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FEASIBILITY OF WAREHOUSE DRONE ADOPTION AND IMPLEMENTATION

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ABSTRACT

While aerial delivery drones capture headlines, the pace of adoption of drones in warehouses has shown the greatest acceleration. Warehousing constitutes 30% of the cost of logistics in the US. The rise of e-commerce, greater customer service demands of retail stores, and a shortage of skilled labor have intensified competition for efficient warehouse operations. This takes place during an era of shortening technology life cycles. This paper integrates several theoretical perspectives on technology diffusion and adoption to propose a framework to inform supply chain decision-makers on when to invest in new robotics technology.

INTRODUCTION

Unmanned drones have been described as “on the verge of blowing a big hole in the supply-chain” (Bamburry, 2015) - an assertion supported by a predicted global market of $22.15 billion by 2022 representing a compounded annual growth rate (CAGR) of 20.7% from 2015 to 2022 (Stratistics, 2016). The military and consumer markets drove much early growth, and recent commercial usage has ballooned from 102,600 units in 2016 to a projected 805,000 units in 2021, representing a five-year CAGR of 51% (Meola, 2017).

Defined as “robot vehicles” that are remotely or unmanned piloted, tethered, or autonomous (Rys, 2016), aerial unmanned drones captured headlines after Amazon made the first unmanned aerial vehicle delivery to a customer in England on December 7, 2016 (Bort, 2017). Regulatory challenges have slowed unmanned aerial drone use in open skies for delivery by companies including Amazon and Domino’s Pizza. At the same time the pace of adoption in warehouse drones has accelerated, conducting infrastructure monitoring and inventory management using bar codes, QR codes, and RFID in combination with industrial Internet of Things technologies, and wheeled unmanned drones working both autonomously and in tandem with humans to pick-and-pull (Appelbaum and Nehmer, 2017). Preliminary results suggest paradigm-shifting improvements for inventory management, with Wal-Mart reporting that unmanned warehouse drones cut the warehouse inventory count process from 30 days using manual processes to one day (Bose, 2017), and Amazon’s 2012 acquisition of robotics powerhouse Kiva for $775 million is cited as the cornerstone to its ability to provide even more efficient and effective next-day and two-day shipping (Kim, 2016; Nichols, 2016).

The process of adoption of technology has resulted in a media cycle of exaggerating the promise of a new technology in the short-run while underestimating its importance over the long run—dubbed the “hype cycle” by Gartner and more generally known as Amara’s law (*PC Magazine*, n.d.)—renders suspect most of the prognostications in mainstream media. Given the importance of warehousing in global supply chains (Frazelle, 2002a) and that warehousing constitutes 30% of the cost of logistics in the US (AT Kearney, 2016), the time is right for a reasoned inquiry regarding the factors that supply chain decision-makers should use to decide when to invest in the new robotics technology.

This paper compares models of technology diffusion in order to develop a hybrid model that combines the insights of several empirically supported perspectives. Warehouse operations are reviewed for the purpose of applying this knowledge to the domain of warehouse drone robots. Next, the thoughts of several supply chain professionals are presented based upon exploratory conversations, followed by a brief conclusion regarding the applicability of technology diffusion models and the hype versus reality of warehouse drone robots in the near future.

Drone Technology

The term "drone" may include a number of different characteristics. In general, "drone technology" involves using unmanned robotic vehicles. There is a tendency to immediately conclude drone technology only involves the multi-rotor or quadcopter aerial devices touted by firms such as Amazon (unmanned aerial vehicles or UAV); however, drone technology may also involve (Drone, n.d.):

- unmanned aerial vehicles (UAV) including multirotor or quadcopter which is a type of unmanned aerial vehicle
- unmanned combat aerial vehicle (UCAV)
- unmanned spacecraft both remote controlled ("unmanned space mission") and autonomous ("robotic spacecraft" or "space probes")
- Unmanned ground vehicles (UGV) such as autonomous self-driving automobiles
- Unmanned surface vehicle (USV) for operation on the surface of water
- Autonomous underwater vehicles (AUV) or unmanned undersea vehicles (UUV) for operation underwater

For this paper, we investigated wheeled unmanned ground vehicles (UGV) utilized for warehouse operations and specify them as "warehouse drones". These include driverless trucks, aerial delivery drones, wheeled, warehouse drones, and warehouse robots.

Technology Diffusion Model

There are several models of technology diffusion, for example, "product life cycle management (PLC)" dominates in marketing, the technology acceptance model (TAM) developed in information technology research, and the spiral life cycle (SLC) model developed to manage risks in software development. Since unmanned warehouse drones represent a unique combination of mainstream product, information technology systems, and software, each model is compared, with insights distilled into a new "spiral cost implementation model."

