



## Algoritmo de optimização para cacifos modulares

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## **MODULAR PARCEL-LOCKER OPTIMIZATION ALGORITHM**

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**2021/2022**

Instituto Superior de Engenharia do Porto  
DEM



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## **LOCKER PI**

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Dissertação apresentada ao Instituto Superior de Engenharia do Porto para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação do Doutor António José Galvão Ramos.

**2021/2022**

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## **PALAVRAS-CHAVE**

Ferramenta de apoio à decisão, otimizar, ocupação, cacifos

## **RESUMO**

Este projeto foi desenvolvido em contexto teórico com o intuito de criar uma ferramenta de apoio à decisão na alocação de cacifos para entrega de encomendas com o objetivo de otimizar a utilização de recursos das empresas que prestam estes serviços.

Neste projeto foi desenvolvido um algoritmo linear inteiro em junção com heurística de modo a resolver um problema de alocação de cacifos modulares. Estas torres de cacifos podem ter várias configurações pois permitem a integração de cacifos de 3 tamanhos diferentes. O objetivo é criar uma ferramenta que em função de uma determinada procura, retorne o número de torres de no máximo 3 configurações que nos melhor ajudarão a diminuir a rotura com o menor número de torres possível. Após a criação deste algoritmo 3 iterações do problema foram estudadas, a primeira onde o modelo tinha como objetivo responder á média da procura, o segundo onde o objetivo era responder ao dia em que mais espaço era necessário e o terceiro onde o objetivo era responder a 95% da procura gerada pela função que a gerou. Os resultados foram estudados e comentados.



**KEYWORDS**

*decision support tool, optimizing, occupancy, lockers*

**ABSTRACT**

*This project was developed in a theoretical context in order to create a decision support tool in the allocation of lockers for parcel delivery with the objective of optimizing the use of resources of the companies that provide these services.*

*In this project, an integer linear algorithm was developed in conjunction with heuristics in order to solve a modular locker allocation problem. The locker-towers can have several configurations as they allow the integration all of lockers of 3 different sizes. The objective is to create a tool that, depending on a specific demand, returns the number of towers of a maximum of 3 configurations that will best help us to reduce the breakage with the least number of towers possible. After the creation of this algorithm, 3 iterations of the problem were studied, the first where the model aimed to respond to the average demand, the second where the objective was to respond to the day when more space was needed and the third where the objective was to respond to 95% of the demand generated by the function that generated it. The results were studied and commented.*



## ABREVIATION LIST

### Abreviations

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PI	Physical Internet
DI	Digital Internet
MAC	Media Access Control
RFID	Radio Frequency Identification
ID	Identification
DC	Distribution Centers
LIP	Location Inventory Problems
B2C	Business to Consumer
MILP	Mixed Integer Linear Problem
EOQ	Economic Order Quantity
SC	Supply Chain
VBA	Visual Basic

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# INTRODUCTION

- 1.1 Motivation
- 1.2 Goals
- 1.3 Structure



# 1 INTRODUCTION

## 1.1 Motivation

In the beginning of society everything was physically connected, people spoke only through word of mouth, objects had to be delivered hand to hand. With progressive technology advancement as well as the organization of society these interactions started to become more effective. People started to communicate through letters, telephones and finally through the internet. Information flows through us at an unimaginable scale for any single human. The objects however could not keep up this evolution due to their physical and intrinsic characteristics. They have volume, weight and cannot be easily dismembered and assembled at the destination like it is done with information today. People rely on shipping companies and delivery couriers to transport their goods. Another step in organizing this system needs to be implemented. With the growth of the internet came the growth of e-commerce and online delivery to an outdated infrastructure that does not optimize its resources. With today's fast paced life, it is unthinkable to stay at home from 9am to 4pm waiting for a package that might, in some cases, be miss delivered. The implementation of pick-up locations has already started to take place, it is not however, optimized in any degree. The installations are rudimental, standardized and not thought with the intent of keeping up with the market. For this reason, an innovative approach is proposed, one that had the ability to change its size and characteristics to adapt to market demand and with an easy and organic growth capability that can be scale up organically. The goal is to create an easy flowing network that allows for physical objects to travel effortlessly from the sender to the receiver at a minimal cost and in a brief time window.

## 1.2 Goals

This report aims to create a tool to help the decision making of locker companies to reduce costs without compromising customer satisfaction and to leave behind the option of a standard locker facility when the next step in parcel locker innovation is given.

### 1.3 Structure

With all this in mind the report will follow a structure where:

Chapter 1 introduces the subject of the report while explaining the importance and motivation that led to this theme. Also, the goals aimed with the development of this tool are mentioned and explained. Finally, it summarizes the structure of the report itself.

Chapter 2 focuses on an extensive and comprehensive reading of existing work, previously related projects and opportunities to combine lockers with other innovations such as the physical internet. Besides existing projects, it also contains mentions of future or in development ideas that could be interesting in this context.

Chapter 3 goes through the problem at hand and building the mathematical model. It also explains how the model was tested, this includes the creation of the data instances, results and sub-sequent analyses.

Chapter 4 contains the conclusion and recommendations for future follow-up work.

# LITERATURE REVIEW

- 2.1 Physical Internet and lockers
- 2.2 Case Studies
- 2.3 Location Problems
- 2.4 location-Inventory Problems



## 2 LITERATURE REVIEW

This chapter serves to explain some key notions that are important to the problem as well as provided some context to the locker solution.

Another very interesting part of this chapter are the different parcel-locker solutions already implemented throughout the globe and possible evolutions of the infrastructure.

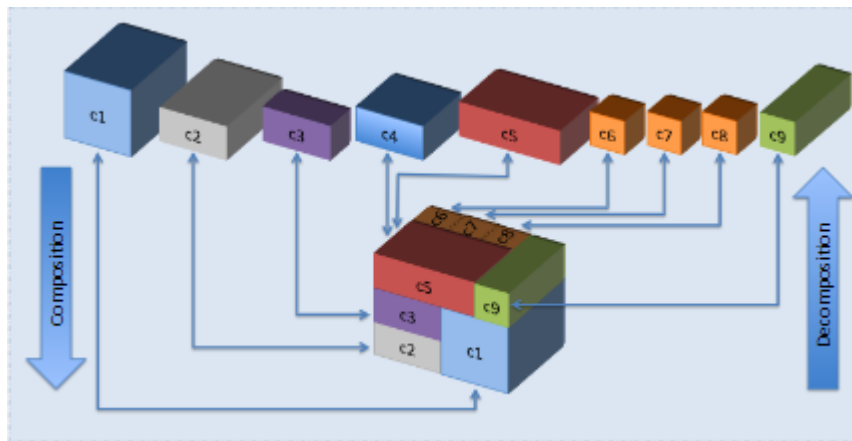
### 2.1 Physical Internet and lockers

#### 2.1.1 Physical internet

The Physical Internet (PI), first introduced as a response to the Global Logistics Sustainability Grand Challenge (Montreuil, 2011), was defined as an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols (Montreuil et al., 2010) with the goal of reducing delivery times through buffering (Crainic & Montreuil, 2016) and CO<sub>2</sub> emissions, inefficiencies, as well as overall traffic in cities and metropolitan areas. It is common to use the Digital Internet (DI) has a metaphor being that the two concepts have a lot of similarities. The same way the DI has protocols that encapsulate the data allowing it to flow easily through a network of routers the PI would have its own protocols to allow physical objects to travel to its destination passing through nodes or  $\pi$ -hubs.

The system centers around standardized, smart containers with the ability to snap together, as shown in Figure 1, to minimize transportation difficulties. They are called  $\pi$ -containers (pi-containers) and are easily trackable and identifiable through RFID-like tags with a unique identifier, similar to a MAC address in the DI (Montreuil et al., 2012) which allows for better identification, monitoring, traceability, faster storage, selection, and shipping. Because the PI ships physical objects within modular containers, these objects should be designed in a way that optimize the usage of the PI, avoiding the shipping of air and in the smallest container possible. The key functional features of  $\pi$ -containers are (Montreuil et al., 2012):

- Encapsulating merchandise so that it is not dealt explicitly by the PI;
- Multiple modular sizes, starting in small packages up to cargo containers;
- Easy flow through multiple types of transports ( $\pi$ -trucks,  $\pi$ -boats,  $\pi$ -planes), handling and storage facilities;
- Easy to handle, transport, store, seal, interlock, load, unload and dismantle;
- Smart tag enabled with sensors that allow identification, tracking and routing;
- Low environmental footprint allowed by environment friendly materials;



- Sealable for security purposes.

