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Automation Technologies in the E-Commerce Supply Chain

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Acknowledgments

I would like to thank my mother, my father, my brother and my relatives who supported me and helped me throughout my studies providing me precious guidance and moral support.

A special thought goes to my colleagues at Politecnico and to my friends of a lifetime.

Introduction

During the last 20 years, Internet has changed the way we communicate. It offers instant access and availability and it has become the go-to means of interaction, work, and socialization. The rapid evolution of information technology was the premise for the e-commerce revolution, a new way of buying and selling products and services over the Internet. Traditional retailers are struggling to cope with the increasing pressure of e-commerce businesses, which offer more selection, convenience and 24/7 accessibility.

The e-commerce model developed and quickly rose to popularity over the years. Today, several companies offer same-day home deliveries on millions of products at lower prices than brick-and-mortar stores. The biggest challenge for e-commerce retailers is the ability of delivering products faster than competitors and at a lower price. This race to the customer's door transformed these businesses from pure online stores to efficient logistics companies. Large internet retailers like Amazon and Alibaba invest millions of dollars every year to develop new technologies and increase the efficiency and performances of their supply chain. A daunting truck driver shortage is projected to hit the logistic and retail business within 10 years and companies are sprinting to achieve a sufficient level of automation to avoid a scenario where there are no resources to move freight or deliver parcels to customers.

In parallel, the growth of e-commerce is not slowing down. As of 2017, e-retailers account for 10% of worldwide retail sales with a handful of big players controlling most of the market. Customer expectations from more selection and availability is rising with the total e-commerce market projected to grow by 20% year-on-year.

The e-commerce competition is fiercer than ever, and it provides fertile soil for the fast growth of automation technologies which will soon become predominant in an industry striving to deliver more parcels, at a higher speed and at lower costs.

Research Methodology and Structure

The methodology adopted for the drafting of this thesis has been defined by the sources and the tools available on the topic. The analysis of the Amazon Robotics Fulfillment Centres has been developed during my internship at Amazon. I was not part of the Robotics team but I had the opportunity to understand and elaborate on their structure, functioning and performance compared to tradition Fulfillment Centers. In order to obtain a complete overview on the topic, I spoke with Senior Operations Manager who work daily in these Robotics sites and I completed my research with white papers and articles.

The use of automation technologies is rapidly changing topic. Companies are constantly testing, developing and implementing new systems or components to increase their efficiency. For this purpose, big e-commerce retailers are reluctant to spread their successes or their main areas of focus and Amazon is no different. Some information has been left out to protect the non-disclosure policy of the company.

The thesis develops in 3 subsequent chapters:

- Chapter 1 introduces the concept of e-commerce and how it rapidly evolved to change the way people shop. It also focuses on the evolution of the retail supply chain during the last 40 years.
- Chapter 2 provides an overview of the future prospects for the automation of different segments of the supply chain.
- Chapter 3 elaborates on the adoption of automation technologies in the Amazon Robotics Fulfillment Centers. How they are able to operate with reduced human intervention and what are the implications for Amazon operations.

1. E-Commerce and the Evolution of the Supply Chain

This chapter describes the concept of e-commerce and its evolution from its origin to today. The focus will then move to the structure and development of retailers supply chain and how it changed with the disruptive introduction of big e-commerce retailers.

1.1 The Technological Premises for E-Commerce

E-commerce or Electronic Commerce refers to the buying and selling of products or services over and electronic platform, primarily the internet. The transactions for physical goods can be electronically processed but always imply transportation and delivery of the good to the customer while digital goods such as software or media contents can be fully exchanged online without any direct interaction between buyer and seller. The first forms of electronic transactions date back to the 60' and it kept growing ever since. Innovation and new technologies allowed selection, availability and convenience to improve over the years.

1960 – 1980

The development of the *Electronic Data Interchange* (EDI) is the first cornerstone for electronic commerce. EDI replaced the traditional exchange of document over fax with a digital data exchange between two computers. Companies started to send orders, transmit documents and invoices using the official North American ANSI ASX X12 data format. Once the order is sent, a third-party host service called *Value-Added Network* (VAN) verifies the order and sends it to the receiver. The introduction of EDI allowed to perform the process without any human intervention.

Michael Aldrich (1941-2014) is credited for being the precursor of e-commerce and online shopping. He was a British inventor and entrepreneur and in 1979, he had the idea of connecting a TV with a computer to manage transactions through a phone line. He created a long-distance shopping which he called tele-shopping.

1980-1990

Since the beginning, it was clear that *Business-to-Business* (B2B) online shopping was economically profitable. However, *Business-to-Consumer* (B2C) online shopping would not have been successful until the widespread use of Personal Computers and the World Wide Web. In 1982, France launched a first a primitive version of the Internet called Minitel, an online service employing a terminal called Videotex with access provided through the phone line. Minitel allowed subscribed users to exchanged texts and built connections between millions of users. In 1990, more than 9 million Videotex terminals were distributed in French households and they were connecting 25 million users across France. The Minitel system reached its peak in 1991 and it then became its decrease with the arrival of the Internet. In 2011, France Telecom announced the total shutdown of Minitel which did not became what is was hoping to be, the Internet.

1990 – Today

In 1990, Tim Berners Lee and Robert Cailliau developed a proposal to build a *Hypertext* project called WorldWideWeb. In the same year, Lee built the first web server and coded the first web browser using a NeXT computer and launched it on August 6th, 1991 as a public service available on the Internet. Building the hypertext on the Internet, Lee created the URL, HTML and HTTP protocols.

When the National Science Foundation (NSF) revoked the restrictions on the commercial use of the Internet in 1991, Internet and online shopping registered a first significant growth. In September 1995, the NSF started to request a fee for the registration of domains. At that time, there were 120’000 registered domains and the number grew to over 2 million by 1998.

In 1992, before Internet became so popular, Snider and Ziporyn, authors of the “Future Shop” explained that technologies would change the way we shop, and they will provide information, insights and forecasts for our next purchases. They stated that for several years the market would increase in complexity, it would become more confused for consumers to navigate and that new technologies will help consumers to overcome this confusion. In 1992, the two authors were already anticipating the disruptive revolution of the e-commerce.

Since the beginning, e-commerce has always been surrounded by skepticism and uncertainty in terms of data security and protection. However, in 1994, Netscape developed a security protocol called *Secure Socket Layers* (SSL) which provided a secure way to transmit and receive data through the internet. At that point, web browsers were able to verify each webpage's SSL certificate and evaluate its authenticity. More advanced and upgraded versions of the SSL certificate are still used today to verify the authenticity of web pages.

1.2 Big E-Commerce Retailers

The commercial use of the Internet marked significant progresses between the '90 and the year 2000. Amazon.com, the world's online biggest retailer, was founded in 1995 to sell books online. Physical bookshops and book stores had limited availability while Amazon was an online store and therefore it had, virtually, no limitations and a much larger offer. EBay was also launched in 1995 as an online auctioneer where private users could display and sell their products. The late '90 also marked the launch of two main search engines which are still widely used today, Google and Yahoo!. Search engines provided accessibility in indexing of the growing number of webpages available. The exchange of money for products over the Internet was supported by PayPal, an online banking system which managed the online transactions for both companies and private users on several websites. As of 2016, PayPal allows money exchange and retention in over 20 currencies and it has more than 100 million active users.

The increasing popularity of the Internet, the introduction of portables devices such as smartphones and tablets and increased consumer trust fueled the growth and expansion of e-commerce. Moreover, social media closed the gap between companies and consumers making interactions and advertisement easier and more engaging. The virtual structure of the e-commerce business has been coupled with increased supply chain efficiency and faster deliveries, allowing e-commerce to obtain an increasingly high market share year-on-year over traditional retail. As of 2018, e-commerce represents 10% of $28 trillion global retail market. While standard retail is projected to grow at 1%-3% rate year-on-year, e-commerce growth is estimated to be at least 20% and projected to reach $5 trillion by 2022. Amazon leads the American and European with market shares of 49% and 17%, respectively. However, it only controls 0.8% of the of the biggest e-commerce market which is China where Alibaba.com holds almost 60% of the share, followed by JD.com at 24.6%.

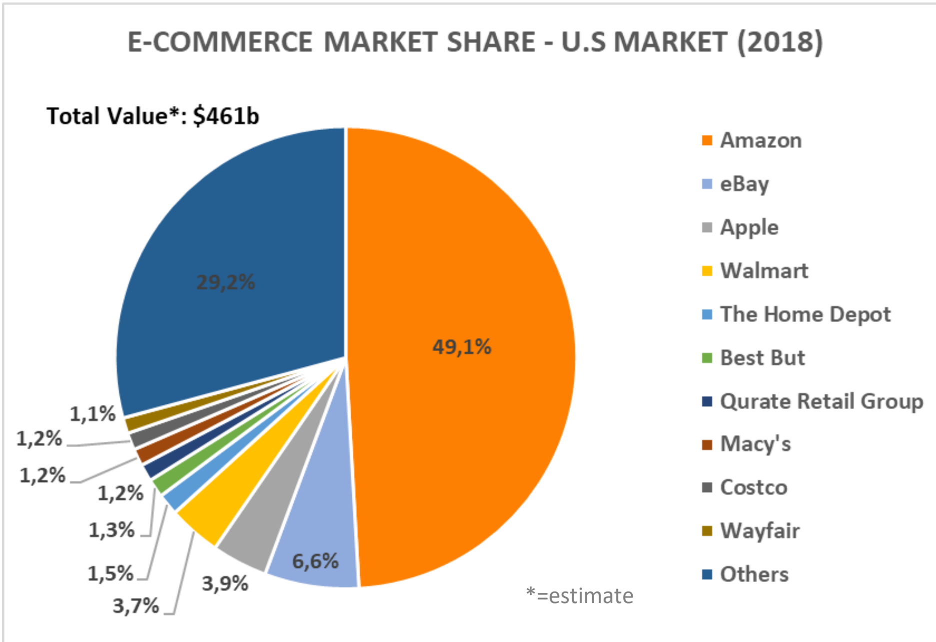

Figure 1-1: US E-Commerce market shares (Statista.com, 2018)

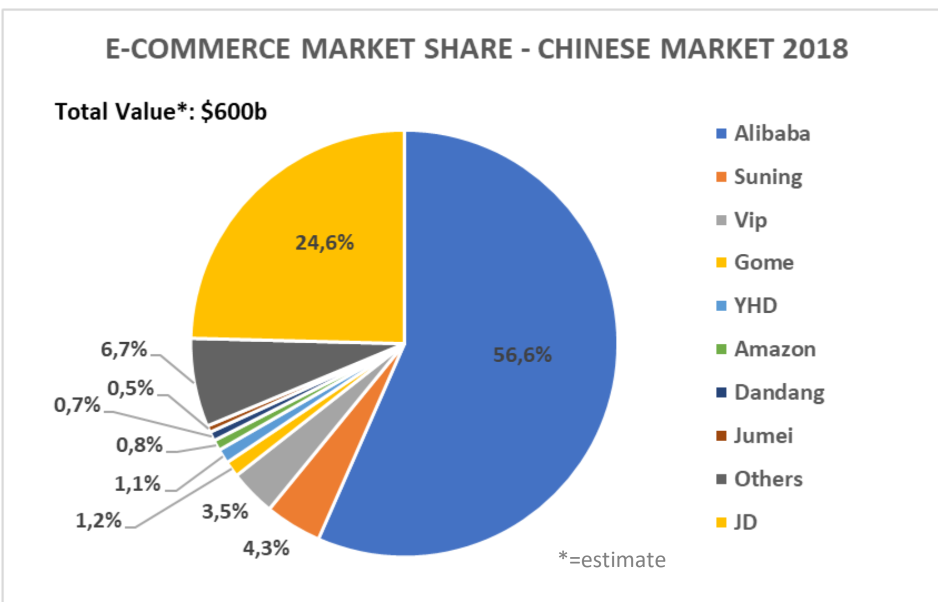

Figure 1-2: Chinese E-Commerce Market Shares (Statista.com, 2018)

1.3 The Evolution of the Retail Supply Chain

Retail distribution has significantly changed though the years and it has gone through several models to adapt to the requirements of a fast-moving market. The figure below summarizes the 4 main phases of this evolution up to today's model.

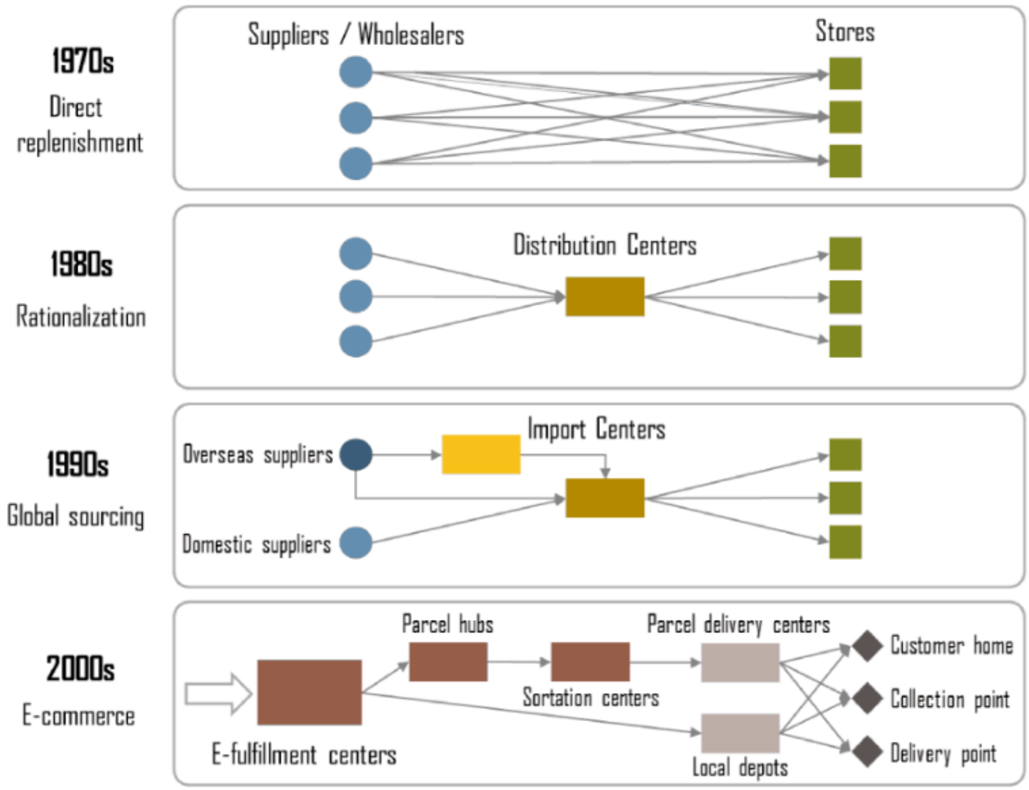

Figure 1-3: Graphic representation of the retail supply chain evolution (Lasalle J. L., 2013)

In the '60, companies start to understand that the physical distribution of their products is becoming strategically important and directly linked with customer satisfaction. Being able to have product availability in specific locations requires a solid logistic structure and retailers started to focus on closely collaborating with suppliers. In the '70, the vast majority of stores was directly replenished by the supplier without any centralized coordination. In the '80, retailers started to make use of the first distribution centers. These distribution centers were able to ingest big quantities of products coming from the upstream suppliers and redirect them to each store. This decade marked a significant change in how the retail supply chains were operated. The introduction of personal computers produced new and improved access to the computational power of these machines, allowing the development of new technologies. This was the premise for more accurate supply chain planning and execution. The ability of collecting and processing data gave new insights to retail companies which understood how expensive was supply chain management.