Product Life Cycle Model

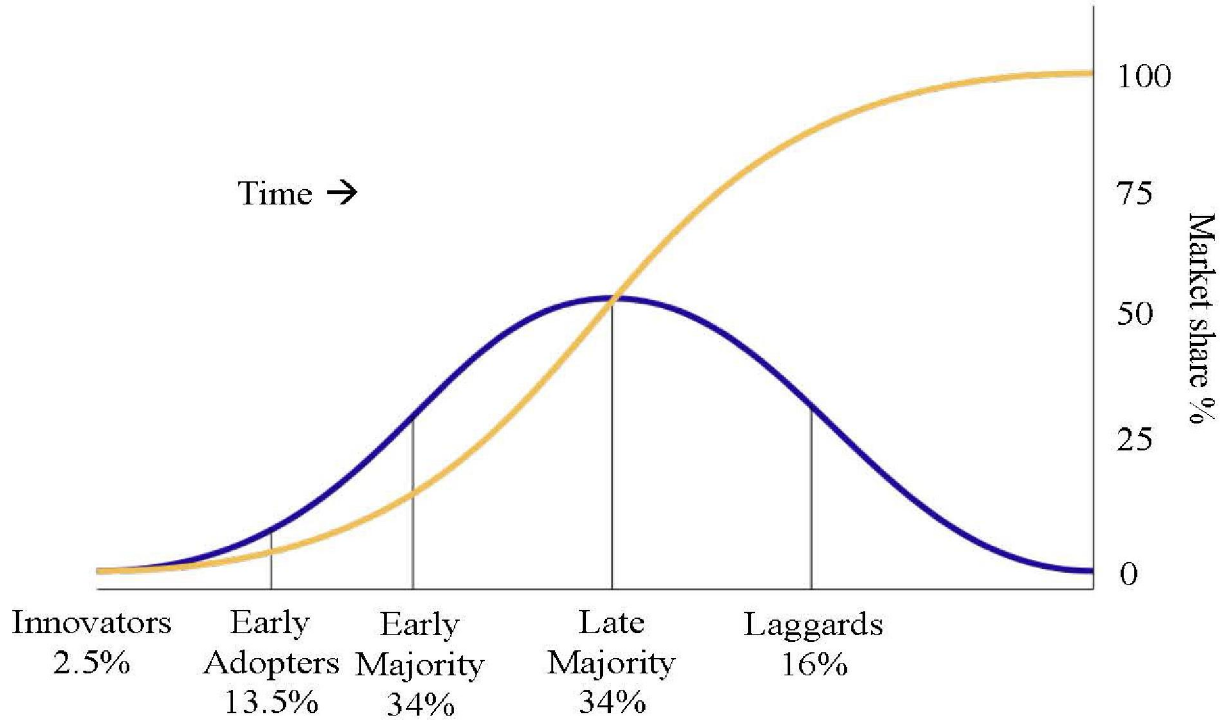
The product life cycle management model was originally developed by Everett Rogers (1962), a communications professor who defined diffusion as the process by which an innovation is communicated over time among the members of a social system through certain channels, with system saturation modeled using a logistic curve (Figure 1). Theodore Levitt (1965) brought the PLC into the mainstream for general business use by matching each stage of diffusion with marketing and product management advice. Subsequently, Frank Bass (1969) published the most widely used forecasting model that describes the PLC mathematically based upon the coefficients of innovation and imitation.

Based upon the rapid growth in market demand of 20-50% (Stratistics, 2016; Meola, 2017), unmanned warehouse drone demand demonstrates the inflection point that transitions from the "introduction" to the "growth" stage of the PLC. The PLC provides some basis for distinguishing customer segments based on their adoption process—they either adopt based on written communications such as technical reports, or they await word of mouth regarding the product or technology's promise. Disadvantages of the PLC are its simplification and aggregation of the complex processes of innovation, diffusion, and adoption—the PLC looks strictly at the aggregate adoption behavior for a new product or technology, and does not incorporate considerations such as technical capabilities, costs, or risks. The next model, the Technology Acceptance Model, incorporates some of these factors.

Technology Acceptance Model

The Technology Acceptance Model (TAM) was

FIGURE 1
PRODUCT LIFE CYCLE LOGISTIC CURVE

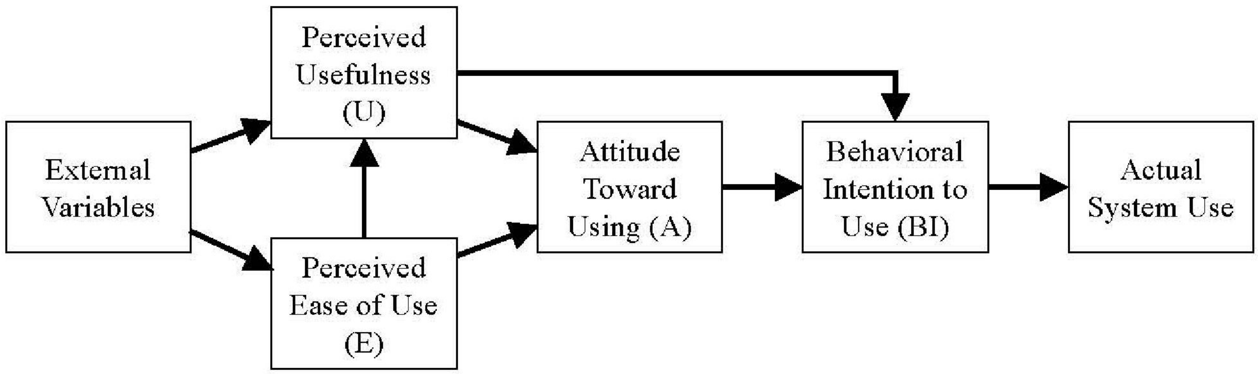


Rogers, E. (1962), "Product Life Cycle Logistic Curve," *Diffusion of Innovations, Free Press, London, NY, USA, Public Domain,* https://commons.wikimedia.org/w/index.php?curid=18525407 accessed on January 15, 2018.

originally developed by Fred Davis (1989) as an extension of the theory of reasoned action (Fishbein and Ajzen, 1975; Ajzen and Fishbein, 1980). TAM's advantage to managers considering adopting warehouse drone technology is that it is the most empirically applied and validated model of users' acceptance and usage of technology (Venkatesh and Davis, 2000; Maranguniæ and Graniæ, 2015), incorporating the external variables of perceived usefulness and ease of use to explain the adoption process. These variables provide insights into the drivers for humans to adopt a new technology or product, with greater levels of perceived usefulness and ease of use predicting a greater probability of technology acceptance.

