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Case Studies in Industrial Engineering and Management

CPLOT

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Preface

This book presents a set of case studies developed over the last years, for the project courses in Masters degrees in the field of Industrial Engineering and Management. The courses are designed for application of the Problem-based learning (PBL) teaching method. These cases are based on real world company problems, and reflect the complexity of the problems faced by companies, and which are not normally dealt with in an academic teaching environment.

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Chapter 1
E-grocery Last-Mile Routing

1.1 Introduction

E-commerce B2C sales have been increasing steadily in the last decade, and they are expected to continue to grow in the following years. This has forced retail companies to look closely at their supply chain operations in particular to all aspects regarding the last-mile delivery.

Last mile delivery refers to the final step in the supply chain, where goods are moved from a transportation hub (e.g. retail store, warehouse, or distribution center) to the final delivery destination (e.g. customer's business or home, or a collection point).

It is important for retailers to ensure a smooth and comfortable "last-mile" delivery service. A superior last-mile experience engages and maintains customers, which are prepared to spend more if they are satisfied with delivery services. Although this can be good news for retailers, the reality is that current last-mile delivery models are not profitable, and a share of the last-mile delivery costs are being absorbed by the retailers, eroding the business profitability.

There are several delivery modes in last-mile delivery. They can be categorized according to the transportation hub and the final delivery destination. According to the transportation hub it is possible to divide it into two categories:

- deliveries from a retail store - theses are facilities usually located close to the customer within urban areas. The orders are prepared by a picker (store-picking).
- deliveries from a specific warehouse - facilities not located in a peripheral area of the customer location. The orders are prepared by a picker (warehouse-picking).

According to the delivery destination it is possible to divide it into three categories:

- Reception Box - a box where access is possible using a key or an electronic code. It can be an:
  - Own reception box - owned by the customer and located at the customer house,
  - Shared reception box (lockers) - owned by service providers and located in a public areas.
  - Delivery box - owned by service providers, are equipped with a docking mechanism they will be temporarily attached to the home of the customer.
- Collection Point - location facilities other than customers' home (e.g. Post Office, convenience store or petrol station)
- Home Delivery - the customer house. It can be:
  - Attended - face-to-face delivery with the customer.
  - Unattended - delivered on the customer's doorstep, mailbox, or neighbour.

Home delivery is an essential, but challenging, last mile delivery option that require the optimization of the delivery process by planning the best routes, managing vehicle sizes, booking delivery slots and ensuring that the orders are picked and stored efficiently.

Retail firms in the food and grocery segment have to provide high level last-mile delivery services while at the same time mitigating associated profitability risks.

The present case study focus on the home delivery route planning of a retail grocery company that deliveries from retail stores.

The retail grocery company is a leading company in Portugal with more than 100 stores. It has three types of stores (hypermarkets, supermarkets and medium-sized stores) supplied by two distribution centers located in the outskirts of Lisbon and Porto. Besides the traditional grocery stores it also has an online retail store.

The service provided by the retailer allows customers to place their orders from a PC or smartphone in the online store (from food products, to non-food products, fresh products, hygiene products, etc.), and then choose one of the three delivery modes available:

- Drive pick-up point - Customers pick up their orders by car from a drive pick-up point in a physical store. The customer selects the time slot with a minimum of 3 hours interval between placing and picking the order.
- Click & Collect - Customers pick up their orders from a physical store or specific pick up points. Similar to the Drive pick-up point delivery mode.
- Delivered to Your Home - The orders are delivered to the customer's home. Available for next-day deliveries, the customer selects the day and time slot for receiving the order.

1.2 The e-fulfillment model

The e-fulfillment model used by the company is based on store picking of orders placed online by customers, and subsequent delivery of the order to the customer.

In each e-commerce service there is a specific back office area and dedicated team that supports all the shop's e-commerce operations. Currently only hypermarkets stores provide e-commerce services. The order fulfillment process starts at the moment the customer places the order on the website. Clients can chose to receive their orders from 8:00 until 23:00, every day of the week. They can chose between the 1h, 2h or 4h time slots available for delivery. The time slots and price are shown in Table 1.1.

Table 1.1 Time slots

Slot	Price	Slot	Price	Slot	Price
08:00 09:00	8 €	12:00 16:00	4 €	17:00 19:00	7 €
08:00 10:00	7 €	13:00 14:00	8 €	17:00 21:00	4 €
08:00 12:00	4 €	13:00 15:00	7 €	18:00 19:00	8 €
09:00 10:00	8 €	13:00 17:00	4 €	18:00 20:00	7 €
09:00 11:00	7 €	14:00 15:00	8 €	18:00 22:00	4 €
09:00 13:00	4 €	14:00 16:00	7 €	19:00 20:00	8 €
10:00 11:00	8 €	14:00 18:00	4 €	19:00 21:00	7 €
10:00 12:00	7 €	15:00 16:00	8 €	19:00 23:00	4 €
10:00 14:00	4 €	15:00 17:00	7 €	20:00 21:00	8 €
11:00 12:00	8 €	15:00 19:00	4 €	20:00 22:00	7 €
11:00 13:00	7 €	16:00 17:00	8 €	20:00 23:00	4 €
11:00 15:00	4 €	16:00 18:00	7 €	21:00 22:00	8 €
12:00 13:00	8 €	16:00 20:00	4 €	21:00 23:00	7 €
12:00 14:00	7 €	17:00 18:00	8 €	22:00 23:00	8 €

The e-commerce team of the store receives the orders and prepares the picking activities. The picking strategy adopted is batch picking (Figure 1.1) combined with zone picking. There are three main picking zones related with the temperature range that products must be stored: ambient, refrigerated (-1 to 12 °C), and frozen (below -18°C). The sequencing of the order picking prioritizes the orders taking into account the delivery time period (time slot) and not a First Come First Served criteria. It is ensured that the first orders prepared are the ones that need to be shipped first.

Fig. 1.1 A picker at work

After the zone picking, the orders are consolidated and stored in the warehouse where they remain until they are dispatched. As the items require storage at different temperatures they are stored at different locations. At this stage of the process the orders are grouped by routes.

In the mode *Delivered to Your Home*, when all the orders are packed and the transport vehicles are available, the orders are loaded according to the determined routes, and delivered to the customers. The routes are determined by a route optimization software of the transport provider.

1.3 The Challenge

With the growth of the online channel in the retail company and the ever decreasing delivery times offered by competitors, there is a need to redesign the way routes are determined. Currently, the company only offers at best, a next day delivery in the *Delivered to Your Home* option. This current scenario provides the company enough time to set the routes and align them with all the previous required processes, such as the picking in the store. The fleet of the company is composed of 3.5-tonne delivery vans with the same characteristics. They have a capacity of 150 bins (combined room and refrigerated temperature).

The company faces two main challenges:

- how to meet the growing e-fulfillment demand
- how to shorten the lead time of online home delivery orders.

These challenges are addressed by increasing the size of the fleet and a new dispatching and routing procedure that can meet the growing demand and support same day deliveries. This means that the dispatching and route determination need to be performed faster as to align the entire e-fulfillment process, and allow the company to offer same day *Delivered to Your Home* option to his clients.

There are two main approaches to solve the proposed routing problem, VRP approaches and districting approaches (Bender, Kalcsics, and Meyer, 2020). The first treats the problem as classical VRP generating a priori routes and making adaptations to cope with changes such as the demand or the driver consistency. The latter considers customers aggregated in small geographic objects (basic units), e.g. streets instead of exact addresses, called districts. The districts are larger geographic clusters that are balanced according to certain criteria, e.g. similar size of the geographic area or similar size of the demand.

Several approaches that combine territorial design and vehicle routing can be found in the literature.There are two criteria that differentiate the proposed solutions, the way the demand is addressed and how it is represented in a network. The demand can be considered as stochastic (Haugland, Ho, and Laporte, 2007; Diglio et al., 2021) or deterministic (García-Ayala et al., 2016) and it can be represented in the edges (García-Ayala et al., 2016) or in the vertices of the network (Diglio et al., 2021).

The goal is to develop a districting approach for the routing, that can cope with the stochastic demand of the clients and improve the consistency of the service. Two main steps are needed solve the problem:

- develop a districting solution
- develop the routing sequence solution for the vehicle.

1.4 The Data

The company will use data from the last 3 months of the Porto region, to develop a new approach for the dispatching and routing procedures. The data includes for each order:

- delivery location - geographic coordinates
- demand (in number of bins)
- date of order
- delivery date
- slot

The location of the hypermarket stores includes:

- location - geographic coordinates
- number of loading docks

1.5 The Deliverables

The deliverables of the project are:

- The report of the solution proposal, that should include:
  - the description and explanation of the proposed solution
  - a performance analysis of the proposed solution
- The solution implementation (algorithms/applications)
- The presentation

References

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Chapter 2
PortLog

2.1 Introduction

PortLog is a company dedicated to pharmaceutical logistics. The company manages the entire logistics chain involving different infrastructures, and the marketing of customised distribution solutions for pharmacies, hospitals and healthcare providers, and other players in the sector. In recent years the company had made an investment in several automation solutions for warehouse operations that provided an increase in the efficiency of the operations, in particular the picking activity. The company A-Frame Automatic Dispenser System (ADS) is a major responsible of the improved efficiency. However, moving past the improvement from a manual to an automatic picking system, the company came to realise that the ADS is not being used most efficiently. It is therefore necessary to redefine the usage of the ADS to increase its performance.

Company background

The pharmaceutical industry is one of the cases in which distribution is more that storing and shipping products from pharmaceutical manufacturers to pharmacies. There is a very high value added in the economies of scale and in the patient safety, that are achieved at an operational level through aggregation efficiencies and safe, secure and reliable delivery.

The wholesale distribution of medicines is a preponderant activity in the pharmaceutical supply chain. It establishes the bridge between the pharmaceutical industry and pharmacies, involving moving millions of euros daily.