The ’90 saw the growth of global sourcing and overseas suppliers. Supply chain started to be more optimized, allowing retailers to buy products in other continents and selling them in Europe or North America. Retailers started to build import centers to receive and process containers coming from abroad and directly inject the products on the national market. Commercial logistics boomed in the ’90, with the introduction of the first *Enterprise Resource Planning* (ERP) systems. ERPs were the natural evolution of the first planning tools developed in the ’80 matched with the idea of integrating the several database systems to produce unparalleled information exchange and improved planning capabilities. Despite some initial difficulties in implementing ERP systems, in 2000 most of the retailers where relying on them. The result of this implementation was a substantial improvement in data availability and precision and the need of even more integration between demand planning and logistic operations. In the year 2000, the first Advanced Planning and Scheduling (APS) software were being developed.

Between the late ’90 and the early 2000s, the first e-commerce businesses started to populate the retail market. It is important to take one step back to understand why e-commerce boomed. One of the biggest perks of the Internet is its instant availability and ease of access. The WorldWideWeb changed the way we work and the way we socialize, e-commerce changed the way we shop. Internet became the new platform for product marketing and advertising, e-commerce became the environment to buy those products and challenge traditional brick-and-mortar retail. In the last 20 years, the e-commerce supply chain has evolved to offer customers faster deliveries and increased product availability. The big e-commerce retailers such as Amazon or Alibaba operate global supply chains which allow them to deliver products to every corner of the globe surprisingly fast. These retailers manage and fulfill orders through 3 main logistic nodes:

- E-Fulfillment Center: they receive and stow freight coming from sellers. The freight is usually received in pallets which are eventually broken down and the single items are stored in precise and mapped locations. A robust IT infrastructure is crucial to keep track of inventory location. The size of the fulfillment centres can vary from 40’000 m^2 to more than 100’00 m^2 and usually operate 24/7.

- Sortation Centres: They collect the daily intake of orders from several fulfillment centres and sort the parcels based on their zip code. Smaller vans will then pick up the parcels and proceed toward the final customer or toward delivery stations.
- Delivery stations: they operate similarly to the sortation centres but on a smaller scale. They represent the starting point of the last-mile delivery to the customer door.
- Integrated technology: An information system collects all the information coming from each node of the supply chain to provide precise data on the speed and efficiency of the delivery process. This piece of information is then processed and used to offer customers a delivery promise based on the current performance and congestion of the supply chain. They are the backbone of delivery tracking systems.

2. Current Implementation of Automation Technologies and Future Prospects

Chapter 2 describes why robotics technologies are gaining importance and traction to slow down and eventually relieve the pressure of customer expectations and labor shortages on the logistics of large e-commerce and retail companies. Section 2.2 analyzes the state-of-the-art technologies to manage every segment of the supply chain, from warehouse management and transportation to last-mile delivery and proposes an overview on the evolution prospect to further supply chain development.

2.1. Labor Shortage

Today the biggest challenge faced by the worldwide logistics industry is labor shortage. The shortage is driven by two 2 main factors:

- Increasing demand for logistics workers: with internet spreading so rapidly, e-commerce sales have grown very rapidly in the past 3 years and are projected to account for more than 15% of total worldwide retail sales by 2020. The chart below shoes the percentage of e-commerce sale over total retail sales. E-commerce sales are expected to mark 10% year-on-year growth in Europe and United States (Wu, 2017) while the Chinese online market is projected to match the France, Germany, Japan, UK and the US value combined by 2020 (Trends in China's E-Commerce Market, 2016).

  Moreover, e-commerce retail business is more labor intensive than brick and mortar retail. Traditional retailers usually handle full pallets of items which are shipped to a limited number of physical stores where the single item will be picked by individual customers from the shevles. E-commerce retailers (e-retailers) handle single units which are individually picked, packed and shipped and the network complexity is increased by single-door delivery. Therfore freight handling is more labor intesive and more expensive.

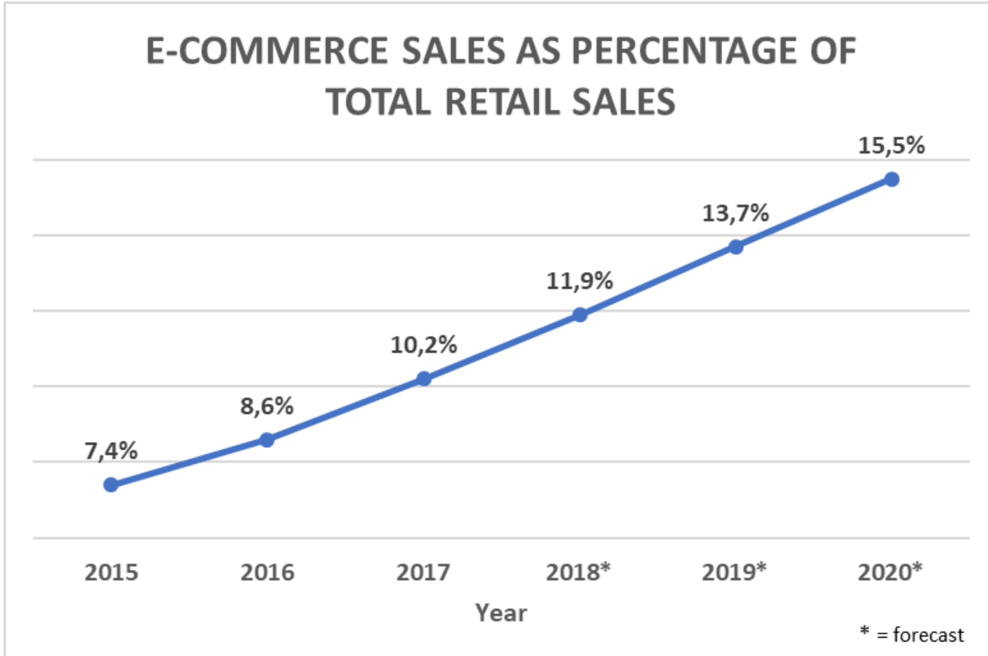

Figure 2-1: E-Commerce Sales as Percentage of Total Retail Sales (Statista.com 2018)

- Shrinking workforce in Western countries: the working population in Western countries is reducing and Europe is projected to lose over 30 million workers by 2050 because of reduced birth rate and the number of elderlies rising. Narrowing the issue to the logistics industry, the causes of this projected shortage are mainly retirement of the current workers, low salaries and an overall lack of interest in these professions by the younger generations. The issue is extended to all areas of the industry, but road transportation is the most affected. The British Freight Transportation Association has reported a shortage of 55,000 truck drivers in 2017. German trucks drivers record an average age of 47 years old and Germany will lose over 40% of its current truck drivers within the next 15 years creating a shortage of 140,000 jobs (Transport Intelligence Ltd, 2016).

If the retail supply chain does not evolve in each of its segments, companies will start to raise costs and reduce service levels because there will simply not be a sufficient number of workers to move an handle and increasing volume of freight. Supply chain managers must integrate more automation in the supply chain to compensate the lack of man hours and increase the levels of productivity and efficiency.

2.2. Supply Chain Segment Automation

The following section aims at describing what are the technologies which are currently being used or developed in the field of supply chain automation. The objective is to showcase one piece of technology for each segment of the supply chain, from fulfillment centers to transportation to last-mile delivery. The focus is to describe how the technology works and what is its impact on the execution of the supply chain from the vendor/seller to the final customer.

2.2.1. Automatic Trailer Loading

Big retailers operate through a network of warehouses called distribution centers or fulfilment centers. Distribution centers store large quantities of inventory which will then be shipped to smaller distribution nodes and they will ultimately reach the shelves of a physical store. In case of e-retailers such as Amazon or Zalando, items will be delivered directly to the door of the final customer. Whether it is a traditional retailer or an e-retailer, units reach and leave the distribution center through a docking bay and into a trailer or a container. In some cases, units reach the distribution center directly form a vendor and they are stacked on a sealed pallet. Palletized freight is easier to handle and quicker to unload. In standard unloading procedures of palletized volume, a forklift drives into the trailer, lifts one pallets, brings it out and lays it on the dock. However, trailers can also be loaded with loose load. Loose load refers to single units or parcels of different shapes, sizes and weight which are randomly loaded into the trailer. Most of the into imported from the Asian countries into the European and North American markets are transported into containers loaded from the bottom to the ceiling with parcels. This allows maximum volume utilization and therefore cost saving on transportation. In the occurrence of a loose load, a conveyor belt is attached to the trailer and workers manually unload parcels on the conveyor. The unloading process of loose load is very labor intensive as workers handle every single unit individually during the process. On average, 2 workers unloading a parcel container can take between 40 and 90 minutes depending on the number and sizes of the parcels (Amazon, 2017) which adds up to between 1.2 to 3 man hours for each parcel container.

In 2003, DHL started to develop a prototype robotic solution to autonomously unload parcel trailers and containers, it was called the "Parcel Robot". The Parcel Robot was essentially made of 3 components:

- A 3D laser scanner to identify the size of each individual parcel in the container
- A robotic arm mounting an extendable gripping system
- A small conveyor belt to carry the unloaded parcel to the main conveyor system.

The laser would scan the first layer of parcels from top to bottom to register the dimension of each box and the pass the information to the robotic arm. For each box, the gripper mount at the end of the arm adjusts its width to grab the parcel without damaging it and then place it on the conveyor. Then, the robot moves forward until the full trailer is unloaded.

Figure 2-2 DHL Parcel Robot Prototype (DHL, 2015)

The 2003 original project was closed because, at the time, the technology was too expensive, but it was re-opened in 2015 (DHL, 2017).

Trailer unloading is becoming more and more popular because it allows to cut labor costs related to the docking operations. However, parcel loading is still far from being automated. The main issue with loading is that is adds complexity to the task the robot has to perform. The software needs to calculate which is the most optimized way to occupy the container volume, considering that boxes have different sizes, shapes, weight and that damage must not occur to the items.

2.2.2. Transportation Automation

Section 2.2.2 focuses on the development and technology surrounding autonomous trucking and transportation. For the purpose of this section, transportation will be referred to as the intermediate segment between large e-retailers distribution centres and smaller delivery station or parcel hubs. Last-mile delivery will be analyzed in a following section. The breakdown of current and future technologies is limited to road transportation and does not take into consideration rail, sea or air transportation.

Transportation refers to “the movement of product from one location to another as it progresses from the beginning of a supply chain to the customer’s handle” (Robinson, 2015). Over the past 20 years, autonomous vehicle technology has been an important area of focus for both truck manufacturers and logistics providers. However, the attention has revolved around passenger transportation rather than commercial line-haul mainly because of ease of implementation and research. Several stakeholders are now shifting their focus on commercial vehicles because the success achieved by autonomous driving can find development in freight transportation. The logistics industry sees the implementation of this technology as a tempting return on investment even though the extent and time horizon of this return is unknown.

The Society of Automotive Engineering (SAE International) has defined a 6-categories ranking to assess the automation level of a truck. From 0 to 5, the vehicle takes over an increasingly higher number of tasks form the driver until full automation is reached (level 5). At level 4 and 5, the truck does not need a driver at all which implies that the tractor can be manufactured without the traditional actuators such as steering wheel, seat and pedals. Levels 0 and 1 are already available on the market and include well-known safety and control systems such as ABS (anti-lock braking system) or TCS (traction control system).

Level	Name	Description	Technology Status
0	No Automation	Human performs all driving tasks, even if enhanced by active safety systems.	Commercially Available
1	Driver Assistance	Vehicle can perform sustained control of either steering or acceleration/deceleration.	Commercially Available
2	Partial Automation	Vehicle can perform sustained control of both steering and acceleration/deceleration.	Pre-Commercial
3	Conditional Automation	All tasks can be controlled by the system in some situations. Human intervention may be required.	Prototype Retrofit
4	High Automation	All tasks can be handled by the system without human intervention, but in limited environments (e.g., dedicated lanes or zones).	Research & Development
5	Full Automation	Automated system can handle all roadway conditions and environments.	Reserach & Development

Figure 2-3: Levels of trucking automation (Slowik P., Sharpe B., 2018)

Truck automation is not limited to the single truck. In order for automaton to works seamlessly, the technology needs to be extended to the surrounding tractors as well. This is the reason why automation and connectivity between different units are often discussed together and as a single topic. The market for truck automation is ready for all levels of automation but the potential return on the investment on this sensing technology is not defined yet. The cost of increasing the cost of automation can be broken down into 2 main components: the upfront investment cost to purchase and install the technology and the per-km operating cost. Level 1 and 2 are already available on the market but there are very rough estimates of the cost for level 3 and above installation and the potential benefits. Simple sensor upgrades for safety and collision mitigation are available for few hundred Euros while level 3 retrofits are estimated to be between €25'000 and € 45'000 per truck. Daimler and Uber are the main companies working on this retrofitted automation systems which can be installed on standard line-haul trucks.

