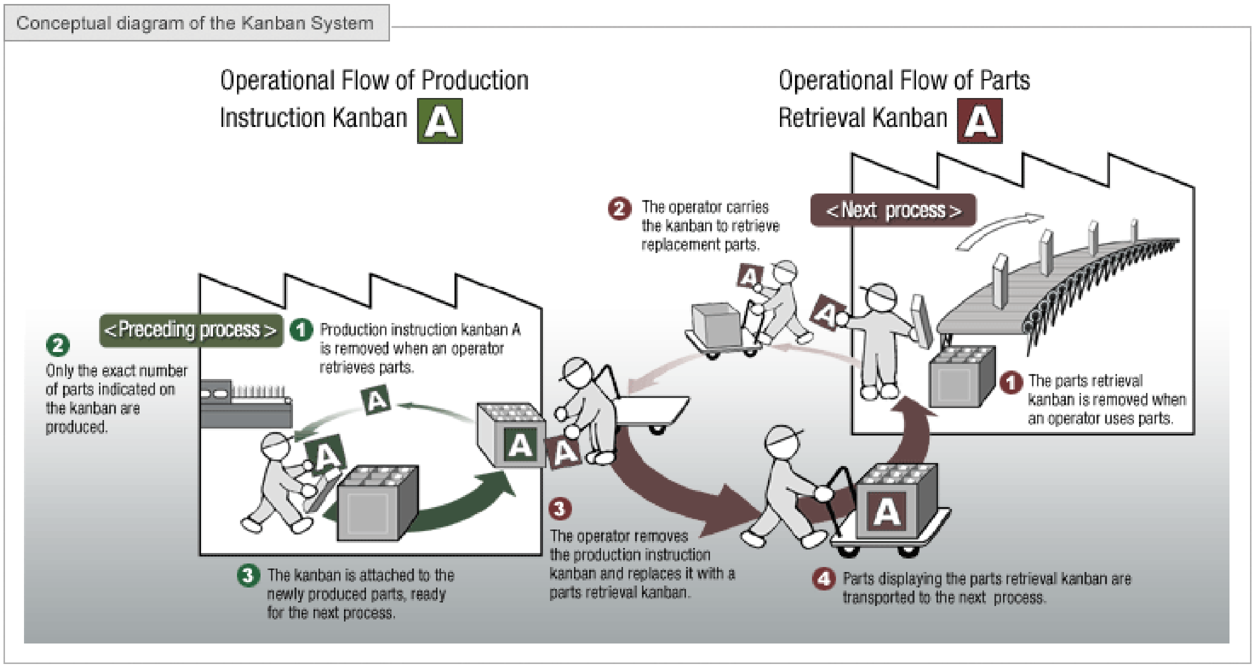
The challenge for indoor growers is having enough capacity to accommodate variability in demand, without (1) growing product they can't sell and (2) compromising quality and yield.

Learning from lean manufacturing. This multiple-SKUs-with-finite-capacity problem is a familiar one for manufacturing companies. Toyota became the most valuable automaker in the world by solving this problem most efficiently. Put simply, while US automakers, like GM, built a different production line for each car model or shut down existing production lines to retool for different models, Toyota created a single production line that could make any mix of their models on a given day.

The US automaker approach to manufacturing different car models was motivated by the idea that building multiple cars in a row of the same model was more efficient than building different models back to back. In terms of raw throughput, they were right. But this created an inflexible production model—given the time it took to create a new production line or retool an existing production line to accommodate demand for different models, the GMs of the world were less capable of producing to match variable consumer demand. The result was an excess of both parts inventory that had no business going into the production line and finished goods inventory that couldn't be sold.

Meanwhile, Toyota created a single production line that could build different models back to back. Since customer orders for various car models change every day, Toyota was better able to match their production schedule to customer demand. If throughput was measured based on cars produced *and sold* rather than just cars produced, Toyota's model beat GM's by a longshot. As a result, Toyota's model became the basis for the "lean manufacturing" philosophy and was subsequently adapted to other industries by companies as far ranging as Nike and Intel.