As a regulated activity, it requires authorisation from Infarmed's board of directors, imposed by fulfilling mandatory requirements, namely the Good

Distribution Practices manual issued by the Ministry of Health, which sets out the conditions for wholesale distributors to operate.

In a pharmaceutical wholesaler, the preparation of orders from pharmacies/health centres is the activity that brings in the most resources in the warehouse. Thus, companies often install automatic picking systems to make the process more productive. This process should be built in a planned and optimised way to get the most out of it.

PortLog is one of the largest pharmaceutical logistics and distribution company in Portugal. Has five logistics platforms, with a total warehouse area of 35,000 m2, with an annual turnover of approximately 500 M€. The main warehouse is the largest of the five logistics platforms (15,000 m2) and is located in Rio Tinto, Porto's outskirts. To increase proximity to the customer, PortLog has five other platforms for better geographical coverage.

PortLog fulfils the orders of approximately 2,000 customers, receives goods from 300 suppliers and manages roughly 18,000 SKU. The warehouses have different workloads in preparing orders, with the main warehouse accounting for approximately 60%. All the warehouses are licensed by Infarmed and can receive and store all types of health products due to the existence of temperature control, appropriate to the requirements of the products.

Several types of technologies are used in the warehouses, which differ between warehouses according to their size, flows, and volume. The Rio Tinto warehouse is automated with various automatic systems for picking, packaging and transporting for dispatch. Voice Picking and Manual Picking are also used is the warehouse.

The market in Portugal is highly competitive and is made up of many competing companies with market shares that vary little over time, a fact that has, for years, enabled these companies to maintain their market positions mainly through the use of price-related arguments.

The wholesale and pre-wholesale distribution market presents competitive arguments centred on price and proximity to the client. These fundamentals are not sustainable in the medium run as the commercialisation margins are under tremendous pressure. It is essential to rationalise the operational cost structure to absorb the negative impacts arising from the constraints in the pharmaceutical market. Thus, it is fundamental for distribution companies to create new differentiating services that enable them to present integrated solutions based on a logic of partnership with the various stakeholders, adding value to the market and reducing the price factor as a differentiating criterion.

The Automated Dispenser System challenge

In pharmaceutical distribution, automated technologies are widely used in order fulfilment operations that need extremely high service levels. However, the specification of an automated system, meeting storage and production constraints, is a complex process. Automated Dispenser Systems (automated order picking)[1] are often used to eliminate manual picking (although restocking is still done manually in most cases). An additional advantage of automation is accuracy in order picking. In a pharmaceutical distributor, the picking process is one of the most resource-consuming in the warehouse. Therefore, PortLog installed automatic picking systems to make the process more productive. However, the management and optimisation of this equipment need constant attention to remain as efficient as possible. There is a control that is neither regular, constant over time, nor dynamic through the analysis of product rotation data and the decision of which products should be allocated and/or removed from the ADS. This data analysis is performed taking into account averages, which is believed not to be the most appropriate statistical measure for the study.

Portlog has an ADS at the Rio Tinto warehouse, which is not believed to be used more efficiently. Some calculations estimate that the ADS dispatches approximately 50% of the order picking lines, and there is the need to seek solutions to improve the performance of this system.

The most common ADS in the pharmaceutical industry is called A-Frame in the scientific literature. A-Frame systems can prepare up to 750,000 units per day and 1,200 to 2,400 orders per hour, with high precision in their execution (Meller and Pazour, 2008). As illustrated in Figure 2.1, the products are placed in side-by-side channels of variable length on two sides of a conveyor, forming an "A" and automatically dispensed onto the conveyor that passes through the tunnel created by the structure.

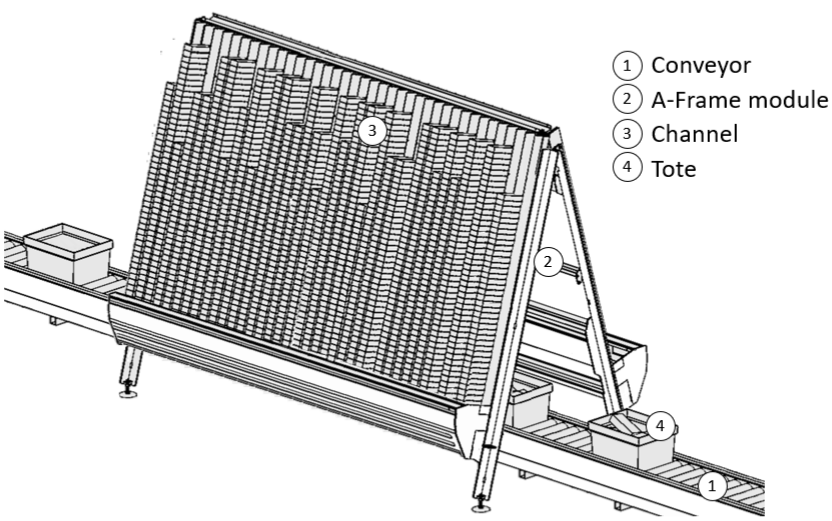

Fig. 2.1 Representation of an A-Frame system

[1] https://www.youtube.com/watch?v=N7ec9Ly6W7I&t=36s

Orders are processed one at a time, with products directed to customer order totes, transported via a conveyor belt to another preparation station. While the machine processes orders, manual replenishment can be performed without impacting dispensing operations. The items are stacked in the channel with their smallest dimension as height. Due to physical limitations, each channel can only store a finite amount of product, and a typical channel has weight limitations. Each A-Frame has several modules, with a certain number of single or double level channels.

Regarding an A-Frame system, the following questions arise in SKU selection and allocation:

- Which SKUs are favourable for allocation to the system, taking into account the demand profile and the total labour costs (A-Frame replacement costs and replacement and set-up costs in the manual system);
- Given the limited number of channels, which SKUs to allocate to the system;
- How many channels should be allocated to each SKU and of which type (large or small).

This project aims to study the current process, identify problems and find improvement measures to increase profitability, covering the issue of better selection and allocation of SKUs to the ADS and optimising the number of picks made by it, to the detriment of manual picking.

2.2 The warehouse operations

Whenever the end customer buys a product in a pharmacy, a set of processes are triggered throughout all of the supply chain.

In the warehouse there are a number of activities that are performed prior to the delivery of the products to the client. These begin with the acquisition of the product from the supplier and ends with its transport and delivery to the client that can be a pharmacy or a health space.

The main activities of the warehouse are:

- Purchasing: acquisition and coordination of goods/services aligned with the strategic organisational objectives. Demand forecasts are used to provide a working basis for planning stock levels based on trends and parameters inferred from historical data. It is at the core of the logistics process to satisfy customer needs in terms of physical and information flows.
- Receiving: receiving, unloading and content check of the goods and respective documents coming from suppliers to certify that the products are in the conditions required for their commercialisation. Each product is given a label with the location where it is stored, and its batch and expiration date.

- Put-Away: movement of products from the receiving dock to the warehouse storage location.
- Storage: Storing the products in their location. If there is already a product in the reserve area, the product is forwarded to the reserve area, otherwise it is stored in the forward area, complying with FEFO (First to Expire First Out) policy.
- Stock Control: control of product expiration date and respective batches, either through the computer system or through lists used for this purpose. Products passed the expiration date are segregated and forwarded to the returns sector.
- Picking: picking the products ordered using ADS, Voice Picking, or manual packing.
- Dispatch/Distribution: organisation by routes of the prepared orders for subsequent distribution by drivers.
- Returns: Inverse logistical process, where the products are collected from the customer for treatment in the returns department. The product can be sent to the supplier, reintegrated into stock or sent to other customers.

Storage and Picking

In all of its logistical platforms, Portlog uses the warehouse areas to improve the processes' effectiveness and efficiency. The pharmaceutical products are located in various areas, depending on their characteristics. They can be located:

- In an Automatic Dispensing System. In this system, high turnover products with adjustable characteristics are placed in channels to optimise the use of labour. The ADS selects the products from the orders and routes them on conveyors to the respective customer tote.
- In a Module Picking System (MPS). In this semi-automated area, products whose physical characteristics do not permit storage in the ADS are stored. This area consists of light shelving and conveyor belts, where picking is carried out to totes using a pick-by-light system.
- In a Cold Room. In this area are placed cold products, narcotics and psychotropic drugs or others that require frequent control. This area consists of a cold room and light shelving for ambient products, and picking is done onto trays that, after picking, are placed on the distribution conveyor belt.
- In the Manual Picking Area. In this area, larger products with more susceptible physical characteristics that do not allow automatic or semi-automatic picking are stored. This area consists of light static and dynamic shelving, and picking is carried out onto trays, which are placed on the distribution conveyor belt after picking.

- In the Automatic sorting system. Products with lower turnover are placed in this area.
- In the reserve area. In this area are placed the products that do not have space in their storage location. This area consists of heavy static shelving.

Automatic Dispensing System

The retrieval of goods from receiving is done cyclically throughout the day. The goods are sorted and wait to be put-away to the storage areas. The products that are picked in the ADS are stored in dynamic shelves, located adjacent to the ADS.

The operator assigned to this task, ensures:

- The correct location of the product by price, expiry date and batch;
- The indication of any change in batch, expiry date and/or price;
- The correct placement of the product in the dynamic shelve, avoiding damage;
- Positioning the product in its designated location;
- Signalling the existence of pallets in reserve;
- The placement of the product evenly distributed by the various rows, when there is a change of batch, deadline and/or price (Figure 2.2);

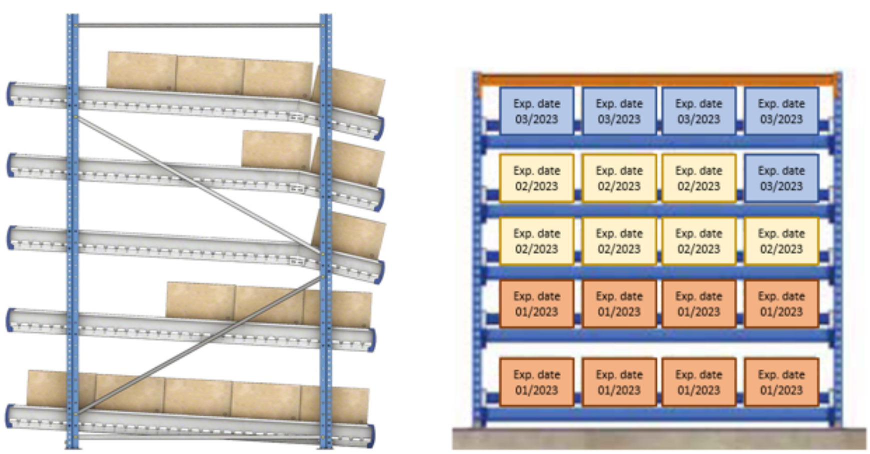

Fig. 2.2 Example of the ordination of goods with several rows per product and with lot changes.