TAM offers the advantage of using easily measurable characteristics to predict the likelihood of adoption at the level of the individual user. The model's measurement instruments have been widely validated (e.g., Adams, et al., 1992) and extended to include additional social and cognitive factors (Venkatesh and Davis, 2000). TAM's disadvantages include failure to consider cost and structural factors that obligate or prevent technology adoption (Lunceford, 2009), and the potential lack of meaning for an individual technology user trying to assess "perceived usefulness" due to its broad and dynamic nature. These disadvantages both diminish the applicability of TAM in the warehouse environment which is cost-sensitive, demonstrate fixed structural factors (at least in the short run), and the issue of deciphering usefulness of a new technology that may require several iterations to optimize. Both of these disadvantages may be addressed using the spiral life cycle model proposed next.

FIGURE 2
TECHNOLOGY ACCEPTANCE MODEL



Davis, Bagozzi, and Warshaw (1989), Figure Art by Nippie, CC BY 3.0;
https://commons.wikimedia.org/w/index.php?curid=14457270, Accessed on January 15, 2018.

Spiral Life Cycle Model

Supply chain managers considering drone adoption often consider the risk and cost involved. Barry Boehm (1986, 1988) originally developed the spiral life cycle model for defense software development in order to shift project decisions from a coding or document-driven process to a risk-driven approach. In the words of Boehm (2000), the spiral model is a "process model generator" because its output prescribes the appropriate process for managing a project based upon a four-step iterative process that incorporates risk assessment and cost (see Figure 3).

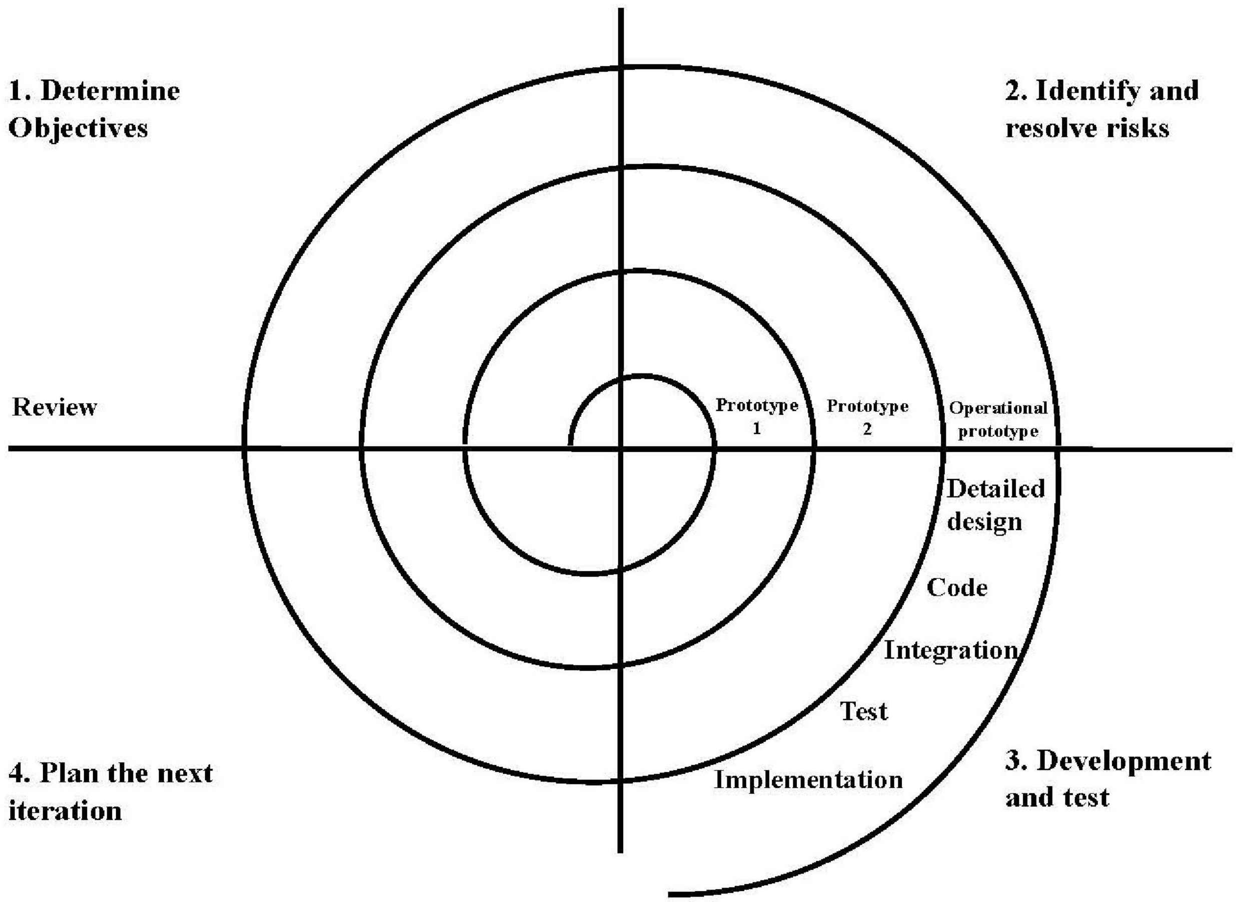
The spiral life cycle model starts in the middle of the diagram with the four basic activities performed during every cycle: determining objectives (planning), followed by identifying and resolving risks (risk analysis), development and testing (engineering), and planning the next iteration (evaluation). At the very beginning of the model, the concept of operations, the concept of requirement, and the operations plan are developed. Cost accumulates as iterations or prototypes are produced, and the spiral model advises how to minimize the level of risk by scaling the level of effort and degree of details. The spiral life cycle model incorporates other extant process models such as incremental, waterfall, and prototyping as special cases depending on the risk patterns of certain projects (Boehm, 2000).