Figure 1 - Illustrating the modularity of unitary and composite  $\pi$ -containers

Modularly sized from small parcels to large maritime containers, the PI containers move through distributed, multimodal transportation networks in which transit sites aggregate containers from diverse origins to optimize the loading on the next segments. Open logistics facilities such as open semi-trailer transit centers, open cross-docking hubs and open warehouses are part of the interconnected networks, enabling a global Logistics Web (Montreuil et al., 2012). The nodes of the Physical Internet allow for routing or storage of the  $\pi$ -containers as well as gateways interfacing with agents out of the PI.

The Physical internet relies on standardized unloading, orientation, storage and loading operations when handling  $\pi$ -containers in a smart automated or human assisted way (Montreuil, 2011) so that it can maintain the same level of operation in different parts of the globe.

In the Physical Internet all that material handling and storage systems deals only with  $\pi$ -containers that operate with innovative technologies and processes taking advantage of the characteristics of the  $\pi$ -containers that allow for a fast, cheap and reliable input, handling, assemble, disassemble, monitoring and output in a sustainable way only achievable through a combined effort of automation and human handling.

All  $\pi$ -containers handling, and storage facilities should follow these capabilities (Montreuil, 2011):

- Enabling fast and reliable input and output performance;
- Seamless interfacing with vehicles and systems moving products in and out, as well as with client software systems for tracking and interfacing with  $\pi$ -containers;
- Monitoring and protecting the integrity of  $\pi$ -containers;
- Securing the  $\pi$ -containers to the desired level;
- Providing an open live documentation of their specified performance and capabilities and of their demonstrated performance and capabilities, updated through ongoing operations

These sites, facilities and systems can be defined by:  $\pi$ -transit,  $\pi$ -switch,  $\pi$ -bridge,  $\pi$ -sorter,  $\pi$ -composer,  $\pi$ -store,  $\pi$ -gateway and  $\pi$ -hub, each of these is dedicated to  $\pi$ -containers and they are designed to perform smoothly, they are streamlined and standardized than their counterparts.

In the Digital Internet, the data packets do not travel directly from the source to the receiver, they pass through a combination of routers and cables in an optimized way that through routing algorithms assure that the data packets arrive in the best way possible. They are not even required to travel together; they can make different paths depending on the restrictions of the networks and are reconstituted upon arrival of the final packet at the desired destination. In a similar way the Physical Internet wants to change the point-to-point transport that dominates current logistics.

One of the biggest problems of current logistics is that trucks do not start their journey completely full due to packaging and geometrical constraints of the cargo, besides that some of the times they would get emptier as the trip goes on and in a lot of cases, they would return empty or must travel a long distance to pick up new cargo in order to optimize the return trip. This is not good for the shipping company, or the environment and it is not good for the driver that must spend a lot of days away from home in these long trips. With the physical internet these trips would be much shorter because instead of driving the truck to the final destination the driver would drive it to a designated  $\pi$ -hub much closer to him compared to the final destination and would unload it there where it would be picked up by the next driver and driven to the next  $\pi$ -hub in the designated journey and so on until the content reaches its final destination, the empty driver would then pick up a new delivery and drive it to his initial  $\pi$ -hub in the optimum scenario such as demonstrated in "Towards a Physical Internet: Meeting the Global Logistics Sustainability Grand Challenge" by B. Montreuil.

The changes required for this scenario to be possible are:

- Different carrier and/or modes performing inter-nodes segments
- $\pi$ -hubs and nodes allowing for synchronized transfer of  $\pi$ -containers
- Web software platform enabling an open market of transport requesters and transport providers

The difference between Digital and Physical Internet is that on the second one every move of a  $\pi$ -container and every physical operation is costly. Second, every one of these takes time. This time allows planning in a way not possible for the Digital Internet, this planning can be researched and optimized in a way only possible for the PI. When a  $\pi$ -truck departs from the origin there are numerous hours to plan where its contents should be allocated upon its arrival at the receiver hub. The shippers would just define to their  $\pi$ -containers the destination, time of departure and their budget. Because of the smart and connected nature of the  $\pi$ -containers along with the connectivity of the Physical Internet elements, decisions would be made on the moment by the  $\pi$ -containers, adjusting it dynamically when presented with new information. They would report back to the shipper only in special situations that would forecast a delay on the arrival or when their integrity has been compromised.

Another option removes these decisions from the  $\pi$ -container and places them on to an agent that gets feedback from the container and transmits it back to the  $\pi$ -container and the PI elements involved in the route.

These options both rely on the logistics provider exploiting the nodes, hubs, links and movers to secure a fast and safe route. With these comes the opportunity to make deals for routine, and schedule daily shipments for a 2-year period for example, which could benefit from lower rates in order to keep a steady flow of deliveries.

Instead of relying in private supply chains or networks, the PI also allows for companies to cooperate and share their facilities such as factories, warehouses, and distribution chains, an Open Global Supply Web, in order to gain a competitive advantage in the market as a first level, the second being open warehouses, logistic centers and facilities dedicated to product finishing and assembly. This solution allows for a company to explore new markets without a big initial investment. It also allows for more proximity to the final customer cutting down delivery time and overall logistic costs.

Supply Webs or interconnected networks composed of supply chains, distribution channels and facilities work according to the following characteristics:

- Their nodes are only accessible to most producers, distributors, logistic providers, or retailers that follow the guidelines proposed;
- The service of the Supply Webs capacity is available on demand;
- Dynamic and intertwined virtual private networks are created by agents to develop and realize the products, services and solutions in anticipation of demands from clients

In the current logistic systems, most warehouses face a low number of different companies within them, most of them by the same enterprise. On the other hand, most enterprises operate in a small number of warehouses or distribution centers. In the PI, due to the fact that products and materials are handled, moved and stored on modular, standard, smart and safe  $\pi$ -containers allows for warehouses and distributions centers to accept work with from a much greater pool of clients without having to accommodate specific products as long as they respect the guidelines in which these  $\pi$ -containers are designed to work. The Global Open Supply Web is characterized by multiple product realization centers, distribution center, warehouses and hubs enabling producers to dynamically export their products to a much greater area of actuation, producing, moving and storing them in a way that speeds the delivery time to the final customer. This increases the supply productivity, adaptability and resilience of a company.

### 2.1.2 Lockers

In recent years, and with a tendency to grow, the e-commerce industry has been dominating the B2C industry. With this grows the need for home delivery. With increasingly large cities the final step of delivery, so called “last mile” has become one of the main issues for logistic providers accentuated by the increase migration of people to urban areas the last mile problem is a serious factor in the congestion of and greenhouse gas emissions of a city.

Being the fast way to compare prices and options between different retailers or the commodity to do it from your own home, the consumer has decided that online shopping is the way to go. Due to the difficulty to find specific addresses or the low volume of delivery to specific areas it is hard to reduce costs on shipping specially when the costumer does not want to pay for something other than the product itself. Delivery time and reliability is also a factor considered when a consumer is making his choice, because of that fast and reliable end-to-end supply chains are crucial to a successful business. For the customers, the current model is also a big inconvenient, sometimes forcing them to stay home all day to wait for a parcel they do not know the exact time of arrival, this is reflected in the low service levels and costumers experience.

For costumers, the parcel locker system would be a big improvement because they could pick up their packages according to their schedule on their daily commuting path within the days the package is held at the access point. From the logistic providers standpoint, it is a much more effective form of delivery, reducing the delivery points by concentrating them to a few designated terminals. This also introduces predictability and improves the planning of delivery routes and schedules. The retailers also gain with this system because it allows them to reduce the shipping fee, the costumer doesn't want to pay for something they don't perceive has added value such as delivery fees.