Urgent products have priority storage and a different signposting that implies they must be stowed before the peak period. These products are marked as urgent on the Reception label and have an empty dynamic row. Thus, they are marked with a red flag on the respective product and immediately placed in the dynamic shelf with the identifier placed in the first box of the queue (Figure 2.2). The purpose is to alert the operator who will supply the ADS of the need to prioritise these products.

After storing the products in the dynamic shelves, the product is ready to be placed in the channels of the ADS. This operation is manage by operators. The following requirements must be met when supplying the ADS channels:

- Always validate the product code:
- Always fill the channel from top to bottom to guarantee FEFO (First-Expire, First-Out);
- Level the product through the different channels of the same product when there is a change of lot/expiration date or insufficient stock to fill all the channels;

It should always be pointed out that the ADS channel cannot be supplied with the identifier "product being updated" when changes in product dimensions are detected or when errors are detected in the product ejectors. The ADS is divided into two parts, each of which has small channels and large channels. A product can be located in more than one channel. This division is shown in Table 2.1 and Table 2.2.

Table 2.1 ADS Locations and References

	# SKUs	# Channels
ADS	1007	1264
ADS2	581	795
Total	1588	2059

Table 2.2 Type of Channels in the ADS

	# Large Channels	# Small Channels	Total
ADS	1007	1264	2271
ADS2	581	795	1376
Total	1588	2059	3647

Currently, when replenished, an SKU must have in the channels enough quantity for 1 or 1.5 days of stock. This value was established so that an operator would only have to replenish the channel once per day. Picking in the ADS is done automatically. When the shift manager places the order for ADS, following the circuit through all the areas covered by the order, the quantity requested is downloaded to the ADS. A product is not picked from the ADS for orders greater than 30 units.

The tray diverts in zone M02, and picking is performed by voice, with the operator going to the dynamic storage location by gravity and placing the product directly onto the tray.

A brief analysis of the movement of products over the last 90 days shows that, due to the lack of routine in checking the ADS products, there are products that at first glance do not seem to follow the criteria for being allocated in the automated system, as can be confirmed in Table 2.3.

Table 2.3 ADS products by days in stock

Stock days	# SKUs
>10	170
>1.5	1423
<1	36

According to the analysis, there are 1423 references whose stock lasts more than a day and a half. There are 170 references whose stock lasts more than ten days of these. In turn, there are 36 references whose stock lasts less than a day. It was also found that 15 SKU have had no movement in the last 90 days. These are examples of items that may not be well allocated in the ADS, in the sense that they do not follow the 1.5-day stock criteria and may be occupying the place of products with higher rotation, assigned TO other areas of the warehouse. On the other hand, there are 36 references in which it is verified that the stock is not enough for one day, which may indicate the need for more channels for the product. In these cases, although less than one, the number of days in stock is very close to one. The number of channels is often maintained due to the difficulty in finding another channel close to the one that already exists. On the other hand, as the calculation of days in stock is made taking into account averages, the seasonality of the products and their inconstancy may influence the values.

Managing productivity in the ADS

The ADS management information is contained in a report that can be extracted at any time. This report (Data.xlsx) shows the turnover of all warehouse products in the last 90 days and the following characteristics can be consulted:

- CNP - national product code
- Description - name of the product
- Length of the unit
- Unit width
- Unit width
- 2500 - no. of units that can be placed in a large ADS Channels, with 10

- Unit height 1350 - no. of units that can be placed on a small ADS channel, with a 10
- Weight
- Volume
- Cx Unit - Units per supplier box
- Zone ID - zone ID where the product is located
- Zone - zone where the product is located
- Side - In case the product is located in the ADS, indicates if the channel is large or small
- Shelf/Level/Position - product location
- Total Locs in ADS - no. of channels that the product occupies
- Outbound lines - no. of picking lines
- Quantity Ordered - no. of units ordered
- Days with order - no. of days with order placed
- Outbound quantity - picking units
- Days With Output SUM - no. of days with picking
- Outgoing Rows Over 30 QTY - number of rows with picking over 30 units
- Qty Outflow Greater than 30 QTD - output quantity picked with more than 30 units
- Rows on the longest day - Daily maximum of picking rows
- Largest Day QTY - Maximum Daily Picking Quantity
- Output lines per day ordered - average of picking lines on the days with an order
- Output quantity per day ordered - average picking quantity on the days with an order
- Output lines 30 per day ordered - average of picking lines exceeding 30 pieces on days with an order
- Output Quantity 30 per day ordered - average pick quantity over 30 pieces on days with an order

The report is extracted and processed so that only the necessary information appears in the analysis. The products are sorted in descending order of days out, lines out and quantity out. A new column is created, where the Stock Days/ADS are calculated, which indicate the number of days that the product satisfies in the ADS, calculated as follows and based on the definition of characteristics performed above:

$$StockDaysADS = \frac{\text{Total locations in ADS} * \text{Height unit 2500 or 1350}}{\text{Output quantity per day ordered}}$$

Based on the results obtained in this calculated column, decisions are made to exchange products from locations. It is assumed that a product in ADS must satisfy one day or one and a half days of stock, so products with higher values are transferred to another area, and in products, with lower values, the number of channels is increased. Subsequently, the analysis is performed for the products located in the MPS and Manual Picking, and those that have conditions to be transferred to the ADS are verified. This analysis cannot be performed taking into account only the numbers obtained, as several constraints affect product localisation, namely seasonality, product size, type of carton, and weight, among others.

Current Productivity

Currently, the efficiency of the ADS is measured using the KPI picking lines per zone. A survey of the lines prepared each month by zone is performed, and the weight that each one has inline preparation is calculated, as shown in Table 2.4.

Table 2.4 No. of Lines per picking zone

Zone	#Lines	%
MPS	108799	31.2
M01	11194	3.2
M02	2039	0.6
M03	8951	2.6
M04	8945	2.6
M05	10165	2.9
M06	12649	3.6
DAS	114435	32.9
DAS	71179	20.4

Through this percentage, the analysis is performed, taking into account the efficiency history presented in Table 2.5.

Table 2.5 ADS Efficiency Indicator

Month	Lines	% Lines /ADS	Target (%)
jan	519169	51.9	60
feb	447310	52.2	60
mar	468656	52.6	60
abr	443692	52.6	60
mai	473162	52.2	60
jun	427892	52.7	60
jul	486397	53.0	60
ago	455393	52.6	60
set	435807	52.2	60
out	476196	52.7	60
nov	448642	51.5	60
dez	462864	54.5	60
jan	497275	52.8	60
fev	444149	53.2	60
mar	519661	53.6	60
abr	346120	53.3	60
mai	187470	53.3	60

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Chapter 3
Multi-part production DSS for Fused Deposition Modelling

3.1 Context

Additive manufacturing is a technological manufacturing process where a product is built, by depositing material in successive layers, from digital 3D data. It differs from the traditional manufacturing process (subtractive manufacturing) where the material is carved or shaped into the desired product by parts of it being removed through different technologies, such as machining processes. Additive manufacturing has grown significantly in the last ten years, and some of its manufacturing processes are currently being used at an industrial production level. There are several types of Additive Manufacturing (AM) processes. They can be grouped into seven categories: vat photo polymerisation; material jetting; binder jetting; powder bed fusion; material extrusion; directed energy deposition and sheet lamination. Fused Deposition Modelling (FDM) is one of the most widely used additive manufacturing processes. It is a material extrusion type of AM process based on the extrusion of heated feedstock plastic filaments through a nozzle tip to deposit layers of material onto a build platform to produce parts layer by layer. FDM is the process used in this project.

3.2 Typical workflow of FDM process

The typical workflow of an FDM process comprehends all stages from the idea to the fabrication of the final part. There are six main stages for this process (Figure 3.1):

1. Acquire or Design 3D Models - The first step is obtaining or producing the 3D model that is to be printed, by accessing repositories for 3D models

(e.g. Thingiverse[1] , Grabcad[2]) or using computer-aided design (CAD) software (e.g. SolidWorks[3], Blender[4]).

2. Generate an STL file – The STL model format is the most commonly used input format in FDM printing. STL uses triangles (polygons) to describe the surfaces of an object, without any representation of colour, texture, or other common CAD model attributes.
3. Prepare the model for printing – 3D models need to be prepared for 3D printing using a slicing software, also referred to as slicers (e.g. Cura[5], Netfabb[6]). The slicer has four main functions:
    - generate the support structure needed for parts with severe part overhang;
    - divide the model into horizontal layers, and for each layer describe the necessary movements to extrude the plastic;
    - set the printing parameters information (e.g. temperature, speed, material flow, supports);
    - generate G-code, which is a widely used computer numerical control (CNC) programming language, translates the movements and parameters into machine instructions.
4. Setup the printer - prepare the printer for a new print job. It comprises:
    - heating the hot end to the filament's molten temperature;
    - loading the filament into the heated extruder;
    - heating the build platform;
    - level the build platform.
5. Print the model
6. Post-processing – usually parts require some post-processing work, which has two primary purposes:
    - Support removal – consists of removing the support material added as a support structure. The supports material can be of two types: soluble and insoluble.
    - Surface finishing – consist of improving the surface finish of the parts by mitigating visible layer lines. Examples include sanding, painting, polishing, and smoothing.