Full automation and connectivity is still far from being available on the market. However, from 2010, companies started to combine the capabilities of different technologies to give birth to the long-haul truck platooning. Truck platooning is the "linking of two or more trucks in convoy, using connectivity technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey, for instance on motorways" (European Automobile Manufacturers Association, 2017). The leading truck sets the pace of the platoon and is responsible for maintaining the route. The other trucks in the convoy maintain a safety distance which ranges between 5m and 20m depending on the speed and work as recipients for the signals coming from the leader. When the leader brakes or accelerates, the information is conveyed to the followers which automatically increase or decrease the pace. In the most basic form, platooning could be performed manually. However, drivers would be required to drive at very close distance which increases safety risk and the chances of crashing into each other. The rise of sensor technology and truck communication allows close following distances and remove the safety concerns because the reaction time of sensors is up to 5 times faster than any human driver. Currently, a driver per truck is always required. The leader operates its trucks normally, while the following drivers only play a supervising role. The software system automatically captures the signals form the leader and operates on the actuators (steering system, braking system and acceleration). The connection between the trucks increases the safety on freight transportation.

Another key benefit of platooning is fuel consumption. The expected saving has been estimated from simulations and track testing as on-road operation is not allowed yet. A 2017 study from Ertico claims that the followers can save between 10% and 16% on fuel consumption while driving in a platoon. The saving comes from the drag reduction provided by the close truck ahead. However, the reduce air intake might negatively affect engine performance and, in the long term, result in power units able to run for fewer km because of insufficient air cooling.

Platooning and, in a broader scope, transportation automation spring debates about their social acceptance and fit in the current regulation scheme. From a business perspective, new technologies carry potential for cost and accidents reduction. Drivers would see a shift in their mansion, from tiring and tedious shifts conducting the truck to a supervision role with the potential of performing side tasks while the truck operates autonomously. However, with this kind of technology spreading quickly, the public opinion and each country's regulators could pose a threat to the full-scale implementation. Below is a summary of the main points of concern from the three players involved in the development of truck automation:

- **Industry:** Unless there are at least 3 or 4 trucks in formation, platooning does not work. The result is that some trucks might need to alter or change their routes in order to meet the other participants of the platoon. Even though the overall costs might be lower, the transit time of a load might be longer. Supply chain speed and agility are two of the critical success factors of the e-commerce business. Platooning will undeniably stretch the time needed to complete the freight transportation and e-commerce businesses are unlikely to reroute trucks to take advantage of platooning.

  Logistic companies will need to invest in further technology maintenance, education of new driver and cross-training of experienced drivers. The direct and indirect costs of implementing platooning technology on the whole fleet is still unknown but likely to be onerous with uncertain period before the return on the investment is complete.

  Security concerns on the overall performance of the system are unlikely to fade away quickly. Like every technology where human decision making is reduced, skepticism rises. Self-driving cars have been around longer than self-driving trucks and yet they are far from being accepted from the public. Trucks are heavier and more difficult to handle than cars. The sensors mounted on trucks need increased spatial and time awareness than cars because the time and space required to stop a truck is longer. Moreover, an accident affecting the leader or any of the member of the platoon is likely to affect the whole formation and potentially have a bigger impact on the surrounding vehicles. Consequently, insurance will charge higher premiums for trucks travelling in platoon. While the logistic industry has an overall positive judgement on transportation automation and platooning, there are still questions to be answered and tests to be performed before this technology can be implemented on public roads.

- **Driver:** the main concern for driver is that their job will have fewer and fewer responsibilities as the trucks become more autonomous up until they are completely replaced. Job loss is unlikely to occur in the next 15 or 20 years but the role of the truck driver is rapidly changing. Platooning will be more stressful for drivers because they lose control over the vehicle and yet they travel at 90 km/h with limited space to the trucks ahead and behind.

Drivers are also worried that regulation will push them to operate for longer shifts when travelling in platoon with an ultimate impact on their health and motivation. With over 30% of European drivers going into retirement without replacement, the transportation industry is entering a transition phase where the focus is shifting toward technology, but drivers are still required to supervise. This outlook is unlikely to attract the younger workforce potentially creating a big occupational gap.

- **Public Opinion:** concerns from the public mainly concern the safety of the passenger cars travelling around autonomously operated trucks. In general, the public opinion is that an autonomous vehicle is a threat rather than a way to increase road safety. The question around how much trust we put in autonomous vehicles is a recurring argument with Tesla cars. It is proven that a handful of accidents where caused by faulty sensors which resulted in fatal crashes and it happened because this technology “only” works in 99.99% of the occurrences. However, the public opinion still struggles to understand that hundreds of lives have been saved and accidents have been avoided because technology came to rescues sleeping or inattentive drivers. Platooning will follow the same steps of autonomous passenger cars. In rare occasions the technology will fail and unfortunately fatal accidents will happen, but the overall impact of transportation automation will be positive and will increase the safety of both commercial and private transportation.

2.2.3. Last-mile Delivery Automation

Last-mile delivery refers to the “movement of goods from a transportation hub to the final delivery destination with the objective of delivering items as fast as possible. The final delivery destination is typically a personal residence”. (Datex Corporation, 2018). With costs amounting between 30% and 50% of total delivery cost, last-mile delivery is gaining a lot of attention from retailers as one of the key action points to improve supply chain efficiency. At the same time, last-mile is one of the biggest obstacles for new and small e-retailers because of the high labor costs and overall complexities of the task. If companies are struggling to cut last-mile costs, customers are demanding high level of service in terms of speed and quality of the delivery.

In the traditional brick and mortar retail business, in-store experience and interactions between customers and staff play a key role in building customer satisfaction and, ultimately, retention. Within e-commerce business, last-mile service represents the only point of contact between customer and vendor and the perceived quality of the delivery is one of the major decision criteria for online customers (McKinsey, 2016). Moreover, in many cases the last-mile delivery is not performed by the retailer itself, but it is rather contracted to a third-party carrier which further reduces the points of contact between customer and vendor.

With the rapid growth of e-commerce and the entry of new players on the market, last-mile is evolving to meet new customer segments. From stay-at-home mothers, to the young college students to occasional buyers, different segments prefer different delivery methods based on delivery speed, reliability and most importantly price. A 2016 survey from McKinsey investigated last-mile preferences from the 3 biggest e-commerce markets, the US, China and Germany. The result shows that 70% of the customers would still choose free delivery over speed or reliability. *Reliable delivery* refers to a guaranteed delivery within a 2 hours delivery window while *instant* refers to a maximum 3 hours interval between order and delivery. The exhibit below shows the results of delivery preference.

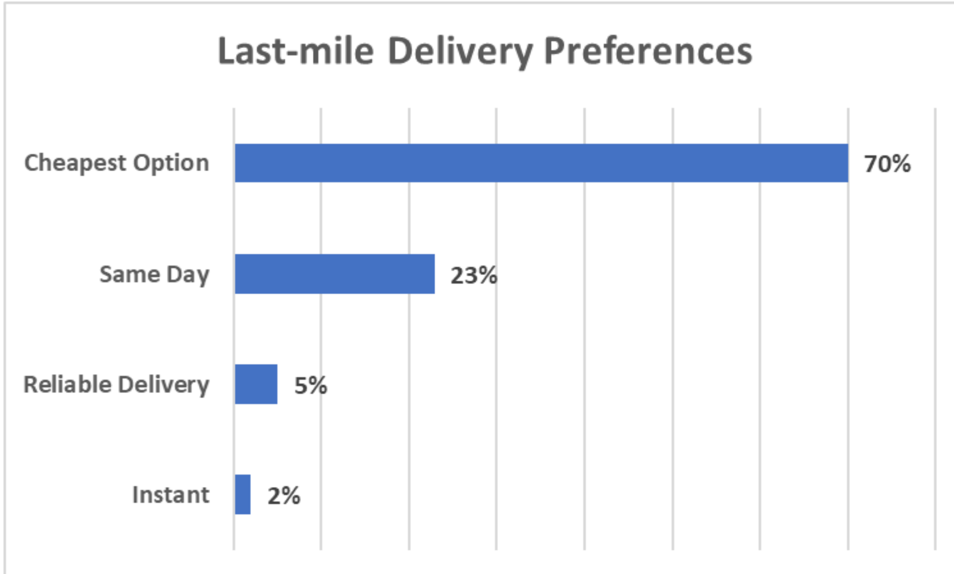

Figure 2-4: Last mile delivery preferences (Magento Insights, 2017)

Although fast deliveries are gaining traction on customers, the majority will always go for the cheapest option. This implies that parcel will be delivered between 1 and 4 days from order based on availability and destination location. Only a smaller portion of customers is willing to pay a premium to get its product faster and this is the main reason why e-retailers are investing into technology and automation to reduce last-mile costs.

In a foreseeable future, the technologies used for last-mile delivery will couple with the current methods to create solutions to meet customer expectations, and destinations (rural or urban areas with different population densities). The following list describe 7 possibilities for last-mile delivery:

- Van couriers: delivery companies employ a dedicated person to pick up a van in a delivery station and bring the parcels directly to the door of the customer. Delivery companies usually own or lease the vans.
- Bike couriers: Like van couriers, bike couriers are employees of the delivery company which deliver small parcels in central and busy neighborhoods of urban areas. They usually deliver documents, small parcel or food.

- Crowdsourcing: It is a delivery method which is becoming more and more popular. It consists in a very flexible and broad pool of workers who sign up to a platform and decide when and how many parcels to deliver based on their availability. Delivery companies are strongly supporting this delivery method because it allows more flexibility in covering peak times such as Christmas or Easter. Moreover, delivery companies do not need to provide any additional assets such as cars or bikes. It also opens new delivery windows outside of normal working hours as the workers decide when and how many hours they wish to work. Amazon launched its crowdsourcing delivery service in the US (2016) and in Germany (2018). Amazon offers a fixed compensation of $60 for a time slot of 3 hours and an average number of 20 to 30 parcels.

The previous solutions are standard methods currently used by all parcel delivery companies. Crowdsourcing is the most innovative in the sense that it is riding the wave of the sharing economy which already boomed with services like Uber or Lyft where private individuals are willing to share their assets (cars) in return for a compensation.

However, the last-mile business is evolving beyond these traditional methods and it is starting to embrace automation to meet the increased customer demand. For the purpose of this document, these technologies have been clustered in 3 main categories:

- Drones: They are unmanned flying vehicles able to travel short distances carrying a limited amount of weight (up to 15 Kg). Although drones are still undergoing testing, they represent the fastest way to cover the distance between the warehouse and the customer doorstep. They can vertically takeoff and land and therefore need very little operating surfaces to operate. Drones need supervision rather than direct control as the route to the customer is automatically provided by the system. Among the many retailers that are currently testing drone delivery, Amazon publicly showcased its first Prime Air delivery on December 7^{th}, 2016 with an impressive Order-to-delivery time of 13 minutes. As of August 2018, drone delivery is very far from being economically feasible and it is limited to rural and low-density areas. Another key issue concerning drone delivery is the current regulation. Laws regulating drone utilization are very different from country to country and it is currently preventing seamless development of this technology.

- AGVs (Autonomous Ground Vehicles) equipped with lockers: AGVs are automatic guided, wheel-based vehicles used to move components within the perimeter of a warehouse. Currently, AGVs use ground marks or wires to autonomously follow a path and reach their destination and their use is limited to company or private soil. The next step is to utilize AGVs for last-mile delivery to final customers outside the warehouse. The idea is to mount a parcel locker on an AGV which will autonomously drive to a specified drop-off location. Then, customers are notified once the AGV has reached its destination and they will be able to pick up their parcel from a locker. The current locker-pick-up model implies that an employer of the delivery provider picks the parcels at the delivery station and replenishes the lockers spread throughout the territory. Lockers mounted on AGVs would be filled directly at the delivery station and then autonomously drive to the delivery location (and come back). Traditional AGVs operate in unclosed environment and follow a specific path. In order to be used for last-mile-delivery, they would need to move and operate on public roads which is much more challenging. Therefore, human supervision is required to manage and operate a fleet of AGVs. It is estimated that one operator could manage between 6 and 8 AGVs.
- Droids: Like AGVs, droids are small autonomous vehicles which can carry one or two parcels. They move at low speed on the sidewalks rather than on the road and are able to deliver directly to the customer's door. The American startup Starship Technologies successfully completed the first droid delivery testing in late 2016. Droids have limited range and capacity; therefore, they will be deployed for small and instant delivery in urban areas. Delivery hub within the city will collect the parcels and load them on the droids which will then cover the short distance to the customer door.

Droned, Droids and AGVs with lockers are not fully deployed yet but they represent the future of last-mile delivery. Because of the size, characteristics and range, these three pieces of technology will find application in different last-mile scenarios. The graphic below summarizes the applications based on 2 delivery factors: population density and delivery speed.

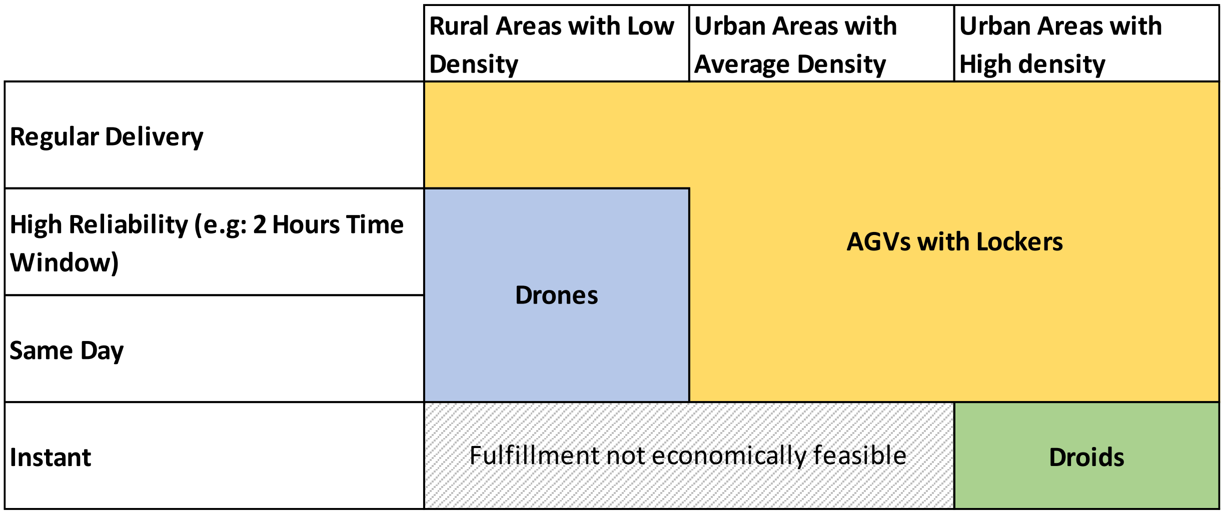

Figure 2-5: Delivery automation outlook (McKinsey & Company, 2016)

Ultimately, last-mile automation will solve one of the biggest issues for delivery companies which is failed deliveries. A 2017 study form Magento Commerce surveyed 300 retailers and their customers in the US, UK and Germany to investigate the causes and the consequences of failed deliveries. A delivery can fail for several reasons; the main one is the customer not being at home to retrieve the parcel but often issues arise from incorrect addresses or imprecise information exchange between customers, retailers and carriers. The results of the survey show that, on average, 5% of the first attempt deliveries fails with significant cost implications for the retailer.