Following the Physical Internet's concepts, open and accessible networks of Smart Lockers Terminals can be the answer to the large influx of e-commerce in urban areas. Some companies have already started to develop their own network, partnering with each other to create shared access points.

The smart Lockers themselves are located near convenient and large flow points where retailers or private clients can store packages for a designated second entity to pick up for a few days. They are automated consolidation delivery points, as shown in Figure 2. The costumer can pick up his package at a time of his choosing during that time window where the product is stored by logging into a terminal interconnected to the company's system using the internet of things, with a code sent to a designated platform being text or email, or even using a government ID. One downside is that it requires the costumer to move to one of these points, however this can be mitigated by deploying them over the city where it would only take them a few minutes to access it, not straying too far or at all from their daily route. These Smart Lockers can be compared to access points where companies have partnerships with delivery points where the costumer can pick up the package, however, the Smart Lockers do not

require human interaction due to their automated nature removing the interaction that leads to queues and increasing the open hours to 24 hours a day being accessible at any time.

One of the main challenges of operating a successful and optimized network of pickup and delivery lockers is the uncertainty of demand. With variables such as the number of packages and the size of these packages it becomes difficult to design and configure each bank to ensure usage of its critical capacity (number of lockers and their respective dimensions). In its current form, a smart locker has a fixed configuration of lockers of different sizes (Montreuil & Faugere, 2017), with the goal of leveling service levels and manufacture costs. This operating system leads to obsolescence since it employs a non-flexible design. The other problem comes from low space utilization since the packages rarely use all the space inside the assigned locker.

The main advantages of this design rely on the opportunity for economies of scale relative to design and manufacture, besides that, it also only represents a one-time implementation cost since it is a fixed network there is no need to redesign it. Moving the smart locker banks is possible but does not require new significant investment.

Nevertheless, this design is very constraining when in practical use, since successful delivery will depend on availability of a locker big enough at the time of delivery this can translate in a rapid over or under capacity since global level of demand may evolve over time varying the number of packages to be delivered at the smart locker bank. It also does not adapt to changing delivery patterns resulting in the mixture of package size. For example, a locker can be designed primarily for small packages and it will perform as expected if the mix of packages delivered stays relatively stable with a bigger influx of smaller packages. If this mix changes and the packages delivered get noticeably bigger the smart locker bank will not be able to keep up with the new demand and might have most of the smaller lockers unutilized. This also calls for a re-route of the bigger packages that cannot be delivered. With upfront advantages in terms of implementation, fixed capacity lockers lack the flexibility required for a fast-evolving market that is difficult to predict.



Figure 2 - Fixed smart locker bank

On the other hand, modular smart locker towers, Figure 3, can also be used, this system has already been implemented in China and uses multiple towers, each with the same width and length with two columns of lockers. The locker bank consists of an assemblage of these towers. The height is dictated by human constraints, so as to be reachable within practical levels of confront for the users. The constituents of the tower can vary in width as long as the total height of the tower remains consistent with the other towers. This requires more flexible manufacturing than the previous system. Modularity allows for adjustments over the course of the usage, by adding/removing irrelevant towers, within the overall space constraints. That assures relative optimization of the smart locker bank. Towers can come from a storage facility or directly from another smart locker bank where they are not being used as effectively when rebalancing capacity. This dynamic movement of lockers allows for adaptation of global demand by adding or removing tower increments. It can also be very advantageous in seasonal markets such as peak seasons like Christmas or even help deal with a huge seasonal migration like those of beach/vacations cities such as Vilamoura or Albufeira that fill up during the summer months and ensure minimal footprint when they are not close to full capacity over the rest of the year. It should be mentioned that this system is slightly more complex having to deal with modular tower inventory and network distribution as required. Besides that, it needs a capacity management policy, this being the frequency at which capacity adjustments should be made as well as rules for the addition/removal of tower modules. Finally, it requires distribution capabilities to transport and install/remove tower.

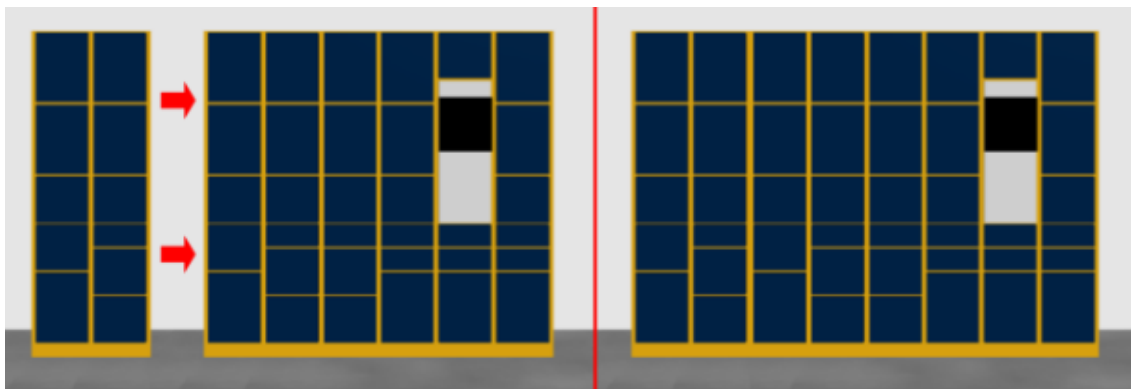


Figure 3 - Modular tower smart locker bank

The next step on the road for modularity are smart locker banks where the smallest block of play is not the tower but the locker itself, Figure 4. The lockers must be provided in different sizes, in accordance with the bank and tower structure dimensions and have connectors that allow them to easily snap together or unsnap in the case of removal. This fine level of adjustments of capacity allows modification of

the entire locker purpose. It can adapt to variations of demand in terms of volume and size of packages handled and it can also cover highly seasonal markets as well as evolve to answer a substantial increase in demand during peak seasons better than the modular towers. Besides this, it is also capable of accounting for variation in delivery patterns since it can adjust the amount of big and small lockers it has at any given time. But like most systems an increase in modularity ensures optimization but also an increase in complexity in management of the systems and the system itself, given by disadvantages like bigger supply times from modular locker suppliers, also modular locker inventory management, they can be seen as smaller towers with a variety of dimensions. Also, just like modular towers, it requires a capacity management policy but at a finer level, and as expected means of transportation for the modules to be installed/removed from lockers. In conclusion, Modular smart lockers are very similar to modular towers in the way they operate with higher gains in optimization and higher difficulty of execution.

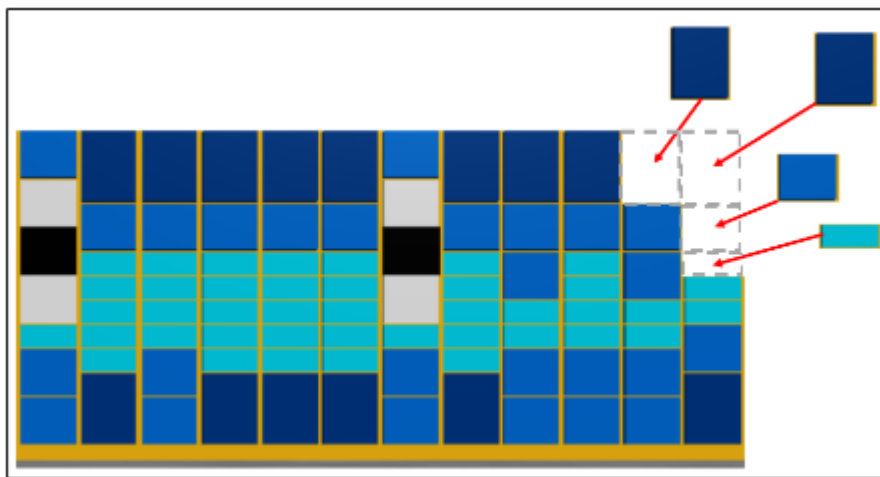


Figure 4 - Modular smart locker bank

The final step on the road to optimization is the use of the Physical Internet containers as a mean to not only transport the goods but also store them until the pick-up by the final consumer, Figure 5. Until now the concepts mentioned differentiate the device used in the transportation from the one used in storage but according to Montreuil & Faugere, 2017 they should be one and the same. In the article it is proposed to use the  $\pi$ -containers as a pick-up and delivery lockers as an alternative to modular lockers and towers using an interlock system or a snapping them onto a grid like bank structure. This solution has the potential to eliminate utilization inefficiencies and increase the response to demand. Accessories like cameras, protection roofs or lights, can also be snapped onto the grid like interactive modules. To perform a delivery or return the user simply needs to snap a box onto an empty grid slot. The exact position where the box is snapped can depend on policy or be chosen by the person performing the task ahead of time. It is also possible to perform returns or deliveries on empty boxes already on the wall if said space is available. When picking up goods there are 2

options to be explored: the customer either takes the entire  $\pi$ -container home and later redistributes it in the system or re-uses it for a different shipment; or the customer opens the front face of the  $\pi$ -container removes the goods and closes it again. In this case empty  $\pi$ -containers should be picked up and redistributed in the open system.