[1] https://www.thingiverse.com/
[2] https://grabcad.com/
[3] https://www.solidworks.com/
[4] https://www.blender.org/
[5] https://ultimaker.com/software/ultimaker-cura
[6] https://www.autodesk.com/products/netfabb/

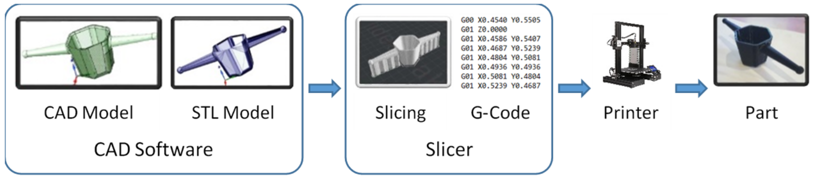


Fig. 3.1 Workflow of FDM process

3.3 FDM printers

There are several types of FDM printers. Without being exhaustive the four main types of designs: Cartesian, Delta, Polar and Scara (Yusuf, 2015). The most common is the Cartesian type. It is named after the Cartesian dimensional coordinate system, which is used to manage positions and movements of the printer. It is a box-type design where the built platform moves along the y-axis, and the extruder moves on the X and Z -axis. The main components of the printer are:

- Print Bed/ built platform - This is the surface where the print will be made.
- Gantry arm - The gantry will control the X (left and right) and Z (up and down) axis movement.
- Feeder - Feeds the specified material to the hot end.
- Hot end – It is where the plastic melts so that it can be deposited onto the print.
- Controller - Manages the spatial movement of the nozzle in the X-Y-Z direction, the feeder, and the hot end.

Figure 3.2 illustrates the essential components on a Creality Ender 3 Pro FDM printer.

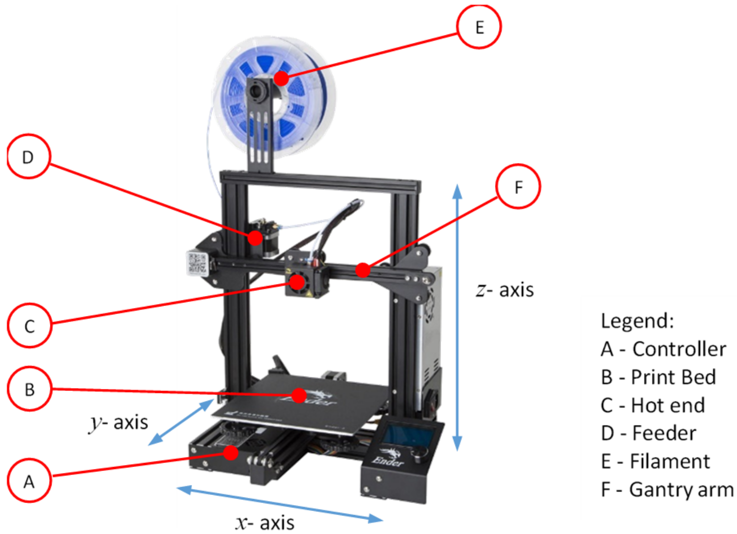


Fig. 3.2 Most Essential Components of an FDM Printer

3.4 Motivation

The FDM layer by layer process offers several advantages in manufacturing, namely the possibility to manufacture several parts on the same build platform simultaneously. The multi-pats printing can lead to significant savings, in setup time and costs (Zhang, Gupta, and Bernard, 2016). It would be expected that to maximise the usage of an FDM machine, the capacity of the build platform should be filled with the maximum number of parts. The problem of placing a set of parts into a build platform, can be seen as an geometric assignment problem, where a set of small items (3d Parts) are to be placed inside a set of larger items (printer build volume) in a way the smaller item do not overlap and lie entirely inside the larger items boundaries. This problem belongs to the more general class of Cutting and Packing problems (Wäscher, Haußner, and Schumann, 2007). According to Wäscher, Haußner, and Schumann, 2007 C&P problems are classified according to dimensionality, kind of assignment, the assortment of large objects, the assortment of small objects and shape of small items. The criterions used by the typology are presented in Table 3.1.

The multi-part placement problem in FDM can be classified as a 3D dimensional problem, with large objects with all dimensions fixed. There are, however, several practical constraints that have a strong influence on the placement solutions of the problem and have to be taken into consideration.

Table 3.1 Cutting & packing typologies based on the classifications of Wäscher et al. (2007)

Dimensionality	**Kind of assignment**
- One dimensional	- Output value maximisation
- Two dimensional	- Input value minimisation
- Three dimensional	
Assortment of large objects	**Assortment of small objects**
- One large object	- Identical small items
All dimensions fixed	- Weakly heterogeneous assortment
One or more variable dimensions	- Strongly heterogeneous assortment
- Several large objects	**Shape of small items**
Identical large objects	(for two- and three-dimensional problems)
Weakly heterogeneous assortment	Regular small items (e.g., rectangles, cylinders)
Strongly heterogeneous assortment	Irregular small items (e.g., polygonal)

Issues like part quality and characteristics of the FDM process are just examples.

3.5 Multi part printing in FDM

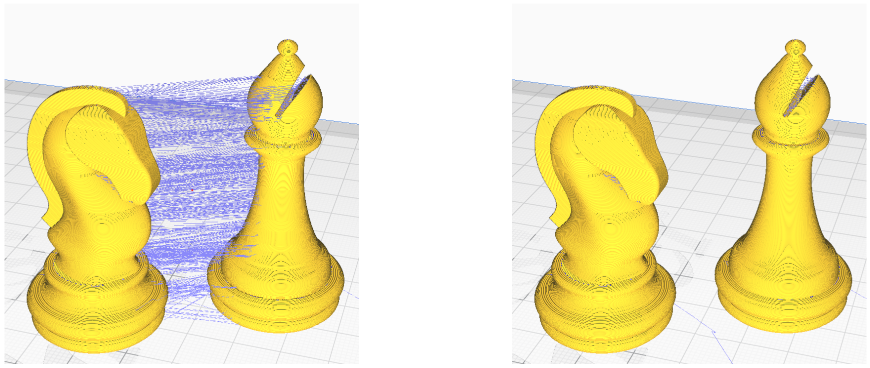
There are two basic types of multi-part (MP) printing in FDM:

- Continuous Printing - The software will generate the slicing of the models of the parts to be printed simultaneously.
- Sequential Printing - The software will generate multiple layers of a single model before transitioning to the next model, so parts are printed one after the other.

Sequential printing offers several advantages (Simplify3D, n.d.):

- Improves the reliability of the overall print – A fail in the FDM process does not ruin the entire batch of parts, only the part currently in printing.
- Improves the print quality - Reducing the amount of movement between models results in a much cleaner surface finish. It also takes advantage of the use of different slicing settings for each model.
- Improves productivity - Reducing the amount of movement between models diminishes the overall printing time.

Figure 3.3 illustrates the difference of the movements between two models, for continuous and sequential multi-part printing. The thin red lines represent movements of the nozzle with no printing.



(a) (b)

Fig. 3.3 Example of continuous (a) and sequential (b) multi-part FDM.

Sequential multi-part FDM (MP-FDM) present one great disadvantage from continuous multi-part FDM. In sequential MP-FDM, the placement of the parts must take into consideration the hardware, i.e., the printing machine dynamic components, so that collision between the parts and the machine does not occur. Collision avoidance is not a constraint for placement of parts in continuous MP-FDM since all parts are built layer by layer simultaneously (Zhang, Gupta, and Bernard, 2016).

In continuous MP-FDM the placement of parts in the build platform can be solved by a 2-dimensional C&P problem with small irregular items, where the shape of the items is given by the contour of each part projected on the build platform, as illustrated in Figure 3.4.

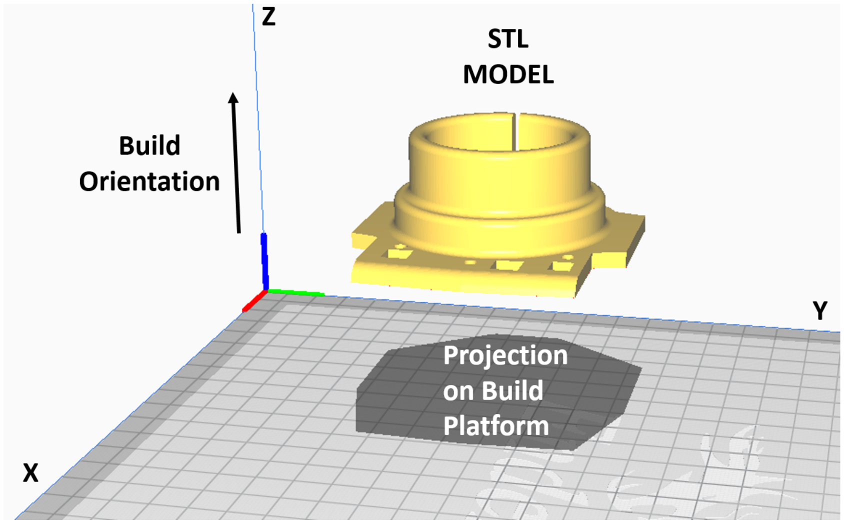
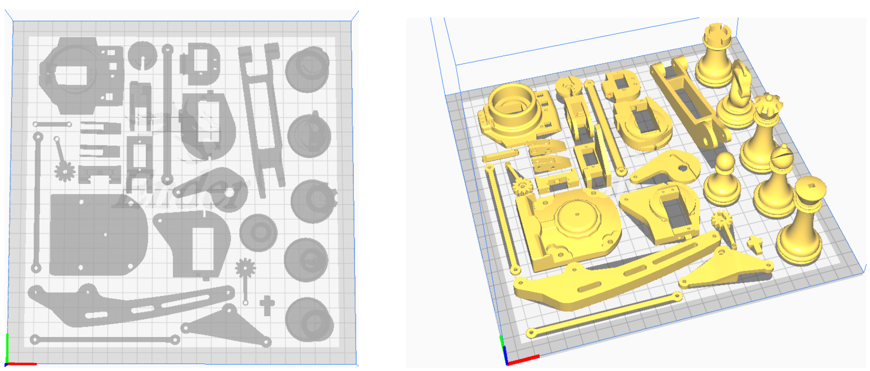


Fig. 3.4 Projection profile of an STL model.