Percentage of Failed Deliveries	4,7%	5,6%	4,6%
Cost per Failed Delivery	17,55 $	14,33 £	14,87 €

Figure 2-6: Costs and percentage of failed deliveries (Magento Insights, 2017)

Retailer often provide some form of reimbursement to customers when the first delivery fails. 64% of retailers refund any shipping cost to the customers and will pay for a redelivery. Others will offer discounts as a form of apology to the customers and therefore the costs of failed deliveries are very high. Moreover, failed deliveries also have an impact on customer retention.

E-commerce is a volatile business with high levels of customer turnover. On-time delivery is one of the key factors for customer retention and one missed deliver might equal to a lost customer. This is the reason why e-retailer are willing to spend so much money to amend a single delivery.

The traditional "deliveryman + van" delivery method presents one key issue which is the misalignment between customer availability and delivery window. Most carriers deliver between 9:00 and 18:00 form Monday to Friday which are the time windows where customers are working rather than being at home and this results in parcels failing to be delivered on the first attempt. For a price premium, retailers are now starting to offer late night (until 20:00) or Saturday deliveries. It is, however, a short-term solution as customers are reluctant to pay a premium on top of standard shipping costs. In this sense, automation technology will be able to solve part of these issues as delivery will move away from being a labor-intensive task. AGVs will leave the delivery station late in the evening or early in the morning to offer a delivery window which matches people availability. In the deployment phases, they could pick up the failed delivery for a determined area and serve as regular parcel lockers staying in the neighborhood overnight. Moreover, they will provide Sunday deliveries, especially in countries like Germany where work is forbidden for the logistics and retail professions.

The technology is substantially already available although it is still not economically feasible. Economic feasibility will eventually be overcome with time and economy of scale as these technologies are gaining increasing traction to solve issues related to labor availability. However, different countries will implement these technologies at different speed based on 3 main factors:

- Opportunity cost: The penetration of e-commerce is very diverse form country to country as well the labor availability outlook. In Western countries e-commerce accounts for a large share of the total retail business and, combined with increasing labor shortages, it represents a fertile ground for automation technologies to develop. McKinsey has estimated that in countries where labor cost is above €12/hour, automation is economically convenient in the long run. Countries with wages lower than the €12/hour threshold (developing countries), have less incentives to develop such technologies.

- Regulation: The automotive industry has made big steps in the last decade in terms of automation while governments have struggled to produce suitable regulation to clearly direct the use and employment of these technologies. The current lack of legislation prevents companies to test AGVs deliveries outside of very controlled environment and strict human supervision. This is hampering the development as the full capabilities of the technology cannot be tested and therefore an evaluation of the real economic potential cannot be completed. Carriers and automotive companies are partnering to train the next generation of “drivers” that will have the task of supervising swarms of autonomous AGVs.
- Public acceptance: Regulation and opportunity costs are obstacles that will eventually be overcome. Public acceptance is much more difficult to forecast and to predict how it will impact the development of these technologies. While autonomous driving and AGVs are already well accepted by the society, the same cannot be said for drones. 65% of people aged 18-30 state that they are likely to use and do not feel endangered by AGVs but only 40% says the same about drones. With the UK being the first country to allow out-of-sight drone flights, tests will become more and more frequent in rural areas.

3. Case Study: Amazon Robotics Fulfillment Centers

The following chapter focuses on the application of robotic technologies implemented by Amazon.com in its Fulfillment Centers. Section 3.1 provides an overview of the company, followed by the description of the main processes within its standard Fulfillment Centers. Section 3.2 dives into Amazon Robotics and describes how a Robotics Fulfillment Center operates. The chapter ends with an evaluation of the implementation of this technology compared to the standard Fulfillment Centers and what is the impact on the order fulfillment process.

3.2. Amazon Operations Network

Amazon.com is the world's largest retailer, generating over $178 billion in revenue in 2017 (Amazon.com, 2018). Founded in 1994 by Jeff Bezos to sell books online, Amazon has expanded over the last twenty-three years to offer the largest product variety of any retailer. They have entered diverse businesses outside of retail, including electronic devices, media and content, and web services. Currently, e-commerce retail and order fulfillment remain the core of their business. While Amazon has the largest e-commerce fulfillment network in the world, they still have significant room for growth. As they expand in the US and overseas, they will continue to look for ways to improve throughput and lower cost in their fulfillment network.

Amazon.com operates a global distribution network, the cornerstones of which are its fulfillment centers (FCs). Fulfillment centers range in size from about 30,000 m^2 to over 300,000 m^2 and serve as the storage point for all Amazon owned inventory and a significant proportion of "Fulfillment by Amazon" inventory. The “Fulfillment by Amazon” (FBA) program allows sellers make use of Amazon supply chain to ship, store and deliver their products to customers. In exchange for an agreed fee, sellers can send their products to Amazon FCs and they will be available on Amazon.com. Furthermore, Amazon also takes care of the reverse logistic for customer returns and of customer service. However, FBA inventory is never sold to Amazon and, even if stored in Amazon FCs, the seller is still the owner of the product until it is sold to a final customer.

FCs are identified by a 4 digits code, the first three being the IATA airport code of the closest international airport, followed by a number (MXP3 or FCO1). Traditional retail warehouses usually ship pallets of goods to their physical stores while the Amazon FCs are able to fulfill each single order and ship each single unit individually. Over the years, the Amazon network has grown and now it counts different types of warehousing solutions such as inbound cross-dock (IXDs) or Sortation Centers. FCs are classified based on the type of inventory they stow and handle:

- Sortable FCs: They can only process smaller products ("sortable products") such as books and small electronics.
- Non-sortable FCs: they only handle larger items such as laptops or TVs.
- Mixed FCs: they can process both sortable and non-sortable items.

Based on the building and the storage area characteristics, FCs can also have more specific capabilities. This means that the FC can handle very particular categories of products which need special requirements. Examples are large batteries, chemical or potentially dangerous products which are part of the Hazmat category (hazardous materials). Hazmat products need enclosed stowing areas and special handling practices to prevent injuries or exposure to toxic agents. Food products need to be stowed at controlled temperature to prevent the food from going bad.

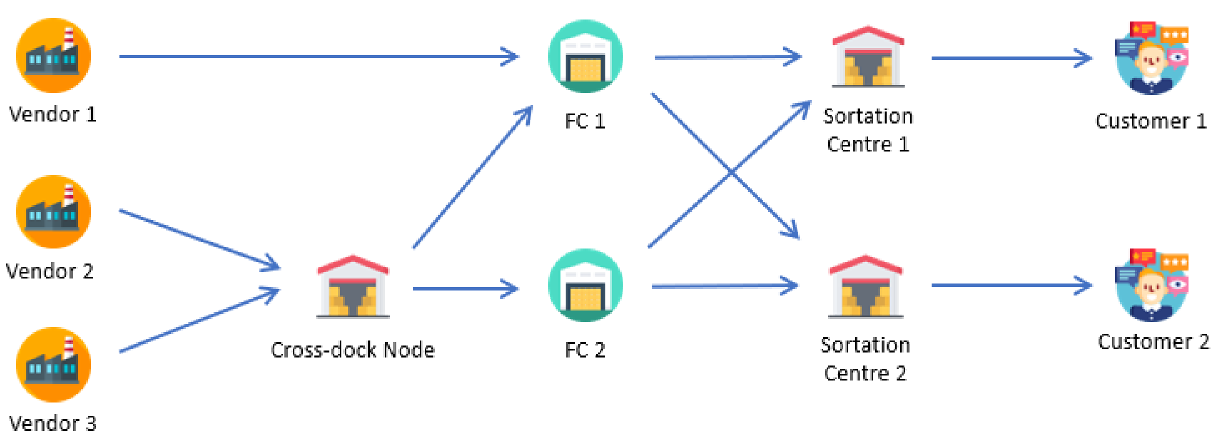

Figure 3-1: Graphic of Amazon Network Operations

3.2.1. Fulfillment Center Operations

The following section describes the core actions performed into a traditional Amazon Fulfilment Center[1] (FC). Within any FC in the Amazon Network, the operation procedures follow worldwide standards. Therefore, the following descriptive sections apply to any Amazon FC worldwide. FC operations are split in inbound and outbound. Inbound operations refer to all the processes aimed at receiving and replenishing inventory. Outbound operations refer to the steps executed to fulfill customer orders.

3.2.1.1.Inbound

Freight arrives to Amazon FCs through means of road transportation. The FCs are structured to receive freight from one or more of the following means of transportation:

- Trucks
- Sprinters
- Containers

Amazon accountability and responsibility of freight starts when a truck crosses the FC gate and enters the FC premises.
The inbound freight flowing into Amazon FCs can be divided into 2 main flows:

- New Transfer in (NTI): These units are already property of Amazon are they are coming from another Amazon FCs. There are several business reasons why Amazon should transfer inventory between two FCs. The main ones are different inventory placement strategies which have the objective of spreading the inventory to deliver quicker to the final customer. Within the European network, NTI represents roughly 40% of the total inbound volume.
- New Vendor Freight (NVF): NVF are new units coming from vendors or sellers.

[1] Traditional/Legacy Fulfillment Center: it refers to a Fulfillment Center that does NOT operate with Amazon Robotics technologies

Inbound Dock

Once the truck is docked to an unloading bay, security checks are performed to evaluate the compliance of the truck and of the load. If the volume is loose, a conveyor is brought into the truck and each parcel is unloaded from the truck and conveyed to the receive area. If volume is palletized, pallets are unloaded and gathered on the dock lane. Aside from special occurrences where volume prioritization is required, inbound volume is usually sent to the receive area in FIFO order.

Before being received into the FC the volume might go through an extra step called prepping. Prepping aims at providing each unit with appropriate protection to be *e-commerce ready*. For example, objects such as knives or other fragile units need special packaging to avoid damage during the handling process.

Receive

Once a unit is unloaded and *e-commerce ready*, it can proceed to the receiving process. Receiving refers to the action of scanning a unit's barcode to electronically add it to the inventory and placing it in a temporary container (tote). This action marks the first time a unit is recorded as inventory in the FC. Prior to receiving the items, Amazon does not virtually acknowledge that the item exists within the FC and therefore is not available on Amazon.com (assuming that the same item is not available in another FC). Once the units are received, it is displayed on the website and it is available for customers to order. Despite being available for order, these units are not in their final location (bin) yet.

Prepping and receiving are only performed on New Vendor Freight. For Transfer volume, the units have already been prepped and received at the source FC. Therefore, the volume can directly proceed to stow.

Stowing

When the item is received, it is physically and virtually placed in a temporary container (yellow tote). The item is already available for order, but it is not located in its permanent location yet. These permanent locations are called bins. The action of moving a received item from a temporary tote to its permanent bin is called stowing. It is important that the time between receiving and stowing is as short as possible. Customers could order an item which is received but not stowed yet. Locating an item which is placed on a mobile tote could be very difficult and this is why it is important to stow items as quickly as possible.

3.2.1.2.Outbound

When customers order one or more units on the website, and order is created in the system to be tracked. This order will be passed to a specific system which will determine where the order will be shipped from to meet the customer delivery promise. The less complex scenario corresponds to an order containing just one unit. First, the system will look where the inventory is available. Then it will calculate from which location it will be cheaper to ship to the customer within the promise.

However, there can more complex scenarios when a customer orders 2 or more items within the same order. If both items are available in the same FC, then the order will be assigned to that FC. If the items are available in different FCs, the system will calculate if it is cheaper to consolidate the items in one FC and ship from there or to ship each item singularly. Usually, consolidating the items in the same FC is the cheaper solution. As a matter of fact, transferring units between 2 FCs is 60% cheaper that shipping toward a final customer.

Picking

Once the order is assigned, the outbound process can start in the FC. FC associates in charge of picking the items ("pickers") receive the information with the aisle and bin number where the item is located. The pickers walk through the FC with a cart with yellow totes. Once they reach the location, they scan the bin, scan the item, scan the tote and put the item inside. Scanning the bin, the item and the tote allows to virtually track the movement of the items. At this point the system will know that one unit of that ASIN[2] has been moved from its bin to a tote. When the tote is full, they bring it to a conveyor belt which brings the items to the next step.

Packing

The conveyors bring the totes towards the packing stations where "packers" put the items in boxes suitable for shipping. The packer picks one item from the box and scans it with the barcode reader. Given the weight and dimensions of the box, the system tells the packer which

[2] ASIN: Amazon Standard Identification Number, an alphanumeric string which uniquely identifies an item

box to use to pack the item and will provide the exact quantity of packaging material to put inside the box to avoid the product being damaged during the next steps of the delivery process. Once the box is closed and sealed, the system prints a bar code label which contains the customer shipping address and information about the content of the parcel.

SLAM (Scan, Label, Apply, Manifest)

Before the final label with the address is applied, a further check is performed to make sure that the box contains the correct product. At this point the system know exactly what is content if the box and the exact weight of the item, the box and the dunnage material. Therefore, each parcel is scanned and weighted to makes sure that the correct item has been packed. In case the weight does not match the system expectation, the parcel is sent to the OOPS area (Outbound Optimization Problem Solve) where the cause of the error is investigated.
If everything is correct, the SLAM machine applies the final label to the parcel with the customer name and the address. The process of weighting and SLAMming takes a little under 1 second.