The main advantages stated are:

- Potential of improving the handling efficiency of deliveries and pickups at smart locker banks;
- The configuration of the locker is ever-changing and does not require to be stationary for a period like the other systems increasing adaptability;
- Does not require locker bank specific resources since the  $\pi$ -containers are resources moving across all levels of the supply chain;
- Minimal footprint and upfront investment.

On the other hand, the disadvantages are:

- Requires implementation of  $\pi$ -containers has a mean of transportation, handling, and storage;
- Relies on the Physical Internet hyperconnectivity to ensure the circulation of  $\pi$ -containers within the network of smart PI-locker banks globally and at an inter-network level;
- Requires significant technological advances to ensure the security of the goods while stored at the lockers since the  $\pi$ -containers must be securely snapped to the grid-wall, sealed and strong enough to protect the goods from damage and theft as well as being convenient for handling and transportation.

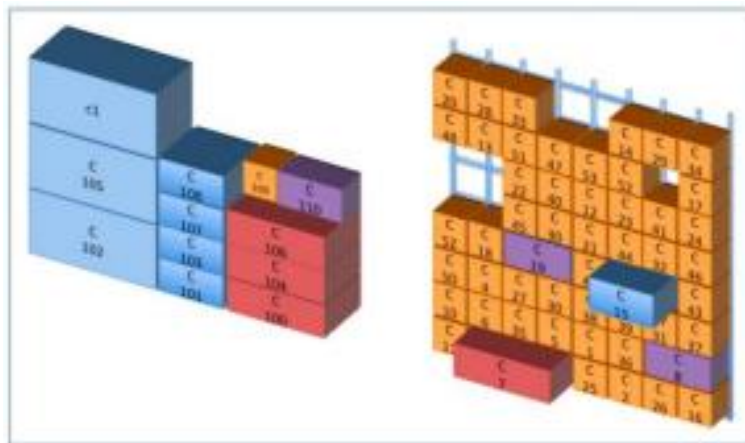


Figure 5 – Illustrating pi-containers snapping as Pickup/Delivery lockers

One concept that it is not going to be explored here but deserves being mentioned is the use of mobile parcel lockers, Figure 6, that have the ability to change their location during the day autonomously or with the assistance of a human driver (Schwerdfeger & Boysen, 2020). This new approach increases the lockers accessibility to the customer that also change their locations throughout the day. The idea bases itself on the premise that in the morning or evening lockers can be parked near the main access point of public transportation since it is where it could reach more people and during the day it would move into the city or business districts since that's where the target

population is. The final goal is either for the same number of lockers to reach the maximum customer base possible or for to minimize the number of lockers necessary to answer a certain demand when comparing to stationary lockers.

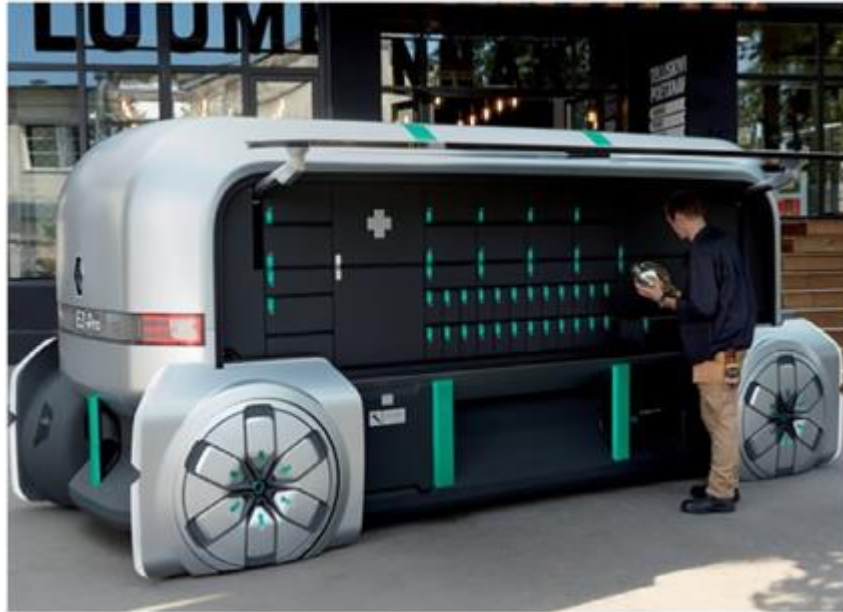


Figure 6 - autonomous driving platform EZ-GO of Renault

## 2.2 Case Studies

With countries all around the globe facing the same B2C delivery problems some have already started to apply these methods in order to overcome them, the first example comes from the polish company InPost that has more than 3000 fixed parcel lockers in over 20 countries (Iwan et al., 2016) where the internet shopper gets his package delivered within 2 business days at which point he receives an e-mail or a SMS with a code to open a specific reception box in a designated machine. At this point he has 3 days to collect the package if he fails to do so the package will be transferred to the nearest InPost location. To minimize safety threats to both the delivering and receiving parties the machines are placed in monitored locations such has supermarkets and 24h car parks as well has being equipped with 4 security cameras and an alarm system. With the goal of reducing the number of deliveries necessary in the city area, including failed deliveries that required a return of the packages, reduction of CO2 emissions according to the analysis of the Szczecin area made by the researchers from the Department of Robotics and Mechatronics at the AGH University of Science and Technology in Krakow in 2013(*Paczkomaty InPost - Ekspertyza AGH, n.d.*)

Table 1 compares the couriers and InPost parcel lockers in terms of distance travelled for a packages to be delivered, the number of parcels delivered, CO2 emissions and fuel consumption.

Table 1 - Comparison of parcel lockers and courier deliveries

	Courier	InPost Parcel Lockers
Nº of km/ day	150	70
Nº of parcels delivered/ day	60	600
CO2 emissions / year	32 500 T	1 516 T
Annual fuel consumptions	22 500 000 l	1 0500 000 l

Regarding location the criteria followed was:

- Dense population spots within suburbs – next to convenience stores
- High traffic pedestrian areas in city center
- Shopping center and supermarket car parks
- Bus and underground stations
- Service stations
- Business center

Another very interesting proposition (Schnieder et al., 2021) argues that a combination between manned pick-up points and fixed lockers is more efficient than parcel lockers designed to answer 100% demand. It also states that this hybrid solution has more financial benefits when compared with modular lockers. To prove these statements the study was based on data, from the delivery company Gwent in Central London, and comprised of number of successfully delivered parcels, failed deliveries, successful pick-ups, attempted pick-ups, shift start, shift duration and travel distance over 13,358 delivery tours from July 2015 to June 2016 and 2 million delivered parcels.

The study ultimately concluded that in order to have enough lockers for 100% of all parcels instead of only 80% with the support of manned pick-up points doubles the number of lockers required. And regarding the use of modular lockers, with an adjustment to the number of towers being made in the first day of each month would still not be financially better.

### 2.3 Location Problems

The location of the locker is one of the most important variables when trying to optimize the usage of said lockers and increase customer satisfaction (Lagorio & Pinto, 2020) since one of the main advantages of smart lockers is the fact that a user does not need to stray very far away from his daily commute in order to pick up a parcel. With this in mind the study by Alexandra Lagorio and Roberto Pinto states that over a careful literary review and a cross reference with real case studies from both national and private postal companies, there are 7 major factors that should influence the location of the parcel locker units (Lagorio & Pinto, 2020).