The problem is known in the literature as the Nesting problem. A continuous MP-FDM placement solution is illustrated in Figure 3.5. An introduction to the geometry of the nesting problem can be found in Bennell and Jose F Oliveira, 2008.



(a) (b)

Fig. 3.5 Example of a parts placement solution (a) and (b) the placed parts on the build volume.

The sequential MP-FDM placement of parts in a Cartesian type FDM printer is conditioned by two components, the gantry arm, and the hot end. These are the two dynamic elements that can collide with multiple parts while printing. In Figure 3.6, It can be observed the possibility of a collision on sequential MP-FDM printing.

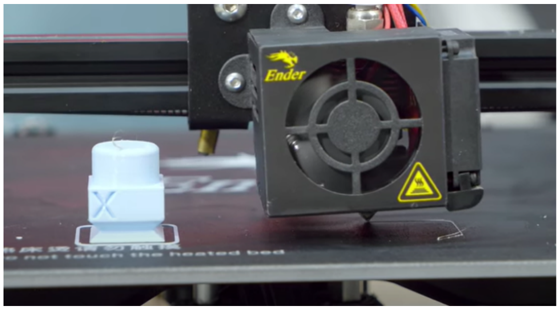


Fig. 3.6 Sequential Multi-part FDM printing.

Given the current industrialisation of AM processes such as FDM, algorithms to the MP-FDM models placement problem, are of great importance.

3.6 Problem description

The problem to address in this project can be stated as follows: a given set composed of different types of small items of irregular shape $k = 1, ..., K$, known as parts, each with a given CAD Model and a minimum surface quality q_k, is to be produced using sequential MF-FDM in a build volume of parallelepiped shape, designated as container C, characterised by its depth (D), width (W) and height, (H). The objective is to achieve in a single setup, the maximum number of produced sets while meeting the following constraints:

- Each model can only rotate about the z-axis;
- Only one set of parts can be incomplete;
- The CAD software is SolidWorks 2019;
- The slicer is Ultimaker Cura 4.6.1;
- The FDM printer is the Creality Ender 3 Pro.

The solution to the problem should provide the quantity of each model to be printed, the location of each model inside the container, the printing sequence of the models, and the G-Code for the printer. The overall problem can be divided into three subproblems:

1. Development and implementation of a mathematical model, heuristic, or metaheuristic for optimal parts placement (Difficulty level – A) The subproblem consists in optimally placing the parts models into the build volume of an FDM printer, using sequential MF-FDM. According to the

typology of Wäscher, Haußner, and Schumann, 2007 the problem can be characterised as a 3-dimensional, output maximisation problem, with one large object with all dimensions fixed, with strongly heterogeneous irregular small items and additional constraints.

2. An algorithm to extract the 2-dimensional profile of a part, from the STL model or the G-Code. (Difficulty level – A)
3. An algorithm to merge G-Code of single parts printing into a multi-part G-Code, given the parts placement and the printing sequence solution. (Difficulty level – C)

Each group will select only one of the three subproblems. The degree of difficultuy of the subproblem is graded given the following qualitative scale: A – Hard; B – Moderate; C – Easy.

For the testing and evaluation of the performance of the proposed solutions, a set of instances based on the SHAPES instance group (José F Oliveira, Gomes, and Ferreira, 2000), is available in the UC page on Moodle. The models of the parts are illustrated in Figure 3.7.

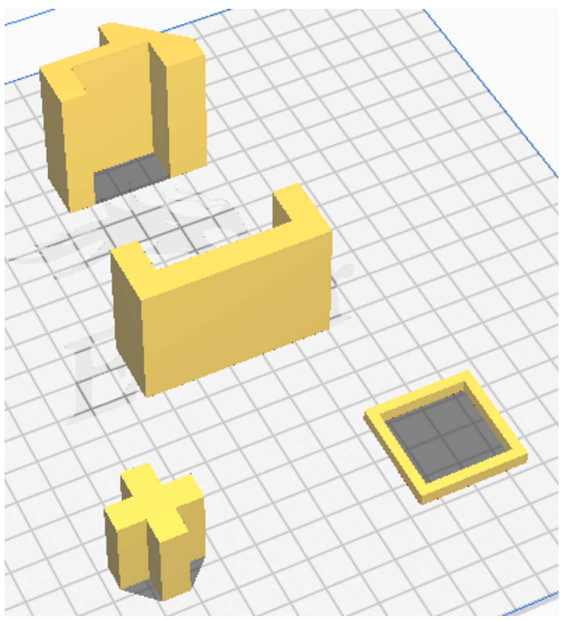


Fig. 3.7 Piece types of the SHAPES instances

A CAD model of the Creality Ender 3 Pro printer (Figure 3.8) is available in Evgeniy, 2020.

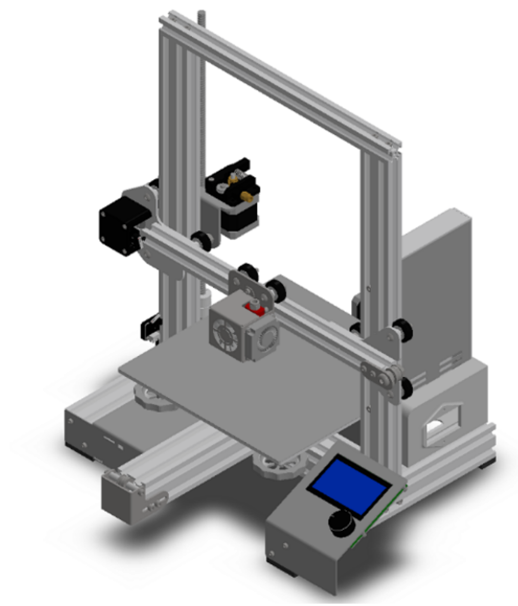


Fig. 3.8 Creality Ender 3 Pro CAD Model

3.7 Deliverables

The deliverables of the project are:

- The report of the solution proposal
- The solution (algorithms/applications)
- The presentation

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Chapter 4
Nomolde
Optimization of a Plastic Injection Production System

4.1 Introduction

Nomolde is an thermoplastics injection company, focusing its activity on the Automobile Industry. This case study focuses on the injection moulding department of the company. As is the practice in the automotive industry, the manufacturing facilities work in just-in-time for all of its customers. This translates into a maximum response time of 48 hours for orders placed via the Electronic Data Interchange (EDI) system.

The JIT systems puts continuous pressure on scheduling and manufacturing to meet the required service levels. Currently the company is struggling to meet the target service levels. The current scheduling process in a near manually procedure using Excel spreadsheets. The process it is a bit daunting as the scheduler needs to retrieve from the company Enterprise Resource Planning (ERP) and from the Manufacturing Execution System (MES) data to perform the daily schedule of the production.

As a result, Nomoldes is convinced that existing production lines in the factories are underoptimized. This conviction gained more strength during the pandemic period, in particular due to the need to reconvert what needs to be produced, the type of product and quantities, the production lines take a long time to adapt and do not take so considering an overview of the plant.

This project aims to study the current process, develop and implement an integrated model of global optimization of the production system that allows generating decision support scenarios in a fast way.

4.2 Description of the Production System

The injection-molding department, whose problem motivates this project, is one of the three departments in a supplier plant of an automotive plastic parts company. It produces several plastic parts for shipment to final assembly plants. The molding plant's objective is to meet daily demand of parts subject to constraints on capacity, machine eligibility, and operator availability. In the plant, there are two additional resource types other than machines: dies and machine operators. There are 141 dies used in the manufacture of more than 260 plastic parts on 39 injection-molding machines. Each part has a die associated with it and its manufacture is completed at a single machine. The same die may be used to manufacture various parts by the introduction of different material compositions. Dies can be mounted on machines according to their compatibilities. Since there is only one die of each type, no parts that share the same die can be processed at the same time. In addition, machine operators are required during the processing of the parts, for monitoring the machines, unloading and inspecting the plastic parts, and trimming extra material. The plant operates 8h per shift, three shifts a day, and 5 days a week.

An MRP system generates the weekly production orders for all parts. The managers of the plant aim to finish the manufacture of the current order quantities as soon as possible in order to leave an amount of time and resource (machine and operator) capacity to the newly incoming orders that may occur along the current week. Henceforth, the objective function is chosen as the minimization of makespan, i.e., the time required to complete all parts. The aim of the project is to develop a scheduling system that will receive MRP orders at the start of each week and then generate the load of machines and the sequence of parts that minimizes the makespan.

4.3 Parallel Machine Scheduling with Setups and Resources

In most of the Parallel Machine Scheduling (PMS) studies, the only resource considered is the machine. However, in most real-life manufacturing environments, jobs also require, beside machines, certain *additional resources*, such as automated guided vehicles, machine operators, tools, pallets, dies and industrial robots, for their handling and processing (Słowiński, 1980; Blazewicz, Lenstra, and Kan, 1983; Ventura and Kim, 2000). Thus, the study of PMS with additional resources is a significant area of research.

Resource-constrained scheduling problems (RCPMSP) are difficult because, as well as the efficient allocation of jobs, it is necessary to consider the feasible grouping of simultaneously processed jobs that will use resources within their availability limits at each point in time (Pinto and Grossmann, 1997).

In the field of PMS with additional resources, a new class of problems, named parallel machine flexible resource scheduling (PMFRS), was introduced by Daniels, Hoopes, and Mazzola, 1996. A PMFRS problem is formally defined as follows. A set of n jobs is processed on a set of m machines where assignment of jobs to machines is specified a priori. In addition, processing of each job requires a single renewable scarce resource and the processing time of each job is a non-increasing function of the associated amount of the allocated resource.