The spiral life cycle model offers advantages for minimizing risk, especially for large projects, and for managing and controlling documentation and approval processes; these features make the model conducive to development of new product lines rather than implementation of a new supply chain operational technology. The model may be costly to implement and not very suitable for small projects, such as implementing drones in a single warehouse. Additionally, while the spiral life cycle determines a project process and incorporates cost, it depends heavily upon identifying risks, which may vary widely depending upon the project. A framework that specifically incorporates supply chain and unmanned warehouse drone risk factors would prove advantageous for managers and researchers assessing incorporation of unmanned warehouse drone, robots, and related digital economy advances.

Spiral Cost Implementation Model (SCIM)

The spiral cost implementation model (SCIM) represents a hybrid framework that combines the previous models in order to encompass their salient positive aspects while compensating for reduced parsimony by reducing the negative aspects. The

FIGURE 3
SPIRAL LIFE CYCLE MODEL



framework modifies the spiral life cycle model by focusing on costs at every stage and repeating the evaluation stages. The model assumes adoption of an existing technology available on the market, which is an important difference from the spiral life cycle model that focuses on innovating a new product or technology, and renders the model particularly appropriate for the warehouse drone adoption decision.

The SCIM framework incorporates a constant review phase in response to the intensely dynamic technology and regulatory environments. A cost review at every stage of the model reflects the rapid changes and the shift of purpose from developing new product lines to on-going supply chain operations. As a visual enhancement, the spiral grows larger or smaller based on the cost in each phase. SCIM incorporates the TAM's perceived usefulness into the planning and evaluation stages. The model loses in its application to creating a new technology, but gains from greater depth of analysis when adopting a new offering available on the open market—a circumstance currently confronted by warehouse managers considering drone adoption.

THE WAREHOUSING ENVIRONMENT

Warehousing represents close to 30% of US supply chain costs (AT Kearney, 2016), with 55% or more resulting from order picking costs which would respond readily to automation (van den Berg and Zijm, 1999; De Koster, et al., 2007). [Warehouse] drone implementation should address current inefficiencies in warehousing most amenable to automation including inventory accuracy, inventory locating, space utilization, redundant processes, and picking optimization (Garcia, 2013; van den Berg

FIGURE 4
SPIRAL COST IMPLEMENTATION MODEL (SCIM) WITH REPRESENTATIVE COSTS

and Zijm, 1999). The key drivers for modern warehouse management is the reduction of inventory due to heightened financial risks, shorter response times, and increased productivity (van den Berg and Zijm, 1999).

Warehousing increasingly relies upon "smart" technologies that incorporate information tracking technologies such as bar coding, electronic data interchange (EDI), and radio frequency identification (RFID) into data processing systems designed to aid decision-making (Autry, et al., 2005)—unmanned warehouse drones represent the logical extension that integrates the virtual information processes with the physical warehouse processes.

The rate of growth of industrial robots provides evidence of this integration. Overall world supply of industrial robots hit an annual record increase for the fourth year in a row in 2016, and increased 84% from 2011 to 2016 compared to the 2005 to 2008 timeframe (IFR World Robotics, 2017). The world population of industrial robots is projected to increase from 1.8 million in 2016 to over 3 million by 2020. Industry reports predict warehouse robotics compound annual growth rate varies from 7.6% through 2024 (Goldstein Research, 2017) up to 11.5% through 2021 (Mordor Intelligence, 2017) and 11.6% through 2023 (Dasyam, 2017). Warehouse robotics has gone from novelty to mainstream for larger companies seeking competitive advantage in an era of labor shortages and highly demanding customers (Futch, 2017).

Practical considerations mean that warehousing offers a particularly compelling application for unmanned warehouse drones compared to oft-hyped direct-to-customer delivery drones. The co-founder of Kiva—the warehouse drone company acquired by Amazon in 2012—identified three major challenges that will delay use of unmanned warehouse drones for direct-to-customer delivery that will take several technology iterations to overcome: vehicle design, localization and navigation, and vehicle coordination (D'Andrea, 2014). Once the technological challenges are overcome, issues such as public reactions, privacy concerns, and government regulation will offer further challenges. Warehouses provide protected and controlled environments that obviate these concerns, and the future of direct-to-customer delivery drones may be extensions of warehouse drones. The SCIM model implies that as market offerings of drone technology continue to evolve, they should diminish the risk of direct-to-customer deliveries while simultaneously reducing the cost per delivery until such a point that the cost and risk become acceptable.