The key to Toyota's process is producing "only what is needed, when it is needed, and in the amount needed" through two key innovations: just-in-time (JIT) manufacturing and the Kanban system. You can think of JIT manufacturing as the *what* and Kanban as the *how*. The point of JIT manufacturing is that if you've got customer orders for five Camrys, you have inventory for five Camrys. The Kanban cards (literally "signboard cards"), as illustrated below, are used to communicate when parts on the production line are depleted, replacement parts are retrieved, and travel back through the supply chain to control the production of new parts as needed. As a result, there is minimal idle inventory and finished goods—everything is tied to a customer order as the production line switches from one model to the next with frequent but short interruptions to the production flow as the production line accommodates different models.



Source: http://www.toyota-global.com/company/vision_philosophy/toyota_production_system/just-in-time.html

Indoor growers are, for the first time ever, able to apply this methodology to the salad market and reap the benefits due to two recent changes:

1. **Drastically reduced cycle times.** Lean manufacturing tactics are useless if you're a traditional soil farmer with a 30 day cycle time—too long to make planting decisions based on incoming customer orders. Thanks to LED lighting, however, indoor growers can now achieve cycle times of 7–18 days—short enough to sync production schedules to accurate order forecasts. In doing so, indoor growers improve top line revenue by reducing supply disruptions and increase margins by reducing waste.

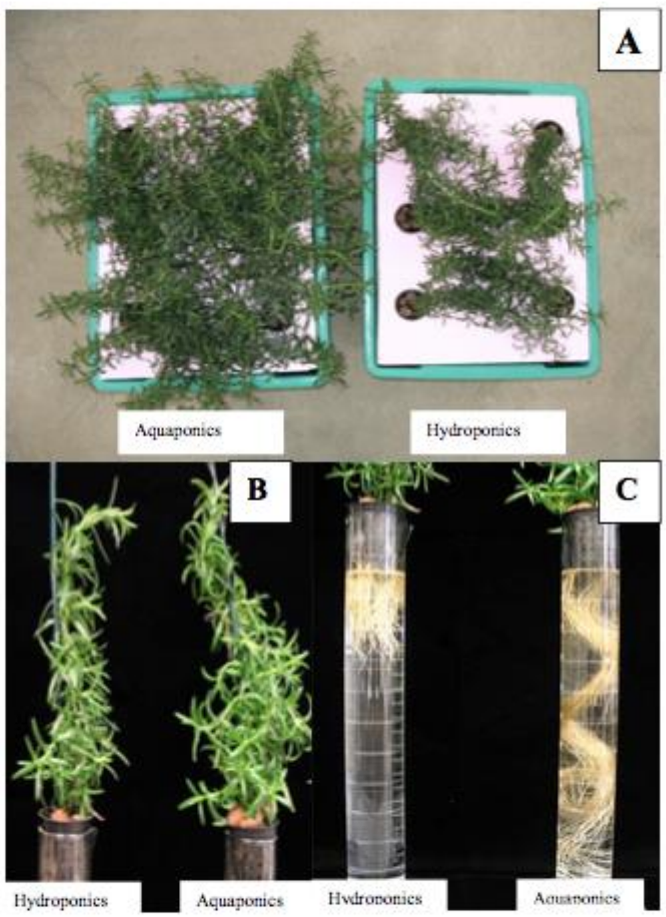
2. **Increasing fragmentation in the types of greens people eat.** Twenty years ago, Americans ate spinach, iceberg, and romaine lettuce. Growers specialized in one or two of them. Lean manufacturing principles gain strength as product lines grow, and that's exactly what's happening in the marketplace. Supermarkets not only are stocking 8+ types of greens, but providing different mixes of these greens. If Whole Foods asks for 200 cases of a peppery mix of radish and arugula greens, delivering your arugula and spinach mix isn't going to cut it.

Why aquaponics is lean manufacturing for indoor agriculture. Aquaponics alleviates hydroponics' capacity problem by using a single fertigation system, with a single nutrient recipe, while maintaining best-in-class yields at top-chef quality. The key is a bacterial kanban system.

Similar to how Toyota's kanban cards regulate how resources are introduced on a just-in-time basis, plant growth promoting bacteria (PGPB) can decide what nutrients the plants need, when they need those nutrients, and how much is needed, moment by moment. PGPB attach themselves to or even grow inside plant roots and detect different metabolites (signaling molecules) emitted by plants depending on their physiological needs. The PGPB block or facilitate the uptake of different nutrients and even manufacture other compounds that plants need, like vitamins or growth factors.