- First of all, its availability, since one of the main advantages of the parcel lockers relies on not having opening hours and being available for use 24/7 it is important to be placed somewhere accessible all the time, if they are located in supermarkets, shopping malls, or post offices they are constricted by the open hours of those places.
- The second criteria is accessibility, it depends on the location and the concentration of the market in the served area, a strategic positioning of the network that ensures a minimization of the effort that the user must make to collect the parcel. In order to maintain a high occupancy, rate the locker must be efficient and it is suggested that for these goals the best locations must consider the concentration density of the population and also their availability, such places can be bus and metro stations, service stations, supermarket car parks, universities, among others.
- Thirdly it is security, this factor is dependent on the “delivery success”, and if it is possible to confirm if a parcel has actually been delivered and verify it. Security also depends on the use of 24/7 cameras to record what happens in the delivery points. Finally real time connection with a security system must be considered and it is used a lot by national post operators like Posti, LaPost and Bpost. Lastly each machine usually has an anti-intrusion mechanism through cameras for terminal supervision.
- In forth comes Environmental impact / land occupation that states the importance of comparing the delivery route of the driver in the case of home delivery, considering failed deliveries that create the necessity for a second attempt, versus the delivery route the driver makes to the hubs and the distance covered by the users. With the parcel locker solution, a kind of “capillarity” is created that reduces traffic and environmental impact.
- The fifth criteria are costs, one of the factors pushing costumers away from home delivery and into parcel lockers is the decrease in price, with that both costumer and the courier are looking for the cheapest option that reduces the cost of the overall delivery. With a lot of factors involved it is difficult to compare different delivery options, but it is possible that the fact of not having to deal with undelivered parcels might mitigate all of those since there is no need to manage a second delivery and reducing stock in the warehouse. According to operators the reduction in costs when compared to traditional methods is 42%. Also, the installation of a locker increases the traffic of the store where it is attached attracting costumers inside. Another use of these locker is the opportunity of commercial space though advertisements printed on the lockers.
- Method of use is also very relevant, the difficulty of use considers economic, psychological, and intellectual barriers. There is a minimum knowledge that the user, being costumer or courier, needs to operate the smart locker interface. It is reasonable to assume that both the costumer that placed an online delivery and the courier that should have some form of training are able to operate the locker successfully.

- Finally, there are regulations that constrict the geographical location where lockers might be permitted. The European legislation does not provide for specific provisions on lockers so similar cases are applied. The locker can be seen has a warehouse. On the other hand, countries like Italy, the building permit requested, is provided in the cases of “free standing lockers”. Also, if the locker is installed in a public place, it can be treated like a newsstand and require a permit to occupy permit land and as well as pay a municipal charge, this however depends on the place and the type of the structure. The uncertainty of these legislations and the lack of guarantee that they won’t change in the future might push for installments in private property.

These 7 factors play an important role in the design and planning phase of a smart locker network when the goal is to optimize the whole operation being it the answer of demand, the usage of the lockers or the ecological footprint.

For a more quantitative approach, Lin et al., 2020, answered the problem of using POP-Locker Alliance to answer a set of costumer zones in Singapore. The goal is to open new more efficient locations and close the inefficient ones so that the overall service level provided by the POP-Locker system is maximized. This study does not rely on the costumer always choosing the nearest station since there are other factors that influence this decision, these factors, however, are hard to observe. With that, the individual choice behaviors were interpreted has probabilistic. Using multinomial logit model to model costumer choice, the problem was formulated and solved with by 2 different methods. The first one was the mixed integer linear programming (MILP) approach together with McCormick inequalities (MC) but since these method does not scale well with the problem size the Quadratic Transform with Linear Alternating (QT-LA) approach was used which outperformed the MILP approach. Lastly, to prove the usefulness of the model, a case study was conducted which stated even more the importance of considering costumer choice behaviors and the difference with previous models.

## 2.4 Location-Inventory Problems

A good model to follow when dealing with modular towers would be the Location-Inventory Problem, when dealing with inventory management there are two very important steps, determine the number of distribution centers (DC) and the amount of stock to have in each of these centers. It is logical that with a higher number of centers the stock in each center diminishes but for every case there is an optimal balance of DC/stock, and this is why both of these quantities should be calculated together to increase optimization.

LIP studies (Farahani et al., 2015) states that the objective function in typical location-Inventory problems is comprised by 6 terms. Term 1 is the fixed cost of locating DCs,

term 2 is the transportation cost from the supplier to DCs and term 3 is the transportation cost from DCs to retailers and terms 4 to 6 represent costs related to holding inventory, safety stock and shortage stocks. The constraints used are related to annual demand in each DCs, insurance that each retailer is assigned to one open DC and the binary nature of the decision variables

Daskin et al., 2002 deals with a three-tier system comprised of suppliers, DCs and retailers under 2 assumptions:

- The locations of the suppliers and the retailers are pre established
- The suppliers and infinite capacity

It is also explained that it is reasonable to model this problem as if there is only one supplier/plant since the shipping costs to the DC are exclusively dependent on the DC and possibly on the distance between the plant and DC. With this it is possible to identify the best plant *a priori*. It is also assumed that the plant/DC lead time is the same for all possible combinations and because of that the choice of plant to supply each DC will not affect the level of safety stock at the DC. All these assumptions allow the model to deal with a single plant/supplier. The study uses a (Q, r) inventory model which translates in ordering the quantity Q every r period where Q is calculated through a EOQ (economic order quantity) model. The following step is to formulate the safety stock equation in order to guarantee that stockouts occur with a  $\alpha$  probability or less followed by the formula for the annual cost of ordering inventory from the supplier where it is derived, matched to 0 and solved for  $n$ . After this  $n$  is submitted back into the annual cost of ordering equation.

To simultaneously determine the locations of the DCs, assignments of retailers to the DCs as well as working and safety stock inventory costs.

In order to solve this model, the authors stated used the Lagrangian relaxation method embedded in branch and bound.

Instead of the usual approach of supplier/plant, distribution centers and retailers, our 3 tiers of the supply chain (SC) would instead be the plant/supplier, re-distribution centers and finally locker stations. Based on the parameters used in previous research, our Location-Inventory Problem (LIP) would be formulated using:

# PROBLEM INTRODUCTION AND RESOLUTION

- 3.1 INTRODUCTION OF THE PROBLEM
- 3.2 MATHEMATICAL MODEL
- 3.2 TESTS
- 3.3 APPLICATION OF THE MODEL
- 3.4 RESULTS
- 3.5 RESULT ANALYSIS



### 3 PROBLEM INTRODUCTION AND RESOLUTION

This chapter will approach the problem in hand as well as all the methods used to formulate the mathematical model which led to its resolution, subsequent results, and the analysis of those results in a real-world context.

#### 3.1 INTRODUCTION OF THE PROBLEM

The problem starts with a tower that has 10 slots, in these slots we can place different types of lockers that accommodate different sizes of packages, this is called a configuration. There are 3 types of lockers, small lockers (blue) that use 1 slot, medium lockers (green) that use 2 slots and large lockers (yellow) that use 3 slots. The small, medium, and large lockers are designated as A, B and C respectively.

The goal is to create a tool that helps the manager of this lockers to easily identify the types and quantities of towers that optimally satisfy specific level of demand for each month.

To better adapt the model a restriction needs to be added a where a maximum number of configurations can be used in any given month.

It is also important to account for the fact that smaller packages can go on larger lockers if that benefits the outcome, but the other way around is physically impossible. The model must account for this as well.

With that the following configurations where made:

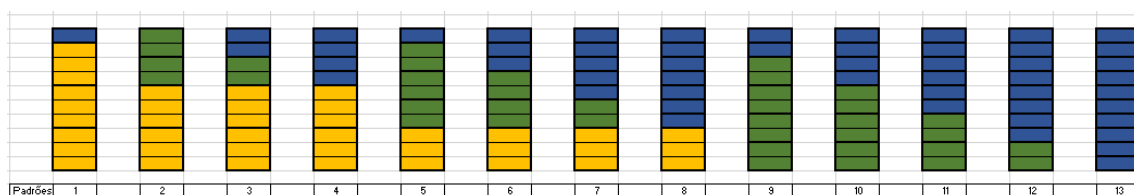


Figure 7 - tower configuration

The main goal of this report is to provide a linear mathematical model combined with a heuristic approach to ensure the optimal use of resources.