Unmanned warehouse drones may greatly improve warehouse operations. As previously noted, warehouse drones may be aerial or wheeled. For difficult to reach places unmanned aerial warehouse drones facilitate inventory management using bar codes, QR codes, and RFID in combination with industrial focused Internet of Things technologies, and wheeled unmanned warehouse drones work both autonomously and in tandem with humans to pick-and-pull, with Wal-Mart reporting that the switch from manual to warehouse drone-based processes cut warehouse inventory time from 30 days to one day (Bose, 2017). Warehouse operators have relatively low profit margins (3-6%), which impedes their ability to invest in technological capital, a fact which accentuates competitive advantage for those who do (AT Kearney, 2016).

Unmanned aerial warehouse drones perform tasks other than moving product. The cost of inventory auditing with aerial warehouse drones is approximately half the annual cost of a live employee and eliminates most of the need for humans to climb warehouse racks and perform other dangerous work (Appelbaum and Nehmer, 2017; PwC, 2016). Amazon has already reduced "click to ship" time from 60-75 minutes with a human to 15 minutes with warehouse drones; additionally, Amazon's drone enabled warehouses carry 50% more inventory per square foot and have 20% lower operating costs, a savings of $22 million per warehouse for 13 warehouses so far (Bhattacharya, 2016). Other companies report costs as low as 10 cents per order for automated picking versus 80 cents for the typical order pick (Banker, 2017). Incorporating low-light, infrared, and other capabilities these unmanned warehouse drones may often observe more with high resolution video or still cameras, useful for temperature controlled items, monitoring vermin, seeing items in dark corners, and identifying signs of leaking roofs or faulty wiring. Unmanned aerial warehouse drones may also provide auditability details such as geo-locational, RFID, and other sensor data. Unmanned aerial warehouse drones may reinforce the auditability of other inputs, such as verifying that RFID tags are attached to the correct product; overlapping of technologies may provide hitherto unachievable inventory accuracy on an hour-by-hour basis.

Warehouse drones hold the promise of taking inventory and facility management to greater heights of efficiency and effectiveness. As one example, in collaboration with two important research sponsors, MIT believes that warehouse drone technology could have saved $3 billion in lost revenue for Walmart, and prevented the US Army from losing track of $5.8 billion in assets (Hardesty, 2017). Determining where warehouse drones may best contribute requires first enumerating the types, activities, and functionalities of warehouses.

Types, Activities, and Functionalities of Warehouses

Warehouses fall into three categories (van den Berg and Zijm, 1999). A *distribution warehouse* collects and sometimes assembles products from different suppliers for subsequent customer delivery. A *production warehouse* localizes in a production facility and stores raw materials, semi-finished products, and finished products in a production facility. A *contract warehouse* discharges the warehousing operation on behalf of one or more customers.

All types of warehouses conduct four primary functional activities (Coyle, et al., 2017):

- Accumulation: receipt of goods from a variety of locations
- Sortation: assembling like products for storage or transfer to customers

- Allocation: matching available inventory to customer orders (break-bulk)
- Assortment: product mixing capability

Picking constitutes in excess of 60% of warehousing costs and represents the greatest opportunity for unmanned warehouse drones to generate efficiencies (van den Berg and Zijm, 1999; De Koster, et al., 2007).

Locus Robotics is an example of how a modern unmanned warehouse drone can work side-by-side with humans, doing most of the 12-16 miles per day that warehouse workers walk but still requiring humans to pick and place products on the robot's tray (Garfield, 2016). Locus Robotics forecasts up to 800% productivity improvements since the robots move faster than humans, can work 24 hours straight, and take no breaks; freeing humans to provide a personal touch to the shipments that are craved by consumers of e-commerce parcel goods, such as personalized notes or fancy wrapping paper.

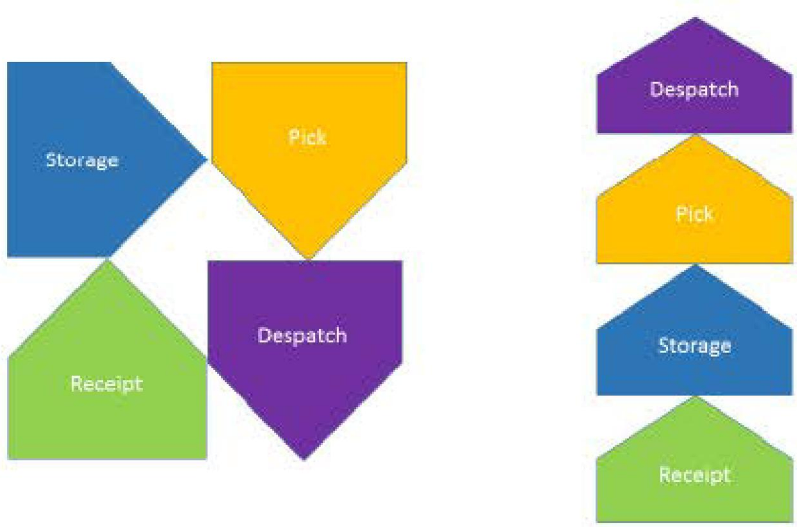
Optimizing Warehouse Flows for Unmanned Drones

Warehouse layouts generally fall into two styles (Figure 5), the U-flow and the through-flow (Frazelle, 2002b). The U-flow design locates fast moving products on the inner side of a U-shaped flow so that product moves less distance at all stages of warehouse operations. This improves use of dock resources since inbound and outbound occur on the same or proximate docks, improves efficient lift truck utilization since fast-moving product is located close to the docks, and improves security since entry and exit occupy the same side of the building.