This is huge. Without PGPB*, human operators are forced to guess what nutrients plants need, how much they need, and when they need it. Even plants of the same crop type have slightly different nutrient uptake patterns—they're living beings with different genetic makeups. If each plant were a person, imagine trying to feed the same diet to thousands or millions of individuals and having them all thrive.

With PGPB, not only do you get optimized nutrition for each crop type, but you get it for each individual plant *without any human intervention.* A grower can get great yields and delicious product from multiple crops growing simultaneously—no need for different production lines, or in this case fertigation systems, for each crop.



Source: http://www.ecogrow.ca/pdf/CDC_Report_Phase_II.pdf

PGPB have lived in symbiosis and co-evolved with plants over thousands (or millions) of years. Their ability to survive rests on their ability to detect and regulate plant nutrition with resolution and on a time scale that's not possible for human operators. Studies pitting plants grown in an aquaponics solution versus an industry standard hydroponic solution bear this difference out.

Academic data aside, if you don't believe bacteria does a better job at promoting plant growth than direct human intervention, take it up with Monsanto. Monsanto launched a joint venture with Novozyme, a microbial R&D firm, to study and develop bacteria-based plant treatments, and is betting its sales forecasts on them. It expects its latest corn microbial, currently in 10–20% of US corn fields, to be in over 90% of US corn fields by 2025 due to its ability to boost yield. That's quite the turnaround for a company that built its $50B market cap on human-directed chemical intervention.

What this means for the business of indoor growing. The trade-off for hydroponic growers is a challenging one: a single hydroponic nutrient system compromises quality and yield, but individualized growing systems for each crop requires building excess production capacity to maintain required output. Accordingly, as farming moves from the field to the greenhouse to the warehouse, lean manufacturing principles will need to be designed into farms from the ground up. We think aquaponics and the microbiome it supports is the right tool for the job.

Aquaponics is a "just-in-time" manufacturing system—multiple SKUs with different nutrient requirements can be produced in the same aquaponic system simultaneously without sacrificing quality or yield, whereas multiple hydroponic systems with different nutrient recipes would be required to achieve similar quality and yield.

This is one of the key reasons that we believe aquaponics is the future of indoor farming.

But what if you stripped away all the benefits of aquaponics? Is aquaponics still competitive with hydroponics on cost if you assumed the same yield, quality, and breadth of product with no fish sales? Unwinding this is the purpose of this blog post, and we find that aquaponics is slightly more expensive with costs 2% higher than those in hydroponics as a percentage of revenue. To compensate for this, aquaponic operators will need to utilize the capacity management methods discussed in our previous blog post to achieve throughputs ~2% higher than their hydroponic counterparts. Below, we break down how we got to these numbers.

But first, there are trade-offs besides cost in choosing aquaponics over hydroponics. Let's start with aquaponics' unique barriers to entry.

Nonstarters

The first two trade-offs with aquaponics are existential. The inability to overcome these first two trade-offs will make it highly unlikely the aquaponic farm will get off the ground.

Lack of off-the-shelf systems and expertise. If you want to be a commercial hydroponics operator, there are dozens of top-notch hydroponic design and consulting firms who can construct turnkey, state-of-the-art hydroponic farms anywhere in the world and even bring in an experienced grower to run the operation. If you're a hobbyist, you can buy an off the shelf hydroponic system, along with the hydroponic bible, Howard Resh's *Hydroponic Food Production*, and get yourself 80% of the way there (it's great—

aquaponic hobbyists should buy it too and get themselves 50% of the way there). In short, hydroponic education and expertise is accessible.

In aquaponics, while there are experts who have designed large scale commercial operations, these experts are few and far between. Scaling an aquaponic farm relies on finding these people, most of whom are not in the US. On the education front, while there are books on aquaponics, the true leaders of the movement are PhD-level researchers who have published narrowly focused academic papers as opposed to accessible, comprehensive, authoritative guidebooks. It's on operators to find the right people, design a stable system, and implement a comprehensive operating plan.

Keeping the fish and plants healthy, at the same time. This is a big one. Each piece of the aquaponic ecosystem—the fish that supply manure, the bacteria that break down the manure into nutrients that are bioavailable to the plants, and the plants that absorb those nutrients and drive revenue—requires slightly different environmental conditions. Optimizing for plant health, as a result, requires monitoring three different systems as opposed to one.