After the creation of this tool, it is of interest to analyse and compare the results in order to evaluate its efficiency.

To make this evaluation first a database needs to be created where demand follows a certain distribution. After the creation of this database, we compare the locker usage to this fictitious demand and come up with an occupancy rate that balances against the locker space used in that month.

### 3.2 MATHEMATICAL MODEL

The first step to creating the mathematical model was to set the parameters. Even though adjusting the number and configurations of lockers daily would outcome in a nearly 100% answer in demand with minimal tower usage, it is not realistic due to logistic costs, instead a monthly adjustment is going to be considered, where in the start of each month a new locker plan (configuration and quantity) is set in place. For this monthly average demand is going to be our demand parameter.

Due to the large number of possible configurations, it is important to restrict the number of configurations in use in any given month otherwise there could be a case where a large number of different configurations is used at the same time increasing logistic costs with minimal performance increase. Because of this the number of configurations per month is set to 3.

A very important part of this model is to remember that small packages can go in medium and large locker, if necessary, as can medium packages go in large lockers but not the other way around. This allows for larger lockers to absorb some demand from smaller packages if it increases the effectiveness of the model.

This model was based on the trim and loss problem since the goal is to create a pattern of lockers minimizing waste (empty space) in conjuncture with an IF THEN restriction that limits the number of different configurations chosen.

With that the following mathematical model was created:

#### Decision Variables

$X_i$  – number of configuration  $i$  towers to be utilized,  $i \in [1; k]$

$y_i$  – 1, if configuration  $i$  tower is utilized, 0 otherwise

#### Parameters

$Y_{ij}$  – Number of  $j$  lockers ( $j = A, B$  or  $C$ ) in  $i$  configuration,  $i \in [1; k]$

$D_{jh}$  – locker demand in month  $m$ ,  $m \in [1; 12]$

$M$  – large number

#### Objective functions

$$\text{Min } z = \sum_{i=1}^k X_i \quad (1)$$

#### Restrictions

$$\sum_{i=1}^k Y_{iC} X_i \geq D_{Cm} \quad \forall m \quad (2)$$

$$\sum_{i=1}^k Y_{iB} X_i + \sum_{i=1}^k Y_{iC} X_i \geq D_{Bm} + D_{Cm} \quad \forall m \quad (3)$$

$$\sum_{i=1}^k Y_{iA} X_i + \sum_{i=1}^k Y_{iB} X_i + \sum_{i=1}^k Y_{iC} X_i \geq D_{Am} + D_{Bm} + D_{Cm} \quad \forall m \quad (4)$$

$$X_i \leq M y_i \quad \forall m \quad (5)$$

$$\sum_{i=1}^3 y_i \leq 3 \quad \forall m \quad (6)$$

$$X_i \geq 0 \quad \forall m \quad (7)$$

$$y_i \geq 0 \quad \forall m \quad (8)$$

$$X_i \in \mathbb{Z} \quad (9)$$

Equation (1) is the objective function and translates to the sum of all towers used, which means that our goal is to have the minimum number of towers while complying with the restrictions. Because demand of C can only be fulfilled by C lockers, equation (2) means that the sum of C lockers in the towers used must be equal or greater than the demand. As said previously, medium packages can be inserted in large lockers, if necessary, because of that in equation (3) its stated that the amount of medium and large lockers in the towers used must be equal or greater than the demand for those same lockers, this allows for medium packages to be placed in large lockers but not the other way around because of equation (2). The same thought process is applied in equation (4) where the amount of A, B and C lockers in the towers used needs to be equal or greater than the combined demand for A, B and C lockers, this allows for small packages to be placed in medium or even large lockers. Equation (5) is an IF THEN restriction that assures that if the configuration  $i$  tower is used,  $y_i$  assumes the value 1, this is then important in restriction (6) where the sum of  $y_i$  has to be equal or lesser than 3 forcing the model to only choose up to 3 configurations as intended. Restriction (7) and (8) ensure the non-negativity of the variables and restriction (9) that  $X_i$  is integer.

## 3.2 TESTS

In order to test and validate the model the Excel Solver function was used. For that several instances were created to have data similar to the one in the real world.

### 3.2.1 CONSTRUCTION OF INSTANCES

With the goal of having A, B and C demand for every day of the year a random demand was applied, this random demand followed a beta distribution with  $\alpha$  and  $\beta$  parameters.

By varying the  $\alpha$  and  $\beta$  parameters it is possible to create different distribution curves for the demand of the different locker sizes.

It is expected that the largest lockers will have the lowest rate of use while the smaller ones will be the ones with the higher one with the medium sized lockers staying somewhere in the middle. The parameters used are shown in Table 2

Table 2 - curve parameters

Parameters	A	B	C
$\alpha$	8	5	2
$\beta$	2	5	8

These combinations correspond to the curves shown in Figure 8, Figure 9 and Figure 10.

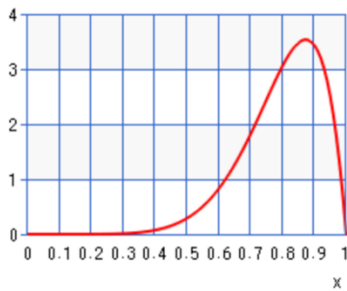


Figure 8 - Probability density function of A lockers

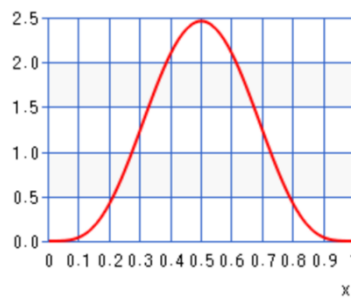


Figure 10 - Probability density function of B lockers

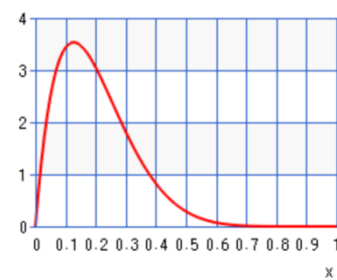


Figure 9 - Probability density function of C lockers

These distributions combined with a lower and upper bound of 50 and 300 (parcels) respectively give the final values for the demand used in order to test the mathematical model, Figure 11 shows a short list of the data generated.

Day	Type	Demand
Jan 1	A	270
	B	184
	C	89
2	A	257
	B	239
	C	104
3	A	261
	B	147
	C	76
4	A	236
	B	234
	C	111
5	A	237
	B	128
	C	102
6	A	274
	B	252
	C	103
7	A	169
	B	188
	C	63
8	A	273
	B	185
	C	59
9	A	277
	B	225
	C	69
10	A	270
	B	182
	C	76

Figure 11 - example of the data generated

### 3.3 APPLICATION OF THE MODEL

In order to test the model a VBA programmed loop inserts the parameters in the desired cells and runs the Solver function, it then saves the results for future analysis and goes on to the next month. With the characteristics of each configurations remaining the same for every month the only parameter that requires changing from month to month is the mean monthly demand for each type of locker.