Through-flow warehouses move all product in a straight line from one side of the building to the opposite, locating fast-moving items along the center aisle of the warehouse and slower items along the walls of the warehouse (Frazelle, 2002b). This layout requires all product to move the length of the building and is less flexible. It provides advantages for avoiding confusion regarding product flowing in and out, and when different material handling equipment is used for in-flows vs. out-flows. Factory warehouses often use the flow-through layout.

The interest in warehouse drones by companies like Wal-Mart and Amazon focuses on leveraging drone strengths primarily to maintain inventory accuracy and to shorten response times for picking in response to consumer orders—an environment conducive to U-flow warehouse layouts. In addition to greater speed of picking, warehouse drones reduce losses to shrinkage—especially relevant for high value finished goods—and the U-flow layout results in shorter trips to recharging stations, a

FIGURE 5
U-FLOW VS. THROUGH-FLOW WAREHOUSES



critical consideration with current battery technology (D'Andrea, 2014). Other factors that suggest that consumer finished goods warehouse drones will initially establish themselves in U-flow warehouses are based on the assumption that U-flow warehouses are more likely to be the design of choice for finished consumer goods, the potential to standardize packaging for consumer goods, improved product identification (barcodes, RFID), and the greater value (and profitability) of finished goods to pay for the early investments in technology.

Through-flow warehouses are often attached to production facilities, and the product more often changes shape and form, which presents a challenge for warehouse drone technology for the near future. Cross-dock facilities represent the application of the through-flow layout to finished goods—the bulk nature of the entering goods diminishes the productivity advantage for warehouse drones vs. human labor. Other challenges to the current state of warehouse drone technology include the ability to move increased product weight and travel further, factors which increase time spent at charging stations. Warehouse drone technology exists with the potential to facilitate through-flow work such as the Automated Ground Vehicles described in the next section, yet it does not demonstrate the rapid growth of smaller, lighter warehouse drones, and additionally appears in U-flow warehouses.

Best Approach for Warehousing with Unmanned Warehouse Drones

Warehousing is a labor-intensive industry, and has become even more so with the strong growth of e-commerce which requires picking more "eaches", or single units of product, in response to consumer order size. This trend has driven part of the 53% increase of warehouse employment from 622,000 in January 2017 to 950,000 in July 2017[1], and has increased wages for warehouse workers 6% in the past year (Smith, 2017) E-commerce warehouses tend to locate near population centers, and offer a better value proposition than retail, an even more labor-intensive industry (Gebeloff and Russell, 2017), even when e-commerce related warehouse jobs command a 26% premium over traditional retail jobs (Mandel, 2017).

Warehouses have also increasingly adopted automation, with one consultant citing an increase from eight in ten clients having some level of warehouse automation (Smith, 2017). The primary automation designed to expedite high volumes of small, multi-line orders (Banker, 2017) are automated guided vehicles (AGV's)that perform goods-to-person (also known as goods-to-picker). In this role, AGV's include robot auxiliaries that take over material transport from human pickers. Large AGV's can move bulk and palletized goods—such as forklifts that work either autonomously or in conjunction with a human—but most act as shuttles between human pickers and packing lines; the latter type of warehouse drone shows particular promise since it does not require modifications to warehouse layouts, comes with essentially turnkey installation, and all types of AGV's save human repetitive labor and movement (Appelbaum and Nehmer, 2017), thus increasing performance and safety simultaneously. As previously noted, AGV's improve efficiencies primarily at retrieving from storage and as an expeditor for human labor, and increasingly share data amongst themselves and with other IT systems such as warehouse management systems, with pick costs going from 80 cents to 10 cents per pick after automation (Banker, 2017) and order pick times going from 60-75 minutes to 15 minutes (Bhattacharya, 2016).

Goods-to-picker, also known as goods-to-person, automate warehouses by bringing goods to humans to pick. Kiva is the goods-to-picker warehouse drone used by Amazon that resembles an automated warehouse drone vacuum (e.g., a Roomba) that goes beneath a set of shelves, lifts it, and brings it to the human picker. Industry leaders indicate expect to adopt commercially viable unmanned warehouse drones in about a year (Baskin, 2017).

The current generation of unmanned warehouse drones performs material transport, acting as a shuttle between humans who pick and pack the goods. The greatest impact of implementing warehouse robotics remains the ability to perform the human tasks of identifying product on the shelf, picking product in non-standardized packaging, and understanding the human context of the goods in order to properly package it for presentation to a human customer. Amazon launched a $250,000 competition, now in its third year to develop a robot that can perform the human portion of order picking reliably; commercial application could occur as soon as next year (Baskin, 2017), albeit the competition focuses on stationary robots and does not require unmanned warehouse drones.

Primary uses for unmanned warehouse drones include inventory audit, infrastructure and security surveillance. Warehousing competitive advantage relies strongly upon data integration in real time, a capability that unmanned warehouse drone use reinforces (Gresham, 2017; Waller and Fawcett, 2013), yet picking represents the greatest need for labor savings. Commercially available unmanned warehouse drones may lift up to 10 kilograms (22 lbs.). (Dronelli, 2017), perfect for e-commerce, and the incentive for labor savings which should drive robotic picking technology to unmanned warehouse drones. Unmanned warehouse drones promise productivity improvements, do not require breaks, improve accuracy, maximize use of 3D space utilization, and alleviate injury, repetitive task, and other worker quality of life issues related to what the warehousing industry calls the 3D's category: dirty, dangerous, and difficult (Fiveash, 2016). Exploratory research suggest that executives may be unaware of the impact of unmanned warehouse drone technology even over the next few years as discussed in the next section.