When compared to the RCPMSP, the distinguishing feature of the PMFRS problem is the dependence of the processing time on the additional resource allocated.

The PMFRS problem in its original form assumes that the assignment of jobs to machines is pre-specified, which eliminates the job-machine assignment sub-problem (Daniels, Hoopes, and Mazzola, 1996). If the assignment of jobs to machines is not specified, we face a more general problem, i.e., the unspecified PMFRS (UPMFRS) problem, where an additional job-machine assignment sub-problem is to be solved (Daniels, Hua, and Webster, 1999).

Consistent with the definition given by Blazewicz, Brauner, and Finke, 2004, we call an additional resource *processing resource* if it is required together with a machine (processor) during the processing of a job. Otherwise, i.e., if the resource is required either before or after the processing of a job, then it is called *input–output* resource.

The additional resources are further classified with respect to their renewability (*resource constraints*) and divisibility (*resource divisibility*) (Słowiński, 1980; Blazewicz, Ecker, et al., 2019). From the viewpoint of resource constraints (Słowiński, 1980; Blazewicz, Ecker, et al., 2019):

- A resource is *renewable*, if its only total usage at every moment is constrained. Once it is used for a job, it may be used again for another job.
- A resource is *non-renewable*, if its total consumption is constrained. In other words, once it is used by some job, it cannot be available for any other job.
- A resource is *doubly constrained*, if it is both renewable and non-renewable.

From the viewpoint of resource divisibility (Słowiński, 1980; Blazewicz, Ecker, et al., 2019):

- *Discrete resources* can be allocated to jobs in discrete units from a given finite set of possible allocations.
- *Continuous resources* can be allocated to jobs in arbitrary amounts within an interval.

They are also considered *dynamic* when resources are not fixed for the whole time horizon.

Besides the additional resources, jobs may often not be processed on any of the available machines but rather must be processed on a machine belonging to a specific subset of the machines (Pinedo, 1995). This situation, called machine *eligibility restrictions*, is also widely encountered in real scheduling environments.

In this project, we are going to consider the general problem with setups and different kinds of resources:

1. specific resources for processing, needed to process a job on a machine,
2. specific resources for setups, needed to do the previous setup before a job is processed on a machine,
3. shared resources, understanding these as unspecific resources that could also be needed in both processing or setup. As an example, consider a plastic processing plant where cleaning equipment is the specific setup resource, molds are the specific processing resource and workers are the unspecific shared resource. Workers are needed to operate the cleaning equipment (setups) and line machines (processing). Another example is when you have specialized workers as in a ceramics factory where there are setup engineers (setups), technical line workers (processing) and unspecialized helpers that have auxiliary tasks to help in both, processing or setups.

Notice that when resources are present, not only assignment and sequencing is needed because it is also necessary to know the time when each job begins since idle time can be present due to resource shortages (referred to as timing). When considering, for the Unrelated Parallel Machine scheduling problem, the Setup and Resources, it could be called UPMSR (Fanjul-Peyro, 2020).

4.4 UPMSR Model 1 based on strip-packing

In a strip-packing 2D problem a set of rectangles must be fit in a box which has one of its dimensions fixed. The objective is to minimize the other dimension. Each rectangle has a height and a width. An approximation to the UPMR (Fanjul-Peyro, 2020) could be to understand that each job has a width, delimited by its processing time (p_{ik}), and a height, set by the number of resources needed for it to be processed (r_{ik}). In strip-packing it is necessary to know the localization of each rectangle, in this case through the coordinates of its top-right corner. In the case of UPMR, where axis x represents time and axis y the number of resources, the coordinates will be given by C_k and R_k respectively. C_k represents the time when job k is finished and R_k the point or height of number of resources. The fixed dimension is height H set by R_{max} and total width W is determined by C_{max}.

For the complete UPMSR problem we need to consider six factors: the processing times, the setup times, the P-resources, the S-resources, the H-resources used for job processing and the H-resources used for machine setups.

Definitions:

- UPM- Unrelated Parallel Machine scheduling problem

- UPMS- Unrelated Parallel Machine scheduling problem with sequence dependence Setup times
- UPMR- Unrelated Parallel Machine scheduling problem with Resources needed to process the jobs
- The resources are assumed as *renewable*, meaning that after their use they are again available and *discrete*, because there are an integer number of resources.
- *unspecified* Parallel Machine scheduling problem when there is no prefixed job-machine assignment,
- *dynamic* Parallel Machine scheduling problem when resources are not fixed for the whole time horizon.
- When resources are present, not only assignment and sequencing is needed because it is also necessary to know the time when each job begins since idle time can be present due to resource shortages.
- UPMSR- Unrelated Parallel Machine scheduling problem with the Setup and Resources.

Parameters:

- A set of n jobs to be processed, $N = \{1, \ldots\ n\}$, indexed by j, k.
- A set of m machines that can process the jobs, denoted as $M = \{1, \ldots,$ $m\}$, indexed by i.
- p_{ij} denotes the time needed for machine i to process job j.
- s_{ijk} denotes the time needed to do the setup on machine i between job j and k.
- $r^P_{\max}$ are the maximum amount of Processing resources. Some of these are needed specifically for Processing jobs, and cannot be used for machine setups. We denote these resources as P-resources.
- $r^S_{\max}$ are the maximum amount of Setups resources. Some of these are needed specifically for machine Setups, and cannot be used for job processing. We denote these resources as S-resources.
- $r^H_{\max}$ are the maximum amount of unspecific resources that are sHared by both, needs of job processing and needs of machine setups. We denote these resources as H-resources.
- r^P_{ij} are resources of P-resources needed to process job j on machine i.
- r^S_{ijk} are the resources of S-resources needed to do setup between job j and job k on machine i.
- r^{Hp}_{ij} are the resources of H-resources needed to process job j on machine i. Processing job j on machine i could require r^P_{ij} of P-resources and r^{Hp}_{ij} of H-resources.
- r^{Hp}_{ijk} are the resources of H-resources needed to do setup between job j and job k on machine i. Doing the setup on machine i between jobs j and k could require r^S_{ijk} of S-resources and r^{Hp}_{ijk} of H-resources.

Decision Variables:

- $X_{ijk} = 1$ if job k is processed immediately after job j on machine i, zero otherwise.
- $Y_{ik} = 1$ if job k is processed on machine i, zero otherwise.
- C_j - completion time of job j (coordinate where processing of job j finishes in the time dimension)
- B_j - completion time of the setup before the processing of job j on the corresponding machine (coordinate where setup of job j finishes in the time dimension)
- $R_j^P \in \left[0, R_{\max}^P\right]$- coordinate of processing of job j in the P-resources dimension (the specific resources employed in the processing of job j).
- $R_j^S \in \left[0, R_{\max}^S\right]$- coordinate of setup of job j in the S-resources dimension (the specific resources employed in the setup before processing of job j).
- $R_j^{\mathrm{Hp}} \in \left[0, R_{\max}^H\right]$- coordinate of processing of job j in the H-resources dimension (the unspecific shared resources employed in the processing of job j).
- $R_j^{\mathrm{Hs}} \in \left[0, R_{\max}^H\right]$- coordinate of setup of job j in the H-resources dimension (the unspecific shared resources employed in the setup before processing of job j).
- D_{jk}^P, E_{jk}^P, F_{jk}^S, G_{jk}^S are binary auxiliary variables with value $= 1$ when the variable value studied in constraints (time or resources) of job k is higher than the variable value studied (time or resources) of job j. The letters in superscript are used to indicate the dimension where they are used.

$$\text{minimize } C_{\max} \tag{4.1}$$

$$\sum_{j\in N_0}\sum_{k\in N,k\neq j} s_{ijk}X_{ijk}+\sum_{k\in N} p_{ik}Y_{ik}\le C_{\max}, i\in M \tag{4.2}$$

$$\sum_{k\in N} X_{i0k}\le 1, i\in M \tag{4.3}$$

$$\sum_{i\in M} Y_{ik}=1, k\in N \tag{4.4}$$

$$Y_{ik}=\sum_{j\in N_0,\ j\neq k} X_{ikj}, i\in M, k\in N \tag{4.5}$$

$$Y_{ik}=\sum_{j\in N_0,\ j\neq k} X_{ijk}, i\in M, k\in N \tag{4.6}$$

$$C_k-C_j+BigM(1-X_{ijk})\ge s_{ijk}+p_{ik}, i\in M,\ j\in N_0,\ k\in N,\ j\neq k \tag{4.7}$$

$$C_k\le C_{\max}, k\in N \tag{4.8}$$

$$X_{ijk}\in 0,1, Y_{ik}\ge 0, C_k\ge 0, C_0=0 \tag{4.9}$$

$$B_k\le C_k-\sum_{i\in M} p_{ik}Y_{ik}, k\in N \tag{4.10}$$

$$B_k-C_j+BigM\left(1-\sum_{i\in M} X_{ijk}\right)\ge\sum_{i\in M} X_{ijk}s_{ijk}, j\in N_0, k\in N, j\neq k \tag{4.11}$$

$$C_k\ge\sum_{i\in M}\sum_{j\in N_0} X_{ijk}s_{ijk}+\sum_{i\in M} p_{ik}Y_{ik}, k\in N \tag{4.12}$$

$$R^P_{\max}\ge R^P_k\ge\sum_{i\in M} r^P_{ik}Y_{ik}, k\in N \tag{4.13}$$

$$R^S_{\max}\ge R^S_k\ge\sum_{i\in M,j\in N} r^S_{ijk}X_{ijk}, k\in N \tag{4.14}$$

$$R^H_{\max}\ge R^{HP}_k\ge\sum_{i\in M} r^{HP}_{ik}Y_{ik}\ge R^{HS}_k\ge\sum_{i\in M,j\in N_0} r^{HS}_{ijk}X_{ijk}, k\in N \tag{4.15}$$

$$C_k-C_j+BigM\left(1-D^P_{jk}\right)\ge\sum_{i\in M} p_{ik}Y_{ik}, j,k\in N, j\neq k \tag{4.16}$$