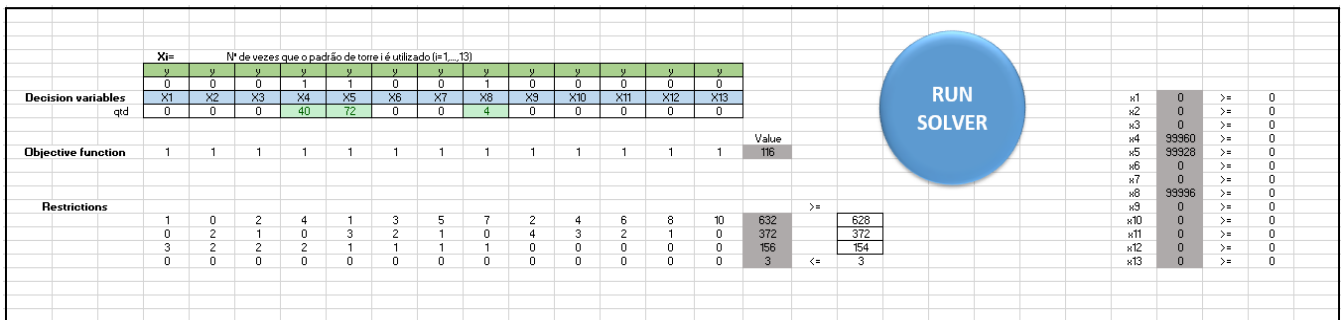


Figure 12 - Testing parameters

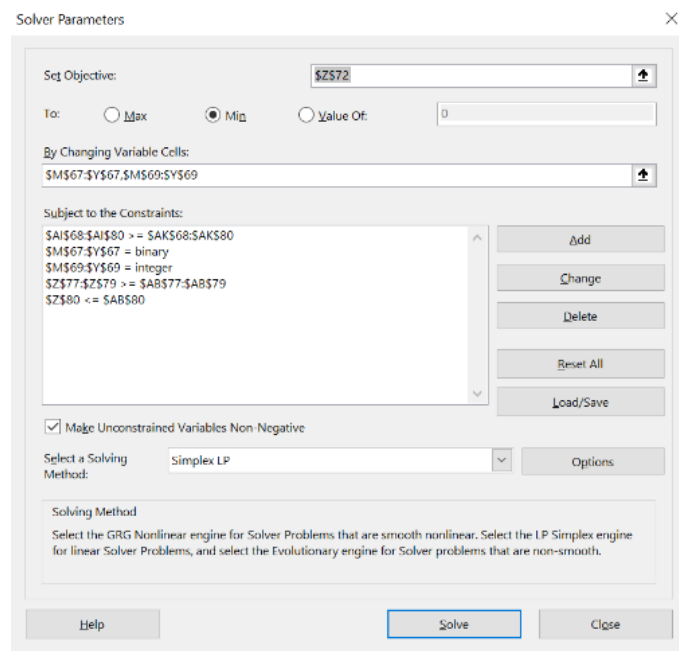


Figure 13 - Solver

Other interesting variations of the problem were considered, such as using the max demand as the demand parameter. The max demand considered was the number of slots used, so a small package would be worth 1 slot, a medium package 2 slots and a large one 3 slots. For each month the day with the most slots necessary would be chosen as the demand parameter or using a service level of 95% as the demand

parameter, using the properties of the beta distribution and the parameters used to create it such as the upper and lower bound the demand value for a service level of 95% was obtained for each locker size and used in the model.

### 3.4 RESULTS

The results are comprised by the chosen configurations and quantity of said configuration, Figure 14 shows the results of the monthly average demand iteration

	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13
Jan	0	0	0	6	60	0	0	24	0	0	0	0	0
Feb	0	0	0	16	54	0	0	19	0	0	0	0	0
Mar	0	0	16	0	0	69	0	0	7	0	0	0	0
Apr	0	0	0	8	58	0	0	22	0	0	0	0	0
May	0	0	0	7	59	0	0	22	0	0	0	0	0
Jun	0	0	0	13	55	0	0	20	0	0	0	0	0
Jul	0	0	52	0	0	0	0	0	30	0	0	0	9
Aug	0	0	48	0	0	0	0	0	30	0	0	11	0
Sep	0	0	0	21	58	0	0	16	0	0	0	0	0
Oct	0	43	0	0	0	0	0	19	0	29	0	0	0
Nov	0	0	0	9	56	0	0	23	0	0	0	0	0
Dec	0	0	0	7	57	0	0	24	0	0	0	0	0

Figure 14 – Quantity of each configuration used in each month using monthly average demand

The result of all 3 iterations of the model (mean demand, max demand and 95% service level) are listed on the Table 3 below.

Table 3 - Results

Month	Average Demand			Maximum Demand			95% service level		
	X4	X5	X8	X3	X9	X12	X4	X5	X8
Jan	6	60	24	52	48	9	33	79	12
Feb	16	54	19	42	72	8	33	79	12
Mar	16	69	X9	71	34	11	33	79	12
Apr	8	58	22	49	46	23	33	79	12
May	7	59	22	66	34	11	33	79	12
Jun	13	55	20	55	48	17	33	79	12
Jul	52	30	9	81	31	1	33	79	12
Aug	48	30	11	41	79	-	33	79	12

Sep	X4	X5	X8	X4	X5	X8	X4	X5	X8
	21	58	16	32	71	11	33	79	12
Oct	X2	X8	X10	X3	X5	X8	X4	X5	X8
	43	19	29	50	66	13	33	79	12
Nov	X4	X5	X8	X4	X5	-	X4	X5	X8
	9	56	23	56	59	-	33	79	12
Dec	X4	X5	X8	X4	X5	X8	X4	X5	X8
	7	57	24	40	72	4	33	79	12

### 3.5 RESULT ANALISYS

The results were analysed regarding daily occupancy percentage in order to figure out the number of times the occupation rate is over 100% which would mean a rupture of stock. Taking into account that smaller packages can go in big lockers it was chosen to fill the bigger lockers first. This means that all C packages would go in C lockers, after this if some of the C lockers are still available, B packages would be placed in C lockers until 100% C locker occupation is achieved, after this B packages are assigned to B lockers and, as before, if some B lockers remain available A packages are assign to B lockers until 100% B locker occupation. Finally, the remaining A packages are assigned to A lockers.

As an example, Table 4 shows the result analyses for the month of march.

Table 4 - March Results

Day	Average Demand			Maximum Demand			95% service level		
	A	B	C	A	B	C	A	B	C
	253	182	101	253	173	187	295	237	157
1	104.7%	131.3%	100.0%	96.8%	100.0%	100.0%	71.5%	100.0%	100.0%
2	97.6%	108.8%	100.0%	73.5%	100.0%	100.0%	51.5%	100.0%	100.0%
3	98.0%	100.5%	164.4%	93.7%	100.0%	100.0%	51.9%	100.0%	105.7%
4	94.9%	100.0%	100.0%	64.4%	100.0%	100.0%	43.7%	100.0%	100.0%
5	75.5%	100.0%	105.9%	47.4%	100.0%	100.0%	29.2%	100.0%	100.0%
6	90.9%	100.0%	103.0%	61.7%	100.0%	100.0%	41.4%	100.0%	100.0%
7	56.9%	100.0%	100.0%	26.5%	100.0%	100.0%	11.2%	100.0%	100.0%
8	82.6%	100.0%	100.0%	52.2%	100.0%	100.0%	33.2%	100.0%	100.0%

9	103.2%	113.2%	112.9%	87.4%	100.0%	100.0%	63.4%	100.0%	100.0%
10	79.8%	102.7%	100.0%	51.4%	100.0%	100.0%	32.5%	100.0%	100.0%
11	89.3%	100.0%	173.3%	88.1%	100.0%	100.0%	49.2%	100.0%	111.5%
12	99.2%	100.0%	100.0%	68.8%	100.0%	100.0%	47.5%	100.0%	100.0%
13	84.6%	100.0%	100.0%	54.2%	100.0%	100.0%	34.9%	100.0%	100.0%
14	108.7%	103.3%	100.0%	80.6%	100.0%	100.0%	57.6%	100.0%	100.0%
15	89.7%	100.0%	100.0%	59.3%	100.0%	100.0%	39.3%	100.0%	100.0%
16	67.2%	100.0%	100.0%	36.8%	100.0%	100.0%	20.0%	100.0%	100.0%
17	97.2%	100.0%	101.0%	67.2%	100.0%	100.0%	46.1%	100.0%	100.0%
18	96.0%	100.0%	110.9%	70.0%	100.0%	100.0%	48.5%	100.0%	100.0%
19	95.3%	100.0%	100.0%	64.8%	100.0%	100.0%	44.1%	100.0%	100.0%
20	88.5%	100.0%	100.0%	58.1%	100.0%	100.0%	38.3%	100.0%	100.0%
21	79.8%	100.0%	100.0%	49.4%	100.0%	100.0%	30.8%	100.0%	100.0%
22	96.4%	100.0%	185.1%	100.0%	100.0%	100.0%	48.5%	100.0%	119.1%
23	106.3%	100.0%	148.5%	95.3%	100.0%	100.0%	70.2%	100.0%	100.0%
24	75.5%	100.0%	100.0%	45.1%	100.0%	100.0%	27.1%	100.0%	100.0%
25	109.1%	100.0%	123.8%	88.1%	100.0%	100.0%	64.1%	100.0%	100.0%
26	54.2%	100.0%	118.8%	31.2%	100.0%	100.0%	15.3%	100.0%	100.0%
27	102.0%	125.3%	100.0%	89.7%	100.0%	100.0%	65.4%	100.0%	100.0%
28	113.0%	127.5%	104.0%	104.0%	100.0%	100.0%	77.6%	100.0%	100.0%
29	98.4%	139.0%	100.0%	96.0%	100.0%	100.0%	70.8%	100.0%	100.0%
30	105.9%	113.7%	100.0%	85.4%	100.0%	100.0%	61.7%	100.0%	100.0%
31	80.6%	100.0%	100.0%	50.2%	100.0%	100.0%	31.5%	100.0%	100.0%