Finally, the parcels are all gathered on one conveyor which runs parallel to all the outbound dock doors. Based on the address and the CPT, the parcel is diverted toward the correct dock door. Here associates will load all the parcels onto the truck which will always leave at the CPT. CPT stands for Critical Pull Time and indicates the time when the truck will leave for the distribution center. No matter if there are still parcels in pipeline assigned to that CPT, the truck will leave at that time and the missing parcels will got to the next CPT.

3.3. Amazon Robotics

Overview

Fulfillment Centers which make use of Amazon Robotics technologies are referred to as AR FCs (Amazon Robotics Fulfilment Centers) to differentiate them from the so-called "legacy" FCs. AR FCs and traditional have several operational differences but they both share the same objective, fulfilling customer orders. Alike traditional FCs, AR FCs are classified based on the sortability of the products they handle (sortable or non-sortable). However, there are no AR FCs with mixed sortability (capable of handling both sortable and non-sortable volume) or with cross-docking capabilities. Moreover, AR FCs cannot handle special categories of products such as food or hazmat. In this sense, AR FCs are much less flexible than traditional FCs. This is one of the issues which will be further discussed in section 3.2.3.

It is important to note AR FCs do not use robots for every action performed in the FC. Robots are used to substitute the human workforce in actions which are considered non-value adding such as covering the distance between the picker and the inventory location. Therefore, robots only account for a minimal part of the total FC operations. AR FCs, like traditional FCs, are very labor intensive and they are far from reaching high degrees of automation. The objective of the following sections is to describe where and how robots are used within AR FCs, what are the key components in a AR FC and what are the advantages and disadvantages compared to a traditional FC.

Amazon Robotics System Structure

The Amazon Robotics system is made by 5 different components, all of which play a key role for a correct functioning of the system.

- Pods: The pods are the shelfs on which the inventory is stored. They are mobile and the bin configuration can be changed to accommodate the inventory assortment. Pods have a QR code glued to the bottom of the structure for identification. Drive units are equipped with a camera which reads the QR code before lifting the pod to make sure that is matches the code provided by the system

- Fiducials: it is a grid of 2D QR codes fixed to the floor. The QR codes are read by the drives' camera to retrieve information about the path to follow.
- Picking and stowing stations: these stations are the access points to the AR field. Associates are able to pick inventory from the pods to fulfill a customer order or to stow received units to replenish the inventory. The stations are engineered to make the associate-pod interaction as easy and quick as possible. Stations are located on along the perimeter of the AR field.
- Drive Units: the orange robots which travel across the floor to lift and move pods to the picking/stowing stations. They travel at a maximum speed of 1.3 m/s. The first generation of robots was developed by Kiva Systems and has been used until 2015. After the company was acquired by Amazon, the second generation has been developed and it is currently used in all AR FCs worldwide. As of today, Amazon Robotics uses two different models of drive units:
  - G-Drives: it is the smaller model and it approximately measures 40x70 cm. It is used in the sortable FCs and it can lift up to 680 Kg.
  - S-Drives: it is the bigger version and it is used in Non-Sortable FCs where bigger units are handled. It can lift and carry both heavy pods and pallets up to 1400 Kg.
- Software: a robust IT infrastructure to keep everything working and allow information exchange between the different components of the system. The software was originally built on site, now everything is run on an Amazon Web Services cloud solution.

The following photo showcases a drive unite delivering a pod to a picking/stowing station where an associate operates on the inventory.

Figure 3-2: Amazon Robotics drive unit, pod and picking/stowing station (Ackerman E., 2018)

Technical Description of the Drive Units

The following section will describe in further detail how the orange drives are built and what are their key components. The analysis of technical and electronic characteristics of the drive units is reported through the words of Ben Einstein who had the opportunity of dissembling a unit and explore its components.

"In itself, the logic of the AR drive is simple. The drive receives information from the centralized software through Wi-Fi connection. Then, it slowly travels the floor to reach the pod location, lifts the pods and then travels to the picking station. Even though the robot itself and the logic may seem simple, the overall system is very complex and allows no room for error. An AR FC has hundreds of robots and tens of thousands of pods weighting several hundred Kgs each. Pods are stored at just a few centimeters from each other, a collision between two drives carrying pods can cause a chain reaction effect and damage to huge portions of the inventory.

The internal components of the drive are protected by an external (orange) shell made of hard plastic. The front and back sides of the drive have a set of infrared sensors for collision detection and avoidance. On the top of the drive there is the X-shaped mechanism to lift the pods from the ground.
"Each robot has three independent axes of motion: two drive wheels and a motor for the "lifter." As the lifter motor spins, both drive wheels counter-rotate so the lifter appears stationary while the robot spins. This reduces the number of drive components and eliminates complex hydraulic or scissor lift mechanisms. The lifter is topped off by one of several massive aluminum castings that make up the structural components of the robot. Each part has a series of secondary machining operations to add reference able surfaces and threaded holes. Many high-quality aluminum parts are made using the same process (including automotive engine blocks and hydraulic actuators). Each IR sensor has its own filter logic built-in and communicates over a serial bus. You can also see the wireless control module and the lifter motor and giant pinion gear. Towards the rear of the bot, there are four lead-acid batteries and high-amperage bus bars. Both fairing halves are made from vacuum-formed ABS. There are a large number of features, which can only be made by multiple secondary machining setups. Both the vacuum former and

the CNC mill/router used to make these parts must be extremely large. This part is complex/expensive enough that I'd be surprised if later revisions of the Kiva bot aren't injection molded.

Rather than building full-length bump sensors, which is notoriously difficult to do on curved surfaces like those on the front/back of the bot, Kiva engineers found a simple, cost effective solution. They utilized vinyl/rubber tubing and a simple pressure sensor so that as soon as a change in pressure is detected, the robot stops all movement. The black box in the right picture receives the pressure line and aggregates all the IR sensors to simplify the protocol and wiring to the main controller.

The lifter mechanism uses a custom-designed ball screw (the single most complex and expensive component, more on that later) coupled to a standard nylon pinion gear and gearmotor (the same one used for all three axes of motion). The motor is built by Pittman (Ametek) and boasts 27 in-lbs of torque and stall power of almost 1Kw. The right-angle bi-directional gearbox is built by Brother in Japan and can handle 407 in-lbs of torque at 72rpm with a 25:1 reduction. This motor gearbox combo runs into the $1,000 range for a single set (likely much lower at volume).

Once the lifter and electronics have been removed, the bot can be flipped over to get a better look at the drivetrain. Here we see the same two motors and gearboxes paired with custom-designed cast Kiva wheels. Flanked on either end are two pairs of dual rollerblade-style 360 degree casters. This drivetrain setup supports zero radius turns.

Three sandcast aluminum parts make up the majority of the body and are joined with simple clevis pins to make a simple, passive double suspension action. They all use the same general purpose 319 alloy and are all post-machined after casting. Kiva engineers likely switched to low-pressure aluminum molding with permanent steel tools as production volume increased. Notice the cooling fins on the top of the front casting on the bottom right: the giant MOSFETs for the custom motor control circuits are resting against the backside of those fins for maximum thermal efficiency, a slick design decision." (Ben Einstein, 2016)

Electronics

“Even though Kiva bots have nearly no decision-making authority (each move is controlled by servers in the cloud), movement of the bot while lifting and controlling thousands of pounds of merchandise requires electronic components.

The system is powered by four 12v 28Ah lead-acid batteries connected in series (for 48v DC). Two of the four batteries also have custom thermocouples installed under their mounting bracket to ensure they don’t overheat.

When the power is running low, bots take themselves offline and return home to a charging station. The design of the charging port allows a good amount of slop in the mating process. I can say from experience, watching one of these bots go home to charge is pretty cool.

Tucked inside the lifter mechanism is one of the key enablers of the Kiva system: a dual-camera imaging module. One camera looks down at the ground to recognize 2D barcodes on the warehouse floor. The other looks upwards at the bottom of every pod. Each has 6 on-board red LEDs for illumination and like the rest of the robot, everything is custom designed. Sandwiched between the two imagers is an image processing board sporting an ADI ADSP-BF548 Blackfin multimedia processor which is doing the Datamatrix detection and relaying results via high-speed serial.

Tying everything together is the main logic board. Motor control circuitry is powered by 48V DC from the batteries and a separate filtered rail powers the logic/communications/CPU. The 3-phase brushless motor drive electronics are fully custom, driven by a Lattice LFXP6C FPGA (hidden under the daughterboard). Each of the three driver circuits has a current sensor, 6 high-amp FETs in full-bridge configuration (and are cooled via the chassis), input for a motor’s rotary encoder, and the giant 4-pin connector.

The daughterboard aggregates system functions by coordinating the wireless module, imaging unit, e-stop, infrared/pressure sensors, power management, and the motor drivers. The MCU is a 32-bit Freescale MPC5123 with a 400MHz clock likely running PowerPC Linux (on bare metal). The two ethernet ports connect to the wireless module and firmware flashing/external hardline connection, but they’re switched by a Mircel KSZ8993.

The only off-the-shelf circuitry on the entire robot is the communications module: the Soekris Engineering Net4526 router which sports a single Winstron NeWeb CM9 wireless module in a dual-antenna configuration, connected to the main logic board via ethernet.” (Ben Einstein, 2016).

3.3.1. AR FC Operations

In traditional FCs, the units can be stored in different storage solutions based on FC layout and sortability type. Example of these solutions are Large Aisles, VNA (Very Narrows Aisles), Picking Towers or Pallet Lands. On the other hand, Amazon Robotics FCs (AR FCs) are equipped with a single storage solution. Units are stored on mobile pods which placed on the warehouse floor. Each pod has bins of different dimensions to maximize space utilization in relation to the item size. When a unit is required, the drive units retrieve the pod and bring it to one of the stations where an associate will pick the unit from the bin. Figure 3-2 represents a simplified version of an AR FC floor. The outer black line represents the border of the floor on which drives operate. The green squares on the outside are the picking and stowing stations where associates "interact" with the inventory.

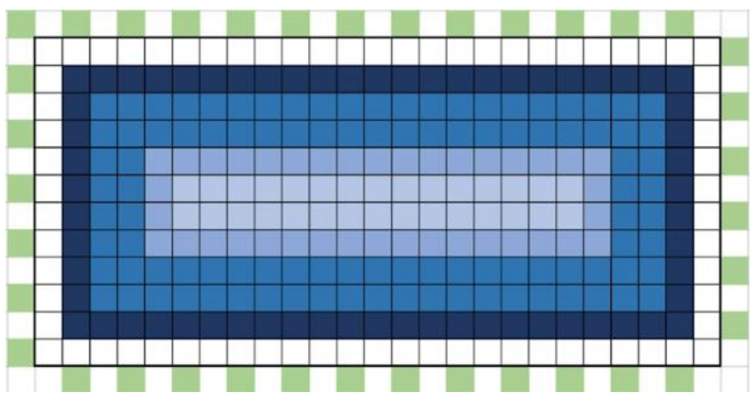

Figure 3-3 Simplified AR field

The squares in different shades of blue represent the pods on which the inventory is stored. Like traditional FCs, the units are randomly stored on the pods and in the bins. There is no criteria for bin or pod utilization. The reason for this ASIN allocation criteria is related to the unpredictability of customer demand. It is difficult to predict which products are likely to be picked together and therefore randomness is, as of now, the best allocation logic for Amazon FCs. However, the system knows which products are picked more often and it will try to keep the pods which contain these units towards the outside of the field and closer to the stations. This will allow the most frequently bought product to be picked quicker. Figure 3-3 shows the locations containing these high velocity ASINs colored in a darker shade of blue. The lighter the blue, the slower the ASIN velocity. The system knows on which pod units are stored and therefore will always try to keep the quicker ASINs toward the outside of the field.

The navigation through the AR field

The floor is divided in squares of equal dimensions identifying a grid on the warehouse floor, each square is identified by a fiducial. The fiducials are QR codes glued to the floor. When a unite drives over a fiducial, it reads the QR code and identifies on which square of the floor it is driving on. A sequence of squares in a row produces a lane which represents a sort of street on which the drives are allowed to drive. Lanes can only be oriented north to south or east to west and each lane allows movement only in one direction. In theory, each lane could also be travelled in the opposite way, but the system knows that a drive moving in the opposite direction will have a very severe impact on the "happiness" of the other drives and therefore it will try to avoid it as much as possible.

Like every road system, there are slower roads and faster roads on which the drives can move. The faster lanes are called highways and they are the quickest way to bring a pod to a picking station. For this reason, drives are not allowed to drop pods in the highways or to stop.

When waiting for an instruction, drives wait under the pods. Based on the drive and the pods location, the system will instruct a drive to pick a pod and bring it to a picking station. Like a true navigation system, the system will send directions to the drive on how to reach the correct picking station. Therefore, the drive now knows that it has to move

AR Stowing

The system will present to the associate a pod with enough free cube. It's then up to the associate to take one of the items from the tote and stow it where he/she deems it appropriate base on the pod's bin utilization. Associates are instructed to place larger items towards the end of the bottom of the bin as and smaller items towards the front of the bin. This will eventually help pickers at to identify the items to pick more quickly. Of course, there are some constraints such as not stowing items which are bigger than the bin itself or in a bin which is already very full.

Items don't have to lean out of the bin because they could fall on the ground during navigation on the floor or touch other pods. Generally, associates can stow the item wherever they want and wherever they see enough space to fit the item. The associate scans the item barcode and the bin barcode in order to record the storage location of the item. System instructed stowing has not proven to be as effective because it take much longer to identify the bin. It showed to improve cubic feet utilization (CFU) because the system is more capable at identifying less utilized bins within the pod, but it had a severe impact on stowing rates and it was abandoned. For most of the Sortable AR FCs the stowing target rate is around 300 units/hour.

AR Picking

The upstream system collecting orders knows that the item (ASIN) is stored in the FC and therefore it sends a signal to the FC system with all the relevant information to fulfill the order. The upstream system does not know where the ASIN is located in the FC, it just knows that it is available to be shipped from that FC. At this point the FC system receives the information and the outbound process can start. The system finds the pod on which the item is located and finds the closes available drive. Then, it sends a signal to the drive to pick up the pods and bring it to a picking station.