Motives for Intransigence

Despite the advantages of warehouse drones and robotics, certain issues create intransigence when it comes to adopting the new technology. Positive leadership support represents the single most important factor for bringing a knowledge or data-related initiative successfully to fruition (Patil and Kant, 2014). While 75% of executives assert the importance of digital transformation across the supply chain, 48% still use non-digital (phone, fax, email) communications; only 15% can access the majority of needed data from trading partners, and 23% have the ability to analyze the data to make better supply chain decisions (Dougados and Felgendreher, 2016). When the same group of 337 executives from across multiple industries were asked to forecast five years into the future, 68% expected that data from across the majority of trading partners in the supply chain will be available to be analyzed and 54% expect to have access to the majority of needed data from their trading partners—indicating that technology is expected to advance rapidly throughout supply chains.

While supply chain executives exhibit knowledge and optimism about information supply chains, the literature suggests that they have relatively little knowledge or optimism about the physical supply chain. The traditional view of the supply chain looks at the information, financials, and product moving in essentially a straight line; but increasingly, supply chains may be divided into support supply chains—those nodes through which the physical product does not flow but which support the physical movement—and the physical supply chain, which encompasses the traditional view of the product accompanied by its information and financials (Carter, et al., 2015).

EXECUTIVE'S STATE OF AWARENESS ON DRONE TECHNOLOGY

In order to confirm the state of awareness of unmanned warehouse drone technology, we present the results of conversations with three executives from three industries about their knowledge of current unmanned warehouse drone use and their thoughts regarding the future of unmanned warehouse drone use. While the executives appear optimistic about the support supply chain that falls largely outside of their direct control, the conversations suggest that executives are much less informed and optimistic about the future technology that impacts the physical supply chain more directly under their control. Given the importance of supply chain velocity and order accuracy—physical and informational—to supply chain integration and competitive advantage (Handfield and Linton, 2017; Hofman, 2004), as well as the quick resolution and mitigation of supply chain disruptions (Craighead, et al., 2007), more work should address the information gap among decision-makers regarding digital technologies such as unmanned warehouse drones and 3D printing that will have an impact on the physical supply chains of the future. The results from our conversations suggest that supply chain decision-makers appreciate the potential of information technology yet remain staunchly traditional in their views of the physical aspects of supply chain technology. Questions and responses appear in the appendix.

Regional Wholesale Club

The vice president of transportation for a regional wholesale club with operations in 15 states is responsible for improving operational efficiencies by automating transportation tasks and optimizing the planning of shipments. The transportation function efficiency depends upon accurate inventory information and tracking movement of goods at distribution centers throughout the shipping process. This executive expressed an appreciation for the ability of unmanned warehouse drones to conduct inventory audits, monitor for security breaches, and trailer pool validation in the distribution center environment.

With regard to the company's greatest warehouse operational bottlenecks, he cited four areas. First, the "put to club" case or tier breakdown consumes much more time than the full pallet cross-dock process. Second, peak volume times see congestion in the building and yard. Third, certain specialized processes require holding inventory at the distribution center rather than sending immediately to the store, which slows velocity. One example is holding candy during the warm months to be processed one day per week in temperature-controlled trailers. Fourth, sorting through non-merchandise returns such as empty pallets, dunnage, plastic, and water jugs is slow and cumbersome.

The wholesale club enjoys several advantages. One is strong internal inventory controls resulting in inventory shrinkage that is well below the industry average. Another is vendor-owned inventory for most cold goods until they reach the stores. The company has achieved very low inventory in storage at only $50 million out of $1 billion of goods moving through its supply chain (5% of total value of goods moved). Company financials reveal the benefits of this performance: inventory turns were 10.6 and receivables turnover was 81.1, more than double and quadruple, respectively, for the retail industry overall (CSI Market, 2017). Such a lean supply chain could be improved even further through unmanned warehouse drones in conjunction with RFID tracking in order to monitor the cargo yard in real time. This could improve visibility and real-time decision-making greatly over the current system of periodically walking the yard and make the company's lean supply chain more resilient against disruptions. Improved cost accountability could be an additional benefit since allocating costs of current activities such as the yard walks proves complex; a drone would provide detailed records of its observations, associated inventories and assets, and time spent.

National 3PL

A national account manager at a national 3PL made the connection between unmanned warehouse drones and tracking trailers, yet prefers GPS tracking as a solution. The 3PL is primarily a transportation company focused on trucking that also provides warehousing, logistics, and intermodal services. The company assets include nearly 5,000 trailers and 2,000 power units with low dwell times, which explains the manager's preference for GPS tracking. The company owns multiple facilities near the ports of Baltimore and Norfolk and leases public warehouse space. With many mobile assets and few fixed facilities, this 3PL could benefit less from unmanned warehouse drones, although unmanned warehouse drones could provide trailer tracking and security of the existing facilities and yards where the company drops its trailers.