$$R^P_k-R^P_j+BigM\left(1-E^P_{jk}\right)\ge\sum_{i\in M} r^P_{ik}\ Y_{ik},\ j,k\in N, j\neq k \tag{4.17}$$

$$D^P_{jk}+D^P_{kj}+E^P_{jk}+E^P_{kj}\ge 1, j,k\in N, j\neq k \tag{4.18}$$

$$\tag{4.19}$$

$$B_k - B_j + BigM\left(1 - F_{jk}^S\right) \geq \sum_{i \in M, l \in N_0} X_{ilk} s_{ilk}, j, k \in N, j \neq k \tag{4.20}$$

$$R_k^S - R_j^S + BigM\left(1 - G_{jk}^S\right) \geq \sum_{i \in M, l \in N_0} r_{ilk}^S X_{ilk}, j, k \in N, j \neq k \tag{4.21}$$

$$F_{jk}^S + F_{kj}^S + G_{jk}^S + G_{kj}^S \geq 1, j, k \in N, j \neq k \tag{4.22}$$

$$C_k - B_j + BigM\left(1 - U_{jk}^{HP}\right) \geq \sum_{i \in M} p_{ik} Y_{ik}, j, k \in N, j \neq k \tag{4.23}$$

$$B_j - C_k + BigM\left(1 - U_{kj}^{HS}\right) \geq \sum_{i \in M, l \in N_0} X_{ilj} s_{ilj}, j, k \in N, j \neq k \tag{4.24}$$

$$R_k^{HP} - R_j^{HS} + BigM\left(1 - V_{jk}^{HP}\right) \geq \sum_{i \in M} r_{ik}^{HP} Y_{ik}, j, k \in N, j \neq k \tag{4.25}$$

$$R_j^{HS} - R_k^{HP} + BigM\left(1 - V_{kj}^{HS}\right) \geq \sum_{i \in M, l \in N_0} r_{ilj}^{HS} X_{ilj}, j, k \in N, j \neq k \tag{4.26}$$

$$U_{jk}^{HP} + U_{kj}^{HS} + V_{jk}^{HP} + V_{kj}^{HS} \geq 1, j, k \in N, j \neq k \tag{4.27}$$

In this model the Eq. (4.1) shows the objective. Constraints (4.2) define the makespan where all setup times and processing times are added for each machine. In constraints (4.3) state that no more than one job is scheduled after the dummy job at the beginning of each machine. Constraints (4.4) force each job to be assigned to only one machine. Constraints (4.5) and (4.6) ensure that only one job be done immediately before and only one job immediately after (respectively) each job if jobs are assigned to the same machine, including dummy jobs. Constraints (4.7) break subtours and give the right scheduling order, because if k is processed after j on machine i, it forces finishing the processing of job k not earlier than $s_{ijk} + p_{ik}$. Constraints (4.8) establish the relationship between C_{max} and completion times of each job. Finally, (4.9) set the limits of variables and set the completion time of the dummy jobs to zero. Notice that Y_{ik} can be relaxed to positive variable instead of binary since (4.5) and (4.6) are a sum of binary variables and (4.4) make its sum be equal to 1.

Constraints (4.13) and (4.14) set the coordinate limits of specific resources used in processing (R_k^P) and used specifically in setups (R_k^S). Constraints (4.15) are the same for unspecific shared resources. Notice that the maximum shared resources available (R_{max}^H) is the same for shared resources used in processing or shared resources used in setups.

Constraints (4.16) show that, if C_k is later than $C\ textsubscriptj$, the difference between these completion times is greater than or equal to the processing time of job k. As an example, binary auxiliary variable D_{jk}^P has value 1 when this occurs and zero otherwise. In (4.17), if R_k^P is greater than R_j^P , the difference between coordinates of these resource points is greater than or equal to the resources used in the job k processing. Finally, (4.18) force at least one of the binary variables to have the value of 1. Since the constraints are defined for all j and k, this implies that, at least: or j precedes k without overlapping its processing on the time axis, or k precedes j without overlapping its processing on the time axis, or the j resource coordinate is higher than k without overlapping its processing resources on the P-resources axis, or the k resource coordinate is higher than j without overlapping its processing resources on the P-resources axis.

Constraints (4.20) show that, if B_k is later than B_j, the difference between these setup finishing times is greater than or equal to the setup time of job k. As an example, binary auxiliary variable F_{jk}^{S} has value 1 when this occurs and zero otherwise. In (4.21), if R_k^S is greater than R_j^S , the difference between coordinates of these resource points is greater than or equal to the resources used in the job k setup. Finally, constraints (**??**) force at least one of the binary variables to have the value of 1. Since the constraints are defined for all j and k, this implies that, at least: or j precedes k without overlapping its setups on the time axis, or k precedes j without overlapping its setups on the time axis, or the j resource coordinate is higher than k without overlapping its setup resources on the S-resources axis, or the k resource coordinate is higher than j without overlapping its setup resources on the S-resources axis.

In constraints (4.23) we show the case when the processing finishing time of job k is later than the setup finishing time of job j. Therefore, the difference between finishing times must be equal to or greater than the processing time of job k. In this case, as an example, the binary auxiliary variable $U_{\mathrm{jk}}^{\mathrm{HP}}$ has value 1 when setup of job j is done before processing job k and zero otherwise. In (4.24) we find the inverse case, where setup finishing time of job j is later than processing finishing time of job k. So, the difference between finishing times must be equal to or greater than the setup time of job j. Eqs. (4.25) and (4.26) are similar constraints to the two previous constraints but in this case using shared resources. Finally, (4.27) force at least one of the binary variables to have the value of 1.

4.5 UPMSR Model 2 based on time

Other MILP models can be considered. In the Model 1, a spatial approximation is used when the strip-packing problem is adapted to be used with resources. However, a temporal approximation could be used (Fanjul-Peyro, L., 2020). The new input data for UPMSR temporal MILP are:

- $E_{ikt} = 1$ if job k is being processed on machine i in time t, zero otherwise.
- $F_{ijkt} = 1$ if job k is in setup after job j on machine i in time t, zero otherwise.
- t_{max} is a time that is large enough.

For this MILP we use Eqs. (4.1)–(4.9) and define B_k as the time when setup of job k is finished.

$$\sum_{t \leq t_{\max}} E_{ikt} \geq p_{ik} Y_{ik}, i \in M, k \in N \tag{4.28}$$

$$C_k \geq \sum_{i \in M} t E_{ikt}, k \in N, t \leq t_{\max} \tag{4.29}$$

$$C_k + 1 - \sum_{i \in M} p_{ik} Y_{ik} \leq \sum_{i \in M} t E_{ikt} + BigM \left(1 - \sum_{i \in M} E_{ikt}\right), k \in N, t \leq t_{\max} \tag{4.30}$$

$$\sum_{t \leq t_{\max}} F_{ijkt} \geq s_{ijk} X_{ijk}, i \in M, j \in N_0, k \in N, j \neq k \tag{4.31}$$

$$B_k \geq \sum_{i \in M, j \in N_0} t F_{ijkt}, k \in N, t \leq t_{\max} \tag{4.32}$$

$$B_k + 1 - \sum_{i \in M, j \in N_0} s_{ijk} X_{ijk} \leq \sum_{i \in M, j \in N_0} t F_{ijkt} + BigM \left(1 - \sum_{i \in M, j \in N_0} F_{ijkt}\right), k \in N, t \leq t_{\max} \tag{4.33}$$

$$R^P_{\max} \geq \sum_{i \in M, k \in N} r^P_{ik} E_{ikt}, t \leq t_{\max} \tag{4.34}$$

$$R^S_{\max} \geq \sum_{i \in M, j, k \in N, j \neq k} r^S_{ijk} F_{ijkt}, t \leq t_{\max} \tag{4.35}$$

$$R^H_{\max} \geq \sum_{i \in M,\ k \in N} r^{HP}_{ik} E_{ikt} + \sum_{i \in M, j, k \in N, j \neq k} r^{HS}_{ijk} F_{ijkt}, t \leq t_{\max} \tag{4.36}$$

Constraints (4.28) and (4.29) are the limits of (E_{ikt}). Eq. (4.30) forces when (E_{ikt}) has value 1 at time t, this time t is greater than or equal to the difference between the completion time of job k and its processing time plus 1. Constraints (4.31)–(4.33) represent the same but for setups, where the time to be considered is s_{ijk}.

Constraints (4.34) force that, at each time t, the sum of all resources used in processing should be lower than or equal to the maximum resources to process. Constraints (4.35) force that, at each time t, the sum of all resources used in setups should be lower than or equal to the maximum resources for setups. Constraints (4.36) force that, at each time t, the sum of all shared resources used in processing and all shared resources used in setups should be lower than or equal to the maximum shared resources.

4.6 Projects

The following projects are available for teams of a maximum of four students:

1. Implement Model 1 in Pyomo mathematical programming language, using *Excel Solver Studio* or *Python* platform, solve the problem for the supplied instance test data using the COIN-OR, CPLEX and Gurobi solvers, and compare the results.
2. Implement Model 2 in Pyomo mathematical programming language, using *Excel Solver Studio* or *Python* platform, solve the problem for the supplied instance test data using the COIN-OR, CPLEX and Gurobi solvers, and compare the results.
3. Using *Python* programming language, solve the problem for the supplied instance test data adapting the metaheuristic approach of the paper "Al-Harkan, I.M. and Qamhan, A.A., 2019. Optimize unrelated parallel machines scheduling problems with multiple limited additional resources, sequence-dependent setup times and release date constraints. *IEEE Access*, *7*, pp.171533-171547".
4. Using *Python* programming language, solve the problem for the supplied instance test data adapting the metaheuristic approach of the paper "Yepes-Borrero, J.C., Villa, F., Perea, F. and Caballero-Villalobos, J.P., 2020. GRASP algorithm for the unrelated parallel machine scheduling problem with setup times and additional resources. *Expert Systems with Applications*, *141*, p.112959".