Associates arrive at the picking station and has rack with 3 or 4 totes. Each tote corresponds to a process path (singles, multis, transshipments). Once the pod arrives at the station, the screen will provide the information about the product and the bin location on the pod. Associate picks the item form the bin scans it and the system will tell him into which of the totes to place it in and a light in correspondence of the correct tote will turn on. The associate will place the item in the bin and press the light. This will trigger the next task in queue. Once the tote is full, the system will instruct the associate to move the tote on the conveyor to send it downstream toward the packing stations and pick a new tote for that process path.

Ideally, pods arrive at the picking station with a just-in-time approach meaning that the pod does not wait in line at the picking station. This would avoid congestions in the proximity of the picking station and result in a smother flow. However, like any road system, pods can find “traffic” while travelling the lanes on the way to the station and arrive later than expected. The worst-case scenario is that the picker has completed all his previous tasks but cannot perform the next pick because the pod has not arrived yet. This situation is called pod gap.

To avoid pod gaps, drive units queue in a buffer area in the proximity of the station. The buffer size is variable between 5 to 15 pods and its objective is to avoid pod gaps. At the same time, the buffer cannot be too big because the queue could block one of the highways and severely slow down drives navigation on the floor.

After the items are picked from the pods and put in totes, the process unfolds in the same way as a traditional FC. Units are sent to the packing stations where they are prepared for shipping. Then, they proceed to the SLAM phase and finally they are sorted based on destination and CPT.

Prohibited areas

It might occur than an area of the floor is disabled, and drive units cannot move on some lanes. Among the several reasons why an area of the floor might be disabled, failures and maintenance are the main ones. When an area is disabled, drive units are not allowed to travel on those lanes and cannot pick pods within the prohibited area. The picture below shows a simple example of an AR field where a drive (orange) has been instructed to pick up a pod (blue) and bring it to a station (green). Because of one of the reasons mentioned above, an area of the field is prohibited (red).

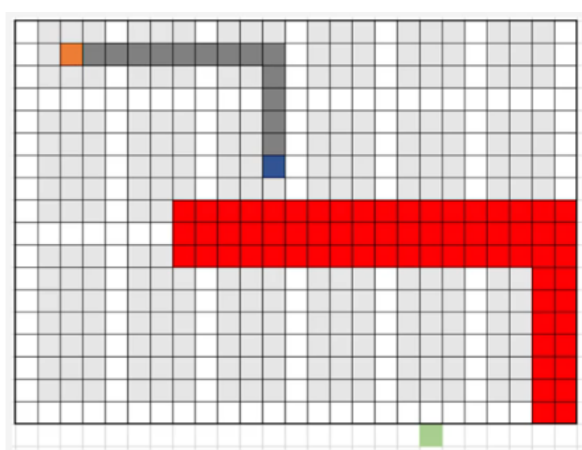

Figure 3-4 AR field with prohibited area

In an ideal scenario without prohibited areas, the drive would pick the pod, reach the closest southbound highway and deliver the pod to the station on the south side of the field

However, with the current floor status, the drive cannot proceed on the quickest way to the station. Once the drive has picked up the pod, the system will instruct the drive unit to reach the station through an alternative route. The impact of prohibited areas could be very different depending on size, location and time required to solve the issue. The possible failure modes of drive units and the overall health of the AR field will be analyzed in further depth in section 3.2.2.

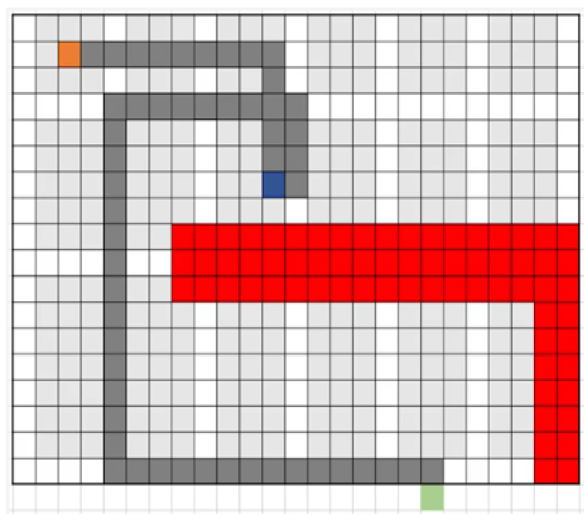

Figure 3-5 Prohibited area avoidance

Like any road system, if one of the main highways is closed, traffic will be diverted on side roads causing congestions and slowdowns. Ultimately, the impact of having part of the floor in prohibited mode means that inventory will take more time to reach the picking stations and the order fulfillment process will be slowed down. The objective of the maintenance team is to identify the failure root cause and reduce the size and the duration of the prohibited area as much as possible.

3.3.2. AR Floor Health

The following section describes the role of the warehouse floor in an Amazon Robotics FC.

In an Amazon Robotics FC, the floor refers to the surface on which pods are stored and where drives operate to lift and carry pods to the stations.

With respect to the drive units, the physical floor health of any given floor is defined as the set of physical conditions external to the drive units which prevents or hampers with the proper operation of those drive units on that floor.

More simply, it means that floor health is defined by how "happy" the drive units are. Issues with floor health can manifest in the form of drive disablements or even crashes between drives. While navigating the field, drive units record information about wheels movement, balance issues, traction on the ground and its position on the floor. This set of data ultimately determines how “happy” the units is to navigate through a section of the field. When drive happiness falls below a threshold, the drive goes into disabled mode to prevent crashes with other units.

There are several floor characteristics that are critical to long-term AR system reliability and performance. These characteristics include, but are not limited to, floor levelness, floor flatness, surface roughness, and glossiness. In order for the AR system to function reliably over the full design life, it is absolutely critical that all components of the system are within design specifications. When components of the system fall out of design specifications, major problems such as pod collisions or traction loss can arise. For complex hardware systems such as this, it’s highly impractical to verify compliance at the system level, therefore individual components must be validated against requirements to ensure that the system will function as intended when all the components interact.

During the hardware design process, tests are performed to ensure that the design will meet reliability and performance requirements. Tests are run on drive units and pod components, drives navigational tolerances, dynamic effects in the pod during movement, and floor imperfections (levelness and flatness). Maintaining sufficient clearance between system components is one of the main points of emphasis because it is crucial to system functionality. Floor imperfections are the most significant contributors in these tolerance studies because they are highly magnified by dynamic effects and the substantial height of the pods.

By qualifying all the system components individually (including the floor), it is ensured that these tolerance studies remain valid and the system will operate as intended. Once the system is assembled, this is no longer feasible. Even if a full-scale system is built and tested, a passing test is insufficient to guarantee the system will continue to operate as designed long-term or at a similar site. There are several reasons for this:

- **Manufacturing variation over time:** Drive units and pod components will change over time due to unavoidable tool wear and manufacturing variation. These components will remain in-spec, but they will change. A pod built yesterday can be slightly different than a pod built today.
- **Component wear over time:** Drive components such as linkages, turntable, wheels, etc. will change over time as they wear. This wear can introduce additional compliance in the system, resulting in change in system clearances over time (such as pod-to-pod clearance).
- **Fiducial placement variation:** As floor fiducials (stickers) are replaced over time, their new positions will differ slightly than original positioning. This shift may result in a new interference that didn't appear in an initial proof-test.
- **Pod inventory changes over time and differs between sites:** Pod inventory can have a big effect on the dynamics of the pod during movement. As pod weights and mass distributions change, a site that's functional now could experience problems in the future. A site with one population of items could perform very differently than a site in another region.
- **AR system failures cannot be pinpointed to specific root-causes:** When a drive loses traction, the root-cause is seldom determined or recorded. Since there are so many potential error codes that can be generated, the metrics can be highly misleading. Furthermore, incident reporting can vary across sites.
- **Some issues are not obvious or easily quantifiable:** As the AR system ages, new issues can arise that did not exist during the poof-test. For example, damage to items that overhang pods or high rates of amnesty due to insufficient pod clearance.

In order to guarantee AR system functionality through the entire design life, it is critical that all system components are properly qualified. The AR floor is the single most important individual component in the AR system; it merits careful validation to ensure all requirements are being met prior to system integration.

However, floor health can deteriorate with time if the surface is not properly maintained. Some of the most common items which have a negative impact on the floor health are:

- **Amnesty**: it refers to items on the floor that can get under the drive or be tangled into the wheels and cause navigation errors. Ultimately, it could cause drives to deviate from their path and crash into stationary or moving pods.
- **Floor dirt**: it can be dirt, dust or residuals of accumulated material. Like any other FC, the floor is regularly cleaned but dust or dirt could ultimately have an impact on the drives' ability to navigate properly.
- **Spills**: they could come from any of the product available in the inventory. A unit in a bin could be damaged during stowing or picking of items in the same bin. FCs store any kind of product, including greasy and slippery substances such as motor oil, dog food, talcum powder, water, and sunscreen.
- **Dirty wheels**: wheels could pick up the normal accumulation of dirt or dust or perhaps a spill that the drive unit drove though
- **Humidity**: high levels of humidity can negatively impact the friction between the floor and the drives wheels
- **Fiducial quality**: refers to fiducials which are worn, torn or dirty up to the point they cannot be read
- **Floor levelness**: imperfections on the floor such as holes, cracks floor wear or tear
- **Floor coating**: if cleaning or protection products are not applied correctly to the floor they might impact drives navigation. This refers to concrete sealants, wax or floor cleaning residuals.

It is important to emphasize some points regarding the physical health of the floor:

- Physical floor health changes over time. Conditions which were acceptable yesterday might not be acceptable today.
- Physical floor health changes from place to place, even on a single floor or even between adjacent fiducials on a floor.
- Physical floor health can be interpreted differently from drive unit to drive unit.

Tolerances

Tolerances are the errors allowed in the different components of a system. All physical systems elements have variations in measurements. The collection of all of the different tolerances of the individual elements/components of a system combine to form the tolerances of the system as a whole.

- **Tolerances are additive**: For a simple example, if a drive unit varies 1 cm as it traverses a fiducial in a straight line and that fiducial has a 1 cm variance allowed in its placement on the floor, then the tolerance of where the drive might go over this fiducial is 2cm. This means that the drive could end up between 2cm to the left or 2cm to the right of that fiducial as it passes over. Note that another drive traveling toward our example drive from the opposite direction would also have the same 2cm combined tolerance. If the tolerance of the first drive was 2cm closer to one side and the tolerance of the 2nd drive was also 2cm closer to the first one, then the drives are actually 4cm closer. This is a simplified example but there are usually more factors coming into play.

- **Tolerances are not constant**: Just because drive units go over a fiducial hundreds of times does not prove that fiducial is correct. The drive units have many mechanisms in place to compensate for issues that the drives encounter so that they can continue to operate. It is possible that some fiducial is marginal in terms of placement or coverage and the tolerances are just on the edge such that there is one chance in 10,000 that there will be an issue. On a busy floor, that one in 10,000 chances may happen several times a day.

- **There are always multiple issues**: It is often not a single item that causes an issue. Overall floor health is comprised of many separate elements. While it could certainly be affected by an obviously torn fiducial, for example, it could also be affected if a fiducial was not torn but was only slightly misplaced. Normally that single misplaced fiducial can be compensated for, but if the drive that went over it has carrying a pod that was slightly off center and there was another drive in the adjacent lane which also had an off center pod and a misplaced fiducial and these elements combined such that the pods were moved closer to each other, this might lead to a pod collision.

In a more common example, a drive unit that has a slightly off-center camera AND there is misplaced fiducial on the floor and the next fiducial after the misplaced one was covered by a piece of paper (amnesty), the drive might experience a missed too many fiducials error and disable. This is a simple, but real-world, examples of how it might take multiple issues to cause a drive to disable.

Manifestation of Physical Floor Health Issues

Floor health issues can often manifest as:

- Large/small slip errors
- Obstacles (both detected and undetected)
- Recovery failure errors
- Large/small estimator errors
- Missed fiducials or missed too many fiducial error
- Pod clipping (when the tops of two pods come into contact)
- Pod collisions

Warning Signs:

- Increasing small slips
- Increase in missed fiducial warnings
- increasing estimator warning
- General increase in drive disablements

When considering floor health, the preponderance of events on a floor must be considered. It cannot be a single drive that is used to determine physical floor health. The floor must be looked at over time and determine that the floor is having more issues than is normal (or acceptable). The floor must also be examined by location to determine if the problems are localized to a particular region of the floor or if it is spread generally throughout.

It also must be examined to determine when the issues started. There are charts in the Big Board which can show if the number of drive disablements has spiked suddenly or if it has been slowly rising over time. If the issue occurred suddenly, then an investigation must be made to figure out what actually happened. Usually it is a spill or a configuration change. If the disablements have been rising steadily over time, it is usually a sign of a need for better floor maintenance.

The point is that the behavior of many drives over time must be considered when determining floor health.

Remedies

Sometimes, there are a few drives that are producing a vast majority of the errors. These are called top offenders. These can be easily found with the big board. If there are top offenders that are obviously out of line with the other drives on the floor, then those drives should be removed from the floor and dealt with.

The site needs to take a large role in figuring out what is wrong. In many cases the onset of drive disablements is (i.e. large numbers of drives started disabling at a particular time) and it is up to the site to figure out what happened to cause that. Usually changes to configurations can be ruled out quickly and there is nothing obvious that changed to cause the sudden increase. In these cases, it must be the local site that determines what happened. Often it is a floor spill, but there have been cases when it was a floor cleaning product (like a floor wax) that reduced the floor traction to cause the drives to start slipping.

If the issues have been slowing increasing over time, then this is generally a sign that the floors are getting dirtier. In this case they must be cleaned. However, depending upon the situation, it may also mean that the drive wheel need to be cleaned. As was stated earlier, it is really up to the drives to decide when the physical conditions have improved to the point where disablements no longer occur.

Considerations on Floor Health

Ultimately it is up to the drive units if the physical floor health is good. The drive units base their reaction to their environment upon the culmination of a number of factors. The drive units do everything they can to compensate for errors and other unexpected conditions. However, when the conditions are such that the drive can no longer compensate sufficiently, then they start to disable or eventually crash.