National Supplier of Electronic Hardware Components

The third conversation was with the warehouse manager at a leading national supplier of electronic hardware components. Much of their product fits in either a large box size of 8.5 x 8 x 3.5 inches (21.5 x 20.3 x 8.9 cm) or a small box size of 6.5 x 4 x 3.5 inches (16.5 x10.2 x 8.9 cm). Average pick time by humans is 1 minute 5 seconds, due to small product size, multiple SKU's, and a bar coding system that suffers occasional signal interruptions common to Wi-Fi technology and the slowdowns common to trying to scan barcodes in general,. The package size and light weight of the company's products seem ideal for future unmanned warehouse drones, especially in combination with an upgrade from barcode technology to a more reliable and sophisticated technology such as RFID. The manager demonstrated insightful understanding of unmanned warehouse drone technology with the observation that they would provide a greater pay-off if the warehouse's ceilings were higher.

Interviews Summary

Overall, these conversations suggest that supply chain managers may not understand the potential for operational improvements offered by the current generation of unmanned warehouse drones. A limited understanding of the current benefits and potential of unmanned warehouse drones underscores an even more limited understanding of the future of unmanned warehouse drone technology.

IMPLICATIONS AND FUTURE DIRECTIONS

Warehouse drones represent a fundamental shift in supply chain management in several ways. Operationally, warehouse drones improve warehouse functionality by better utilizing available space, reducing production downtime, reducing labor turnover and downtime, improving health and safety, increasing warehouse flexibility, and increasing productivity output. These benefits argue in favor of adoption of warehouse drone technology especially as costs continue to diminish as the industry matures.

Substantial research has assessed technology adoption and the rate of technological diffusion, and this research suggests combining extant models to provide more comprehensive guidance for decision-makers to assess cost and timing of technology adoption in order to determine investments in warehouse drone technology. Limited research assesses the specific impacts of robots on economic and productivity outcomes (Muro and Andes, 2015), especially in the supply chain context, making further research in this area vital.

This paper offers several important questions that should be addressed in future research:

1) Future research should confirm early findings that robots have contributed to productivity gains on the scale of the steam engine's effect on late 19th century productivity, the archetypical general purpose technology (Graetz and Michaels, 2015).

2) Assuming these findings regarding general robotics productivity gains find confirmation in subsequent research, they suggest that work needs to be done to explore the perceptions of executives regarding the advantages and disadvantages specific to the context of warehouse drones.

3) Relatedly, future research should measure the financial impact and cost trade-offs of drone technology in the warehouse setting. Financially, drones shift from human labor that constitutes variable costs to fixed investments in capital. Higher fixed costs create an impetus to maximize productivity so as to spread the cost of capital over more units—making warehouse drones apt for the high volume, high-throughput e-commerce distribution center environment.

4) With talent shortages predicted of at least 6 openings to each available laborer (Ruamsook and Craighead, 2014), many distribution center and warehouse managers confronting the supply chain talent shortage may see the opportunity for relief by replacing human workers with drone automation. In this scenario, automation may have two effects, firstly alleviating the challenge of filling technically qualified positions, and secondly freeing up resources so that companies can better afford to train workers for the work that automation cannot perform. Assuming that countries

where more automation prevails actually generate more jobs or at least lose less jobs (Graetz and Michaels, 2015), automation seems unlikely to solve the talent shortage, yet may become the price of entry into an industry competing for efficiencies and workers. More research needs to address the important role of warehouse drones in particular and automation in general in relation to the issue of employment and human resource management.

5) Future research should be conducted and oriented toward understanding the circumstances under which drones and automation could replace or complement human labor. This requires more complete enumeration of the functional roles and physical capabilities of drones. The current state of drone applications focuses on surveillance, inventory management, and picking, with picking reliant on humans to pick up-and-place the inventory while the warehouse drones and robots perform shuttle duties. As noted previously, experts project that in the near future robots will be able to pick most forms of products and seem likely to be able to master the challenging task of identifying and retrieving a single item from a jumbled box (Baskin, 2017). Warehouse automation technology can currently handle approximately 75% of products. Some warehouse tasks continue to pose additional challenges, especially assembly tasks, delicate small items such as produce, and packaging in plastic or partially obscured products, such as garment-on-hangar (Ackerman, 2016). A comprehensive typology of applications would facilitate the advancement of both drone technology and managerial decision-making regarding adopting new automation technology.

6) Strategic managerial and organizational factors related to the rate of adoption of warehouse drone technology, and the timeline for implementing new technologies in supply chain settings should be defined. An indicator of the potential for improvements appears in the Capgemini (2016) report which found that almost half of managers (48%) communicate with supply chain partners primarily through "traditional" technologies like phone, fax and emails rather than internet or cloud-based technologies—the same survey-based work revealed that two-thirds of the same executives expected adoption of major new technologies to integrate their supply chains in the next five years. Managers will need clearer guidance for this new technology and others to follow. Adoption and application of warehouse drones present many additional opportunities for future research.

CONCLUSION

Current unmanned warehouse drone technology offers the potential for significant efficiency gains both for inventory handling and inventory transparency. Unmanned warehouse drones offer strong potential with inventory audits and real-time supply chain visibility. Warehouse drone technology supports supply chain competitive advantage vis-à-vis supply chain integration and shortened cycle times to support improved customer service levels and supply chain responsiveness. Based upon recent developments in the Amazon warehouse robot competition, the application of unmanned warehouse drones to reduce the greatest warehouse cost—picking—appears to be on the verge of rapid adoption. The Amazon warehouse competition may have generated innovation of robot pickers to commercial application in four years, and it seems reasonable to expect a similar timespan for the technology to incorporate unmanned warehouse drones. As early adopters companies that invest in unmanned warehouse drones will garner operational benefits sooner and be better positioned for the next generation of unmanned warehouse drones.

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(Footnotes)

[1] US Bureau of Labor Statistics,

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