Even if you were to install a well-designed aquaponic system and manage the operational trade-offs, black swan events happen. If the fish develop an infection, if you develop a fly infestation, or if pythium (a common fungus that wreaks havoc on plants) takes root, the standard remedies of antibiotics for fish or toxic pesticides for crops won't cut it in a traditional aquaponic design.

Your production is entirely dependent on maintaining a healthy ecosystem and plant microbiome. When you kill the bad microbes through antibiotics or pesticides, they tend to kill the good microbes too. Most pesticides, even organic ones, are not "fish safe"—fish are particularly chemical sensitive. For aquaponic farmers, the ecological approach to farming doesn't just apply when yields are steady. It applies 24/7, 365 days a year, barring traditional, toxic, pesticidal approaches to solving these problems.

All that said, hydroponic and aquaponic operations are converging towards similar operating constraints due to technology improvements and consumer demand. One of the most sought after labels in produce is "pesticide free". As a result, many of the latest generation of hydroponic operators have taken up the label, limiting themselves to the same biological and ecological remedies aquaponic operators are inherently restricted too. At the same time, "decoupled" aquaponic systems, where water only flows in one direction—from the fish to the plants (and not back again)—are growing in popularity due to their ability to treat the plants without worrying about the effect on fish. The result is the ability to use the same plant treatments as a traditional hydroponic facility.

Luckily for all camps, there are plenty of ways to remedy these issues in pesticide free facilities that are more cost effective than traditional approaches. In indoor farms especially, the incidence of most issues can be reduced through rigorous standard operating procedures for both day to day practices and early detection of and response to ecological stress.

If you're confident that you have the expertise to design a stable aquaponic system and to handle both the operating basics and ecological considerations during black swan events, then it's worth digging into the operating costs of aquaponics and hydroponics.

Comparing operating costs

There are certain added costs associated with aquaponics—there's no free lunch, so growing all those fish has to be accounted for somewhere. For aquaponics to be a better business than hydroponics, the added costs must be compensated for by either higher throughput of salad greens or fish. In our previous blog post, we showed how aquaponics can achieve higher throughput than hydroponics. **In this analysis, assuming fish are never sold, we show that throughput needs to be ~2% higher in order for aquaponics to beat hydroponics on cost, which is well within aquaponics' potential.**

We have put these trade-offs in a spreadsheet for a more convenient comparison. You can see the spreadsheet here, while reading below for context. **The numbers here are not reflective of Edenworks' designs and projections.** We're basically asking "if we ran our competitor's farms aquaponically instead of hydroponically, what would the business look like?" For example, Gotham Greens projected an EBITDA for their first facility at "greater than 15%," and so we've targeted a 15% EBITDA margin for the hydroponic facility, then made a few changes based on industry-standard assumptions to back out the aquaponic cost analysis.

Net Income	**$$**		**as % of revenue**	
	Aquaponics	**Hydroponics**	**Aquaponics**	**Hydroponics**
Revenue	10,483,200	10,240,000	100.0%	100.0%
Cost of goods sold				
Aquaculture labor	55,000	0	0.5%	0.0%
Fish feed or nutrient cost	175,088	33,279	1.7%	0.3%
Overhead costs				
Rent	704,791	694,590	6.7%	6.8%
Total variable costs	**934,879**	**727,869**	**8.9%**	**7.1%**
Non-variable costs	8,000,000	8,000,000	76.3%	78.1%
Total operating costs	8,934,879	8,727,869	85.2%	85.2%
EBITDA Margin	**1,548,321**	**1,512,131**	**15%**	**15%**

source: Edenworks spreadsheet analysis

The following line items are the largest cost differences:

Added expense of fish feed. While hydroponic fertilizer is most often composed of mined mineral salts, fish feed for aquaponics has the fat and protein that the fish need along with the minerals that both plants and fish need. For aquaponics in a recirculating shallow water culture system, we calculate[1] the expense of fish feed to be about 9 cents per pound of harvested greens, a 7 cent premium over synthetic hydroponic fertilizer. Assuming best in class yields for both systems, this comes out to a 1.4% difference in nutrient costs between the two systems, as a percentage of revenue. However, with the world farming more fish than ever before, new technologies are coming online that are expected to substantially lower the price of fish feed, while also making the feed more sustainable.