It is not up to the local site to determine if the floor health is sufficient. The sites many try all sorts of actions to address the problems but if the drives are still experiencing issues, then the floor is unhealthy. Many sites have expressed frustration that they have followed a cleaning program or have inspected fiducials and yet disablements remain. Frustration in that case is understandable, but unfortunately does not address the issue. In such cases, the local site needs to figure out what is making the drives unhappy and address whatever combination of items it takes. On the literally dozens perhaps hundreds of calls on this same topic, it often cannot be isolated to a single point cause as to what is making these issues occur. Often is it a combination of multiple events that all combine to contribute to the issue and fixing one such element may have no effect.

The solution is always the same: lower the drive accelerations to the point where their drive behavior reaches an acceptable level. It is up to each site to determine what that acceptable level is.

The best practice for maintaining or improving floor health is to address the floors holistically. Focusing on just cleaning the floor, for example, often will have no noticeable effect. However, clean floors are one critical item that must be maintained. So is maintaining proper fiducials health.

3.3.3. Advantages and Disadvantages of an AR FC Compared to a Traditional FC

Since 2006, Amazon's revenue has grown by at least 20% Year on Year and reached peaks of +40% in 2010 and 2011. One if the key success factors that fueled Amazon's growth are speed and on-time delivery. Over the years Amazon has significantly improved its supply chain performance to improve customer satisfaction and, ultimately, to deliver parcels quicker. Speed can be increased at any point of the supply chain with the overall objective of offering customers a better (quicker) promise. The deployment of an improved version of the Kiva System allowed the American retailer to further automate its Fulfillment Centers and reduce the costs of its operations. The following sections analyze what are the impacts of such technology.

3.3.3.1.Advantages

The following section describes what advantages AR FCs have brought to Amazon Operations and Fulfillment Center management.

Increased Storage Utilization

When analyzing a warehouse storage area, there are two key metrics to take into consideration, storage density and storage utilization. Storage density is measured as follow:

$$Storage\ Density = \frac{Total\ Storage\ Volume}{Total\ Warehouse\ Volume}$$

It identifies how much of the total warehouse volume is employed for inventory storage. Storage density is determined during the design phase of the FC. Therefore, it is difficult to expand or reduce and it is considered as fixed. However, measuring storage density with this formula yields a gross measurement of the overall volume of the FC dedicated to storage. It does not consider shelves, aisles and the frames to hold the bins. To calculate net density, the sum of the net volume of each individual bin is to be taken into consideration. Assuming that all bins have the same size and volume, net density is calculated as follows:

$$Net\ Density = \frac{\sum_1^n (Bin_n\ Net\ Volume\ \times\ fill\ rate)}{Total\ Warehouse\ Volume}$$

Considering the fill rate, AR FCs do not perform better than traditional FCs. The bin fill rate is a percentage measure which indicates how much of the net volume of the bin is filled by inventory. Both AR FCs and legacy FCs have bins of different dimensions to stow items of different dimension and the stowing logics are equal. It is up to each associate's capability to maximize the usage of each bin. Therefore, AR FCs do not bear any substantial advantage over legacy FCs concerning net inventory density. However, the real advantage of AR FCs relies in the number of bins the can fit per square meter. With comparable fill rates but with a higher number of bins per squarer meter, AR net density and space utilization are much higher.

Storage space utilization indicates what is the storage volume (either net or total) per square meter and it is defined by the formula below:

$$Storage\ Area\ Utilization = \frac{Total\ Storage\ Volume}{Total\ Storage\ Area}$$

AR FCs can store almost 48% more inventory per square meter compared to legacy FCs most dense solution, the pick tower. This substantial increase in storage area utilization is driven by the structure of the AR system.

A legacy FC with a traditional pick tower or library-deep storage needs wide side aisles between the shelves to allow at least two picking carts to navigate through the aisle, allow maneuvering room and some tolerances. Picking/stowing carts are pushed by associates who don't have the same navigation accuracy of a robot and therefore need increased tolerances to push the cart at a quick pace without bumping into the shelves. On the other hand, AR FCs do not need big tolerances to allow drive and pod movement through the field. Because of the fiducial matrix on the floor, drive units can travel the lanes with more accuracy. Therefore, the space saved with reduced tolerances is used to fit more inventory per square meter.

Another important gain in terms of storage utilization is given by the structure and the layout of the pods. In traditional FCs, the highest storage area utilization is provided by the pick tower. The pick tower features four or five floors of parallel rows of aisle-facing bins. This implies that every bin needs to have an aisle from which it can be accessed. Therefore, as it can clearly be observed in the picture below, roughly 50% of the surface of the pick tower is occupied by the aisles.

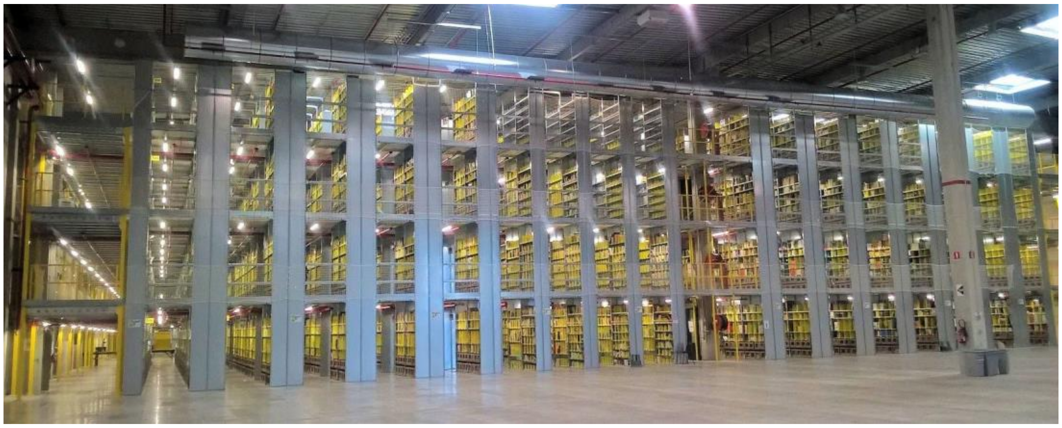

Figure 3-6 Traditional FC pick tower

In AR FCs, bins do not need to be accessed at any time as the only point of contact between the picker/stower and the inventory is at the stations. Therefore, the pods can accommodate bins and inventory on all the four sides of the bin. As mentioned before, the size of the bins is the same as in traditional FCs but the layout of the filed allows bins not to be accessible at any point of time and this results in more inventory per square meter. The picture below shows the AR field of a North American FC.

Because of lower land costs and more permissive fire regulations, North American AR FCs tend to have very extended AR fields operating on a single level. In Europe, where land is more expensive, AR FCs operate on several independent floors (up to 4 levels) to maximize surface utilization.

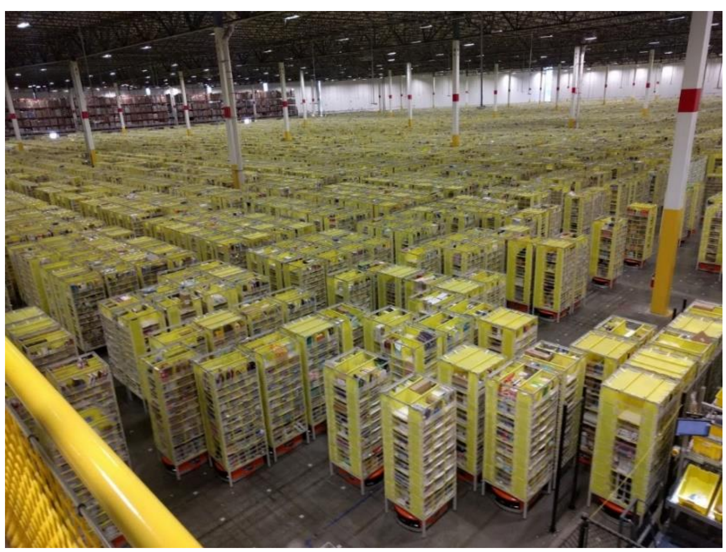

Figure 3-7 AR filed

Higher speed and higher rates

Amazon fulfillment strategy has always been oriented toward delivering parcels to customer in the shortest time possible. To improve delivery speed, every segment of the outbound supply chain has to be more efficient and, most importantly, to be executed quicker.

Even before ordering, the website offers a promised delivery if the item is ordered within a certain time-frame. The example below indicates that we are approaching the order deadline for a next-day delivery. This delivery promise is based on the current fulfillment network situation and other factors such as specific FC outbound congestions and transportation schedule.

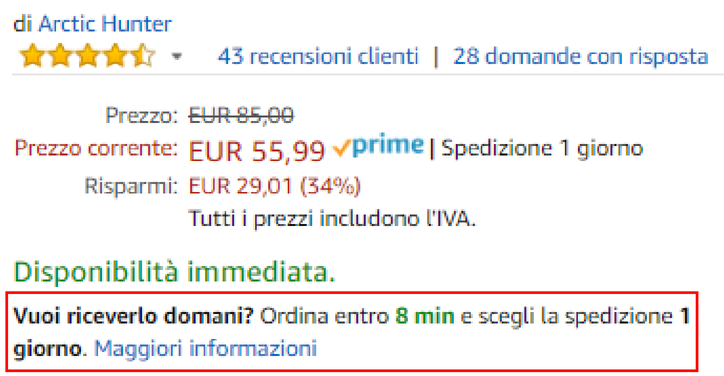

Figure 3-8 Delivery promise example

The order fulfillment process starts when the customer places the order. Then, the centralized system decides from which FC the order is going to be fulfilled to meet the delivery promise. Each FC will then identify in which bin the item is located and create a picking instruction. In a traditional FC, the picking instruction is sent to a picker’s hand scanner. The picker will find the bin, pick the item and place it in a tote to be sent to the packing stations. The time between when the order is placed by the customer and when the item is picked is called click-to-pick time.

In traditional FCs the click-to-pick time is, on average, between 50 and 65 minutes depending on how many associates are currently working on the shift and how “busy” they are at picking previous orders. In AR FCs the click-to-pick time has been reduced to an average of 20 minutes.

Although this improvement seems marginal compared to the total time between order and delivery, it is one of the key components of the order fulfillment process and it fits Amazon's objective of accelerating the delivery. In traditional FCs, click to order time takes between 25% and 35% of the total time an item requires to be ready to be shipped. In AR FCs, it only takes up to 15% of the total time. Assuming that the throughput of the downstream processes is equal, a reduced click-to-pick time implies that the total time required to fulfill the order is reduced.

The reason why the click-to-pick time is reduced by more than 100% is the result of much higher picking rates in AR FCs. Picking rates are measured as number of items picked in a determined unit of time, usually 1 hour. In legacy FCs the target picking rate is 110 u/hr while in AR FCs the target is at 320 u/hr meaning that AR picking is almost 3 times higher than standard picking. This is driven by the change in picking methodology, from Person-to-Goods (PTG) in legacy FCs to Goods-to-Person (GTP) in AR FCs.

The PTG methodology requires associates to walk to each single bin and the travel time accounts for more than 60% of the total picking time. Therefore, associates spend most of their time on a non-value adding and extremely tiring task. On the other hand, GTP systems eliminate the travel time between bins locations and present the pod to the picking station without any human intervention. The advantage of the GTP systems deployed in AR buildings is not restricted to performance improvement but it is extended to associates' health and engagement. It saves associates from covering several km walking every shift while pushing carts therefore reducing chances of injuries, fatigue and ultimately absences due to illnesses.

Cost savings

Amazon's value proposition is focused on offering a large selection of products at low prices and with a fast delivery promise. To consistently deliver this value to customers, the company has always invested to expand its fulfillment network with the opening of several new fulfillment centers every year. Depending on size, layout, throughput, location and numerous other factors, the cost to build a traditional fulfillment center ranges from $100M to $300M. However, equipping the FC with Robotics solutions requires an additional investment which ranges between $20M and $30M. The additional cost to set up the AR field changes according to the number of drive units and the number of picking/stowing stations.

The initial investment is covered by lower operating costs. The operating costs of a AR FC are reduced by 21% compared to traditional FCs mainly driven by labor costs reduction. Thanks to higher stowing and picking rates, Robotics FCs require less staffing to stow and pick inventory.

Despite several investments to optimize the e-commerce cost structure, Amazon is still facing rising costs compared to its net sales. Competitors are catching up with Amazon's supply chain performance in terms of speed and inventory selection and the American retailer is struggling to squeeze profits out of its e-commerce operations. The chart below underlines the increasing cost pressure that Amazon is facing with fulfillment and shipping costs rising at a higher rate than net sales.

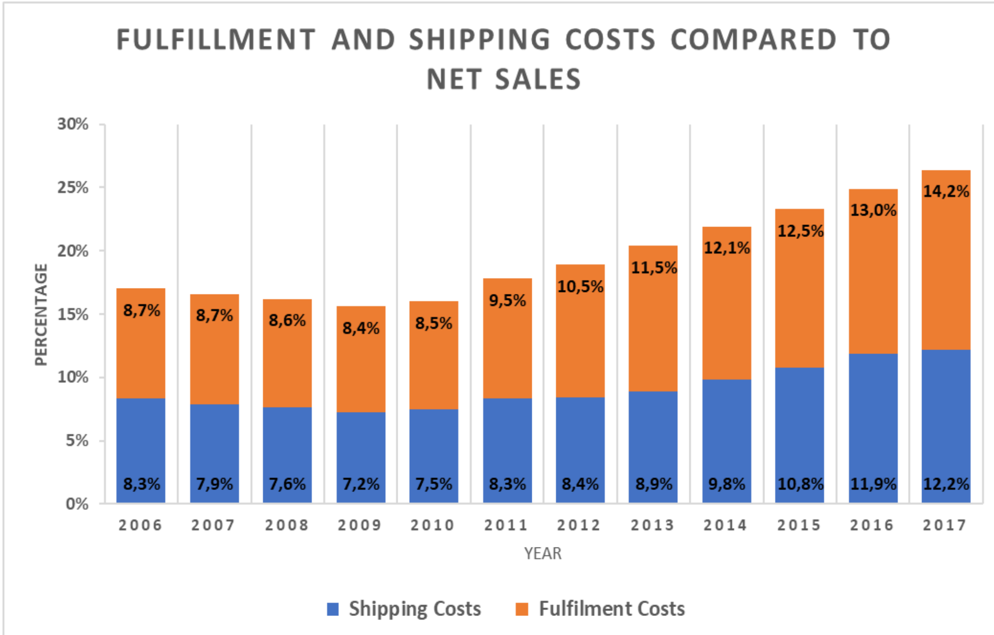

Figure 3-9: Amazon Fulfillment and Shipping Cost compare to Net Sales (Statista.com, 2018)

The acquisition of KIVA Systems in 2012 and the subsequent implementation of AR FCs are the first steps toward build a more cost-efficient supply chain. However, the majority of Amazon fulfilment network is still running on the traditional FCs. In the United States, around 20% of the volume is handled by Robotics FCs while in Europe it is limited to 13%. As of early 2018, Amazon has deployed 100,000 robots in 25 out of its 138 North American FCs (both existing and planned to open soon). AR FCs have operating costs reduced by around $22M per year compared to legacy FCs. If all the remaining 115 FCs were to be turned into Robotics, the total annual saving on fulfilment costs would be $2.5B. However, installing and deploying an AR field costs $20M per location resulting in a $2.3B investment to turn all traditional FCs into Robotics. Comparing the $2.3B one-time investment and the $2.5B recurring annual saving, Amazon's payback time would be 11 months.