The results of each approach of the 12 months were compiled into 3 tables containing the total number of stock ruptures in a month, since for each day we look into A, B and C stock rupture each day can fail 3 times, it is important to make this analyses side by side with daily ruptures. Next, on Table 5 there are the percentage of total ruptures of stock for the entire month followed by the number of days where there was at least one rupture of stock, number of days where there was not a rupture of stock and the subsequent percentage of days without rupture of stock. The tables below regard the results of the mathematical model using the monthly average, maximum demand and 95% service level respectively.

Table 5 - percentage of ruptures comparison average demand

	total nº of ruptures	% of ruptures	nº days w/ ruptures	nº days w/o ruptures	% days w/o ruptures
Jan	38	41	21	10	32
Feb	31	37	16	12	43
Mar	30	32	19	12	39
Apr	31	34	19	11	37
May	32	34	19	12	39
Jun	31	34	20	10	33
Jul	35	38	21	10	32
Aug	36	39	20	11	35
Sep	38	42	20	10	33
Oct	32	34	20	11	35
Nov	35	39	21	9	30
Dec	29	31	20	11	35

It is important to state that these results were obtained using the monthly average demand in the  $D_{jh}$  variable, with that a normal outcome would be that in the month of January, which has 31 days and with 3 possible products (A,B and C lockers) there were  $31 \cdot 3 = 93$  instances where a rupture of stock could occur and it was expected that half of those would occur since the mean monthly average was used. However, the percentage of ruptures is well under 50% with its biggest value being 42% in the month of September. This is due to the combination of the optimal solution provided by the mathematical model as well as the heuristic used where the C lockers are filled first followed by B and then A as explained previously. Regarding the number of days without ruptures the results are all under the 50% benchmark which is to be expected being that with in a single day out of the 3 products only one needs to no fulfil the demand for the day to count as a ruptured day.

Table 6 - percentage of rupture max demand

	total nº of ruptures	% of ruptures	nº days w/ ruptures	nº days w/o ruptures	% days w/o ruptures
Jan	8	9	8	23	74
feb	1	1	1	27	96
Mar	1	1	1	30	97
Apr	1	1	1	29	97
May	4	4	3	28	90

Jun	0	0	0	30	100
Jul	1	1	1	30	97
Aug	1	1	1	30	97
Sep	2	2	2	28	93
Oct	1	1	1	30	97
Nov	0	0	0	30	100
Dec	0	0	0	31	100

Using the maximum demand, Table 6 presents a few cases of rupture. This is because the maximum demand for each month is calculated by adding the number of lockers times their given weight in slots (A lockers take up 1 slot, B lockers 2 slots and C lockers 3 slots) this makes it so that in one given day, even though the overall weight of the lockers is smaller than the maximum demand day, the number of C lockers needed to fulfil demand, for example, is still larger. It is also possible to observe that most of the times, rupture of stock only happens in one product per day since the number of failures to fulfil demand occurrences is monthly similar to the number of the days it has happened. The percentage of days without failure to fulfil demand is very high, most of the times above 95%.

Table 7 - percentage of rupture 95%

	total nº of ruptures	% of ruptures	nº days w/ ruptures	nº days w/o ruptures	% days w/o ruptures
Jan	1	1	1	30	97
Feb	2	2	2	26	93
Mar	3	3	3	28	90
Apr	2	2	2	28	93
May	1	1	2	29	94
Jun	2	2	2	28	93
Jul	4	4	4	27	87
Aug	2	2	2	29	94
Sep	1	1	1	29	97
Oct	3	3	3	28	90
Nov	1	1	1	29	97
Dec	0	0	0	31	100

When aiming to fulfil 95% of the demand, Table 7, the number of cases where there was an overcapacity is slightly superior then when the maximum demand was used, as expected. The month where there were the most cases of rupture of stock was July

with 4%. Just as in the maximum demand iteration, most of the overflow happened in different days.

After comparing the occupancy of the 3 iterations it is necessary to also consider the cost or weight of the selected combination for each one. The table below shows the percentage of failures occurrence alongside with the cost of the combination.

Table 8 - Rupture occurrence vs cost analysis

	Ruptures (mean demand) (%)	Cost (mean demand) (slots)	Ruptures (max demand) (%)	Cost (max demand) (slots)	Ruptures (95% service level) (%)	Cost (95% service level) (slots)
Jan	41	900	9	1090	1	1240
Feb	37	890	1	1220	2	1240
Mar	32	718	1	1160	3	1240
Apr	34	880	1	1180	2	1240
May	34	880	4	1110	2	1240
Jun	34	880	0	1200	2	1240
Jul	38	910	1	1200	4	1240
Aug	39	890	1	1200	2	1240
Sep	43	950	2	1140	1	1240
Oct	34	910	1	1290	3	1240
Nov	39	880	0	1150	1	1240
Dec	31	880	0	1160	0	1240
Total (average)	36.4	881	1.8	1175	2.0	1240

As shown in Table 8 the cheaper option is, as expected, the first iteration where the monthly average demand is used. The results are well under 50% which shows de efficacy of the mathematical model and heuristics combination. When comparing the maximum demand with the 95% service level it is revealed that despite being cheaper to tailor our capacity to our demand it also has a lower rupture occurrence rate, even with the outlier month of January. This happens because by using a 95% service level based on the data distribution the capacity stays the same and does not keep up the variance in each month. In the last row it was purposely shown another decimal point in order to emphasize the gap between the rupture occurrence rate compared.



# CONCLUSION

- 4.1 CONCLUSION
- 4.2 PROPOSITIONS FOR FUTURE WORK



## 4 CONCLUSION AND PROPOSITIONS FOR FUTURE WORK

### 4.1 CONCLUSION

In a worldwide community struggling with scarce and poorly distributed resources, all the tools that concern supply logistics, organizational management and reduce traffic and the consumption of fossil fuels should be seen has great advantages for future problem solving.

During this report a mathematical model that aids decision-making regarding locker allocation in the new supply chain revolution that is the parcel locker system allied with the physical internet was developed. Approximated data was also created in order to test and show the efficacy of the model as well as a analysis of this results.

The model does data treatment and presents a solution based on the pre-determined parameters inputted by the user. These parameters can range from the targeted demand as shown in this report or it can also target the size and configurations of the locker or locker slots. It is up to the user to select, adapt and input the pertinent information for the problem they might me trying to solve.

### 4.2 PROPOSITIONS FOR FUTURE WORK

As suggestions to further this subject, there is still much to be developed in this area as this leap of technological and organizational evolution is very recent. However, a good place to start could be to study a quantitative way to select the locations to place the parcel locker facilities and then adapt the model to work in various post at the same time and using their neighbour post to source or deploy lockers as necessary. It would also be very interesting to apply this model to a real parcel delivery company using a real-world prediction and trying to plan demand for the upcoming months and evaluating the occupancy rate that way.



**BIBLIOGRAPHY AND OTHER  
SOURCES OF INFORMATION**



## 5 BIBLIOGRAPHY AND OTHER SOURCES OF INFORMATION

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# APPENDIX



## 6 APPENDIX