Added labor. Most indoor farming facilities have a long way to go until they can be considered highly automated. Despite incorporating automation and machine learning techniques for things like climate control and disease detection, modern indoor farms still complete many tasks, such as harvesting, by hand. The biggest labor efficiency gains are fertilizer (i.e. hydroponic / aquaponic) agnostic. Those gains come from automating the movement of plants through the production system, along with the unit tasks of seeding, transplanting, harvesting, packaging, and cleaning. This is where Edenworks has invested substantially in IP, but that's a story for another post.

All that said, raising fish does require someone who knows how to spot potential health issues, how to harvest fish, and how to maintain aquaculture equipment. None of this is time intensive, but it does require hiring an aquaculture specialist at each facility.

Space for the fish. Aquaponic fish tanks and hydroponic nutrient reservoirs require similar space. However, aquaponic systems require a bit more space overall for the extra pumps, sumps, and biofilters for converting fish waste into nutrition for the plants—an additional 1.7% more space in our analysis of an approximately 70,000 square foot hydroponic facility. Assuming rent for warehouse space is $10 per square foot, this comes out to a difference of 0.1% of revenue.

Quantifying the total trade-off.

Assumptions are based on commonly used designs, equipment, and raw material suppliers, which are noted in the spreadsheet. Furthermore, in order to get close to an apples to apples comparison, we assumed the following:

- Both systems sell baby greens for the same price.
- Revenue from fish, and the associated costs of selling fish are not included.
- Both systems are vertically stacked, indoor farms.
- Yields for both hydroponic and aquaponic systems are the same. For the purpose of this study, we use our yield estimate for AeroFarms. AeroFarms has projected yields of 2 million lbs of greens at their Newark facility. Looking at the size of their facility (69,000 s.f.) and their geometry, we estimate their growing space is ~160,000 s.f.[2] in vertically stacked beds. This gives AeroFarms 12.5 lbs yield / s.f. / year, which is in line with other best-in-class yields for hydroponic and aquaponic indoor leafy greens farm.
- Both systems have similar needs, and therefore costs, for the following line items: energy, packaging, growing medium, seeds, delivery, rent, cleaning and other general farm supplies, and merchandising.
- This leaves just three significant differences between the costs of the two systems: nutrients (fish feed vs synthetic fertilizer), labor (employing an aquaculture specialist vs. having one less employee), and rent (extra space needed to break down organic nutrients vs. not needing extra space).

Given the assumptions behind these hypothetical facilities, we estimate aquaponic systems' costs as a percentage of revenue are 2 percentage points higher than hydroponics'. In order to compensate for these added costs, aquaponic facilities need to sell 2% more of their capacity than hydroponic facilities. As explained in our previous post, with typical per-SKU sales swings in packaged salad of up to 20% week on week, hydroponic farms that cannot grow different crops in the same production system suffer from significant capacity constraints. Aquaponics, on the other hand, can grow wide varieties of crops in the same production system, enabling them to sell higher percentage of their capacity (certainly higher than 2% more).

To top it all off, enhanced flavor and higher consumer preference for ecologically grown products make aquaponics better aligned with consumer and operator interests. It is for these reasons, in addition to its competitiveness with hydroponics on cost, that we believe aquaponics will become the primary fertilization technology for indoor operators as the market continues to grow.

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[1] This calculation is based on standard aquaponic feed ratios from Dr. James Rakocy and hydroponic feed ratios from Howard Resh's book *Hydroponic Food Production*. These calculations are in the third tab of the spreadsheet and are what we used in this analysis. Comparing one "standard" feed rate to another "standard" feed rate seemed apples to oranges to us though, so we also compared feed costs based on nitrogen content of each feed, and came up with very similar cost ratios. These are presented in the fourth tab of the spreadsheet.

[2] Aerofarms' bedspace estimation comes from public websites. For bed width and length, see (a) and (b). For number of beds, see (b) and (c).
(a) https://patentimages.storage.googleapis.com/pdfs/US8533992.pdf
(b) http://www.foxbusiness.com/features/2015/07/28/farming-in-sky-inside-wall-street-backed-vertical-farm.html
(c) https://www.nytimes.com/2015/04/08/realestate/commercial/in-newark-a-vertical-indoor-farm-helps-anchor-an-areas-revival.html