However, it is unlikely that Amazon will transform its legacy Fulfilment Center into Robotics sites. To accomplish this metamorphosis, Amazon would have to shut down operations in the site for a period of at least 5-6 months, transfer all the inventory to other locations, dismantle the current layout and install the Robotics technology. The cost of not being able to fulfil demand from one FC is unknown but it would put the remaining nodes in the network under tremendous stress and increase transportation costs to fulfil orders from other FCs.

3.3.3.2. Disadvantages

AR FCs have undeniably increased Amazon's efficiency and order fulfillment speed, but they also present some disadvantages compared to traditional Fulfillment Centers. The following sections describes the main limitation of Robotics FCs and why, in given occasions, their performances are lower than legacy FCs.

Flexibility

Amazon's e-commerce is a very seasonal business, peaking in Q4 of every year when Christmas approaches. Every year, an increasing number of customers decides to shop on Amazon for its Christmas gifts avoiding the hustle of busy shopping malls. Q4 (Peak) also brings two major shopping events for Amazon, Black Friday and Cyber Monday. Both days are characterized by big discounts on every product category which attracts further customer demand. The chart below shows Amazon's quarterly net revenue for the past 10 years. Q4 accounts between 30% and 40% of the yearly net revenue.

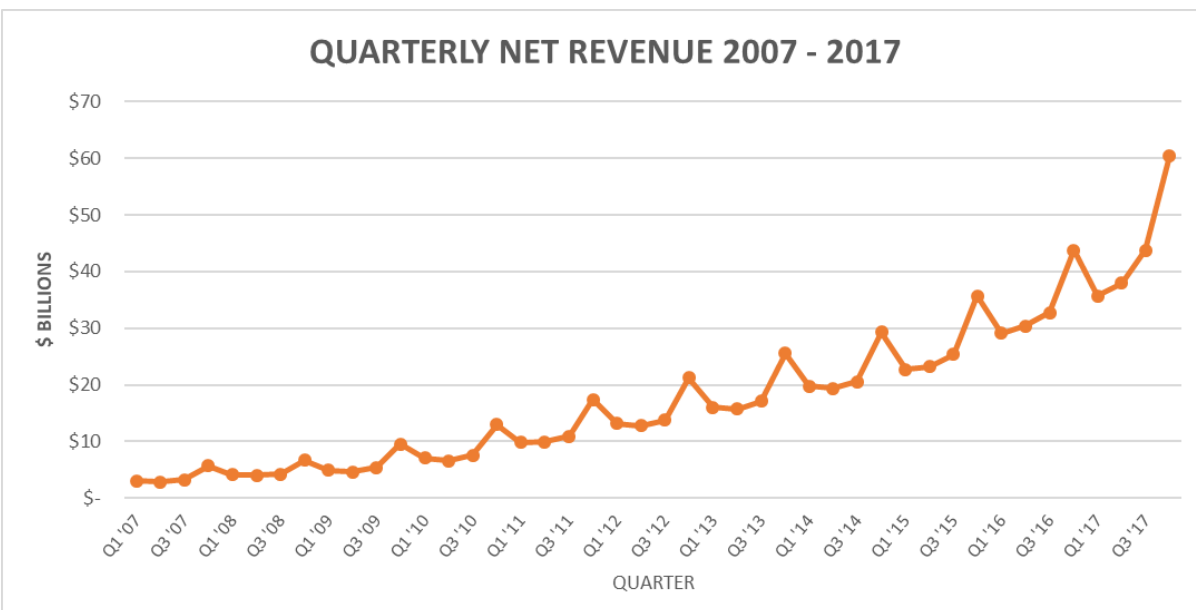

Figure 3-10: Amazon Quarterly Revenue 2007-2017 (Statista.com, 2018)

The benefits and the convenience offered by Amazon during Q4 put the fulfillment network under tremendous pressure. FCs across the globe start to prepare for Peak several weeks in advance. Preparation includes increasing inventory selection and quantity to fill the FCs at maximum storage capacity. During the month of December, inbound operations are reduced, and the workforce is shifted to maximize outbound shipments.

Trough peak season, traditional FCs ship almost double the number of units they ship off peak and they achieve it by doubling the workforce. For peak 2017, many of the European sites hired almost 1,500 workers on top of the 2,000 full-time employees, in total Amazon hired 100,000 temporary people worldwide. Robotics FCs are not able to ramp up with similar figures. They are machined constrained by the number of stations and the number of drive units on the field. Therefore, no matter how many people work in the FC, the performance will always be limited by the number of stations:

$$Max\ Throughput = \sum (stations)\ x\ picking\ rate$$

AR FCs do not have the flexibility to respond to demand with high volatility. Designing and deploying a Robotics FC with the capacity of withstanding peak requirements would be too expensive and half of the stations would only be used for one month per year.

AR FCs face the issue of reduced flexibility all year round. Amazon's associates staffing and hiring decisions are based on 8 weeks outbound forecasts. Given the forecast for customer orders, the FC will hire or dismiss temporary workers accordingly. The objective of this policy is to reduce idle time and maximize the utilization of the available workforce. This strategy works perfectly in traditional FCs where there is no machine constraint and, ultimately, the number of associates picking determines the overall throughput of the FC.

However, AR FCs have more difficulties in applying the same strategy. The picture below represents a simplified AR field with all the picking stations active (green).

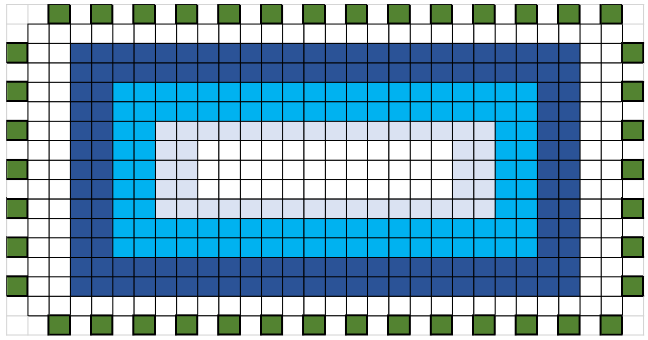

Figure 3-11 Simplified fully staffed AR field

The pods containing the inventory are colored in different shades of blue based on their ASIN rotation. The most requested ASINs (dark blue) are stored in the prime locations toward the perimeter of the field to be closer to the stations and be picked quicker. The less an ASIN is requested (lighter shades of blue), the more it is going to be stored toward the center of the field.

If the field is completely staffed (figure 3-8), then the AR field runs smoothly at its maximum capacity and the click-to-order time is optimized. However, if we consider a different level of staffing, the performance is worse. The picture below represents the simplified AR field where only half of the stations is staffed with pickers (green) and the other ones are not operating (red). In this situation, there is high rotation inventory stored in the West area of the field. This section of the field is far from any of the active stations and the result is that the order-to-pick time could double. Moreover, it takes several days of operations to move all high rotation inventory toward one side of the building while stations staffing varies on a shift basis.

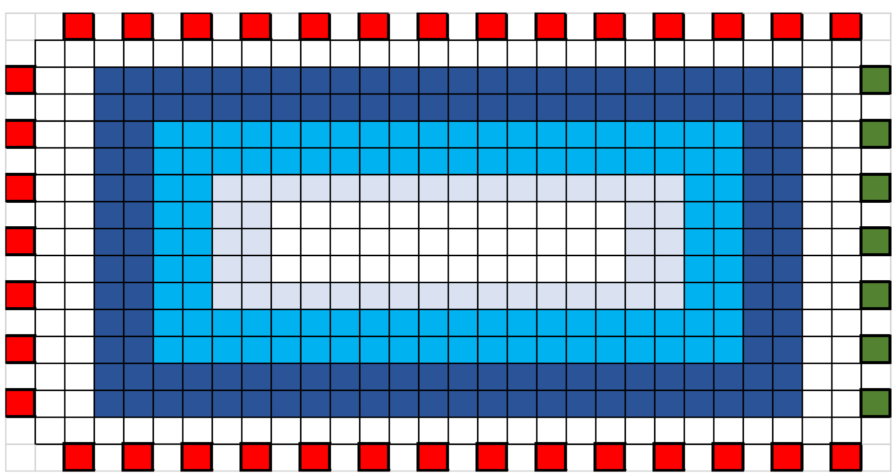

Figure 3-12 Simplified AR field with reduced staffing

The previous example was and extreme stretch of the AR operations stiffness. Most of the AR FCs have access to the field only from 2 opposite sides as reported in the picture below. Usually, one side is used of stowing and the opposite side is used for picking. This layout follows the natural flow of units from the inbound area toward the outbound dock and simplifies the network of conveyor belts required to transport the totes within the FC. However, is still requires constant staffing to work properly.

During peak and special days such as Prime Day, Black Friday and Cyber Monday, the focus is on maximizing outbound performance. To achieve this performance, the stowing stations are utilized for picking. The result is that suddenly, drive units would be required to bring high rotation inventory toward the opposite site of the building with the effect in diluting order-to-pick time.

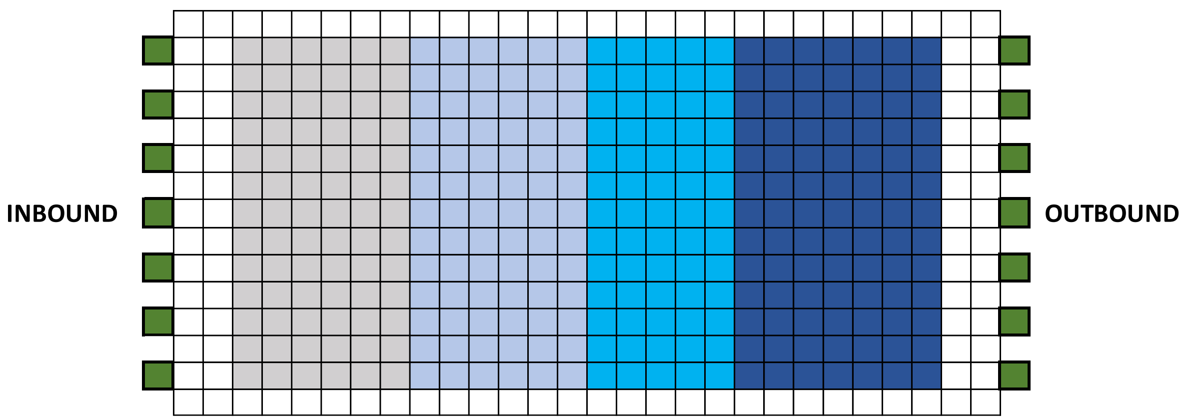

Figure 3-13 Simplified 2 side AR field

Final Considerations on the Implementation of Robotics Technologies in Amazon Fulfillment Centers

In conclusion, the implementation of robots in Amazon FCs has undeniably increased the efficiency and speed of the order fulfillment process, while lowering fulfillment expenses and increasing storage area utilization. It removed walking from bin to bin which was a tiring and non-value adding task for associates to perform and substitute it with ergonomic stations. With the total acquisition of Kiva Systems in 2012, Amazon has secured one of the most advanced goods-to-picker systems on the market and, with the subsequent cancellation of previous Kiva deals with other companies, the company has cut out its competitors. However, like any robotic deployment, it presents limitations in terms of adaptability to a very volatile demand and it is still very far from being completely automated. As a matter of fact, Amazon has “only” automated the walking between inventory locations. Any other action performed within the FC, both in inbound and outbound, is still very labor intensive and Amazon is very far from full automation.

Conclusion

Within the field of supply chain development, automation technologies play an increasingly important role. Competition and customer expectations are putting e-retailers under tremendous stress. It is difficult for human workforce to achieve the required level of performance and companies are looking at automation as the solution to reduce costs, increase efficiency and edge the competition. The adoption of automation technologies is as step process, starting from small ergonomic improvements for human workers to full robotics implementation and operation. From trailer unloading, to transportation until to last-mile delivery, e-commerce businesses are striving for automation. Amazon has proven that humans and machines can operate together to achieve better performances. The Robotics Fulfillment Centers provide better space utilization and improved order-to-pick times which ultimately result in being able to deliver parcels quicker to the customers. The Robotics system eliminates the walking previously required to pickers and stowers which improves the working conditions and reduces health and safety issues. However, automation still comes at cost. Machines perform better than humans on repetitive task, but complex and automated systems are rigid and do not provide the flexibility of human workers. Nowadays, automation is a good compromise but not a definitive solution. It represents a transition phase until robots will inevitably perform every manual task better than human and will have superior adaptability skills.

On a general level, process automation is easier to implement where there is no direct interaction between humans and machines. Drones, autonomous vehicles and robots excite the industry for their potential impact on supply chain efficiency, but they scare the public. People and machines are already starting to work together in factories and drive alongside each other on public roads but governments and legislators are struggling to find appropriate regulations for these technologies which perform better than humans but do not have consciousness, yet. The role of human workers will undeniably change, operators will become supervisors and repetitive tasks will be drastically reduced in favor of more value-adding and creative functions.

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