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Chapter 5
Decision Support System for Inventory Management

5.1 Context

A beverage distribution company has a distribution center (DC) located in the Porto district. The DC, as part of the supply chain, has the main functions of storing items from different beverage producers and preparing and consolidating orders for different customers.

Items

The main items distributed from the DC are soft drinks and water. The items, indicated in Table 5.1, are supplied by two companies, one for water and another for soft drinks. For all items, there are units of commercialization (packs) and transportation (Euro-pallets).

Family	Item	Unit./Pack	Pack/Pallet	Weight/Pallet (kg)
Soft Drinks	Can 0.33	24	54	727
	Bottle PET 1L	6	100	667
	Bottle PET 1,5L	6	84	798
Water	PET 0.33	6	320	707
	PET 0.50	24	60	771
	PET 1.5L	6	84	801
	PET 5L	2	72	758

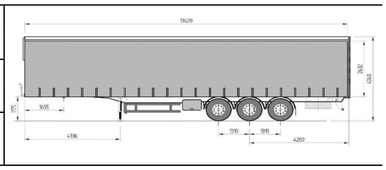
Table 5.1 Distributed Items.

The daily demand for the items in units of commercialization in the last 15 months is indicated in the file Dados_TG.xlsx (This file is sent by email to each working group after receiving an email with the group composition).

Inbound Transportation

The inbound transportation from suppliers to the DC is carried out by semi-trailer trucks with standard side curtains, as specified in Table 5.2. The unit of transportation for the items is the full pallet (pallet composed of identical items with the base occupied at its maximum capacity).

Table 5.2 Specifications of Semi-Trailer

Dimensions (m×m×m)	$13,62 \times 2,48 \times 2,72$	
Load Capacity (Euro pallets of floor space)	34	
Maximum Load Weight (kg)	25000	

Storage

The DC operates five days a week, from Monday to Friday, between 8:00 and 18:00. Deliveries to the DC are made in the morning from 8:00 to 12:00. Shipment from the DC to its customers is done during the afternoon period between 13:00 and 18:00.

Goods are received at the warehouse docks, where semi-trailer trucks are unloaded using electric pallet jacks. After checking the unloaded merchandise, the entry of the items is recorded in the warehouse information system. After receiving, the items are either stored or undergo cross-docking. In the case of storage, a location is assigned to the respective pallet. Storage is done in conventional shelving.

After the items are stored, order preparation for shipment (outbound) takes place. In the shipment process, approximately 80% of the items are shipped on full pallets, and 20% on picking pallets (pallets not fully occupied). Cross-docking is only performed for full pallets. When the shipment is made, the departure of the items from the warehouse is recorded.

Replenishment of Items at the Distribution Center

Currently, the responsibility for placing orders with water and soft drink suppliers lies with the Purchasing Department. They receive a daily file from the Commercial Department with records of daily aggregate demand per item and from the Operations Department with the quantity dispatched daily, aggregated by item (An example of these files is sent by email to each working group after receiving an email with the group composition).

Inventory management of each item is independent, and orders placed with suppliers are made to provide coverage for one week of demand. Orders are placed on the day when a predetermined inventory level is reached for each week (order level). Whenever inventory of an item is depleted, the order is placed, i.e., the customer is served as soon as the item is available for shipment.

Let $\overline{D}_i$ be the average weekly demand for the last five weeks prior to week i, L be the supplier lead time, and D_i^s be the second highest value of weekly demand in the last five weeks. The order level (NE_i) is defined as the estimated demand during the lead time plus a safety factor to accommodate demand variations. The expression for the order level is presented in Equation 5.1.

$$NE_i = \overline{D}_i \times L + (D_i^s - \overline{D}_i) \tag{5.1}$$

The quantity of pallets to order Q is determined at the end of day t when the order level is reached, considering the actual values of demand y_t and the inventory level at the end of day I_t. The quantity to order is determined by Equation 5.2.

$$Q_t = \left\lceil \frac{2 \times (NE - I_t) + \sum_{j=t-5+1}^{t} Y_t}{\#packs/pallet} \right\rceil \tag{5.2}$$

Orders are placed at the end of the day and have a lead time such that orders placed on day t are received on day $t+4$. The days t refer to weekdays.

The inventory level of each item on January 6, 2019, is indicated in the file Dados_TG.xlsx.

5.2 Future Scenario

Starting from March 2, 2020, the water and soft drink suppliers will change their delivery policy as follows:

1. The soft drink supplier will send the orders placed by the DC in the previous week every Monday, in full load, i.e., always utilizing the maximum capacity of the semi-trailers (whether it is the number of pallets or the weight).
2. The water supplier will send the articles on any day of the week, also in full load, but they need to receive the orders with a two-business-day notice. For example, an order placed on Monday will be delivered on Wednesday of the same week.

Both suppliers allow for different articles to be sent on the same semi-trailer. According to the company's expectations, overall demand is not expected to undergo significant changes in the coming years.

5.3 Problem Description

Due to the changes in the delivery policies by the suppliers, the company aims to determine the most suitable model for managing inventories and develop a computer tool for inventory management at the DC. To achieve this objective, the task has been divided into 3 phases:

1. Characterization of the current situation:
   - Based on the inventory management system in place until February 28, 2020, and existing historical data, determine the value of performance indicators (service level, stockout rate, and average stock) and the inventory level of each item on March 1, 2020.
   - Characterize the time series of demand for each item.
2. Define and parameterize future inventory management models:
   - Define forecasting and inventory management models.
   - Determine the optimal parameters for the forecasting and inventory management models.
   - Define rules for parameter updating.
   - Design performance levels and costs of the proposed solutions.
   - Define the data model for the inventory management tool.
3. Develop the inventory management tool. The tool should include at least the following functionalities:
   - Recording daily demand for each article.
   - Recording the quantity dispatched for each article per day.
   - Determine performance indicators.
   - Generate reports and consumption statistics by article and article families.
   - Generate inventory replenishment alerts.
   - Propose inventory replenishment orders to suppliers.
   - Issue alerts for changes in article behavior (work valuation factor).

Note: Whenever necessary information for problem-solving is not available, assumptions should be made.

Chapter 6
Configuration of a Warehouse of Finished Products

6.1 Context

A sugar refining and marketing company has its facilities located in the Aveiro district. The facilities are divided into two units: the refining unit and the packaging unit. The refining unit has a capacity of 100,000 tons per year and operates 24 hours a day, 7 days a week, for 11 months. The packaging unit is responsible for packaging, storage, and shipment of the different products sold by the company. Storage and shipment take place in the Finished Product Warehouse (FPW), an area that must be physically separated from the area where the packaging machines are located. The customers are the top 10 national retail distributors.

The packaging unit has been experiencing service levels below the company's defined objectives, largely due to old equipment with low productivity, low automation level, and an inefficient configuration. The current configuration is the result of the company's adaptive growth to changes in demand over time. In order to improve service levels, the company has acquired a set of new packaging equipment, which requires redesigning the configuration of the packaging unit. The reconfiguration work carried out so far has focused mainly on determining the layout for the new packaging equipment. Figure 6.1 shows the layout of the company, where the location of the refining unit, the packaging area, and the available area for the FPW can be identified. The usable height of the FPW is 9 meters.

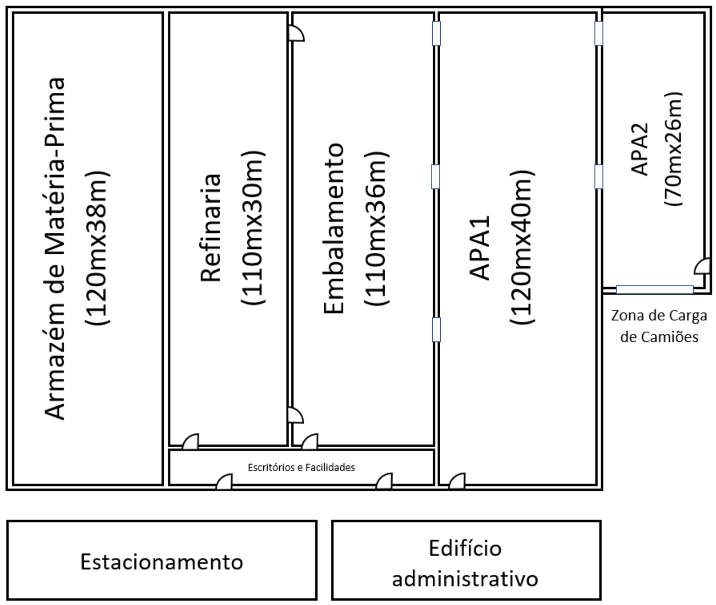


Fig. 6.1 Simplified layout.

The Items

The main items distributed from the FPW are indicated in Table 6.1. For all items, the designation, type of sugar, form, and primary packaging are indicated.

Item	Type	Form	Packaging
White Granulated Sugar	White	Granulated	1 kg
White Granulated Sugar	White	Granulated	1 kg
White Granulated Sugar	White	Granulated	2 kg
Brown Sugar	Brown	Granulated	500 g
White Granulated Sugar - sachets	White	Granulated	1 kg
White Granulated Sugar - sachets	White	Granulated	600 g
White Powdered Sugar	White	Powder	250 g
White Granulated Sugar - cubes	White	Cubes	750 g

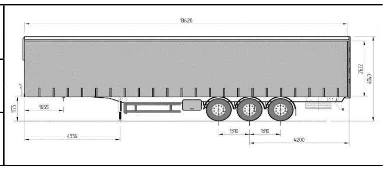
Table 6.1 Packaged Items.

The daily demand for the items in the last 15 months in indicated in the file Dados_TG.xlsx (This file is available on the UC page on Moodle).

Outbound Transportation

The outbound transportation from the FPW to the customers' distribution centers is carried out by semi-trailer trucks with standard side curtains, whose specifications are indicated in Table 6.2. The unit of transportation for the items is the full pallet (pallet composed of identical items with the base occupied at its maximum capacity).

Table 6.2 Specifications of Semi-Trailer

Dimensions (m×m×m)	$13,62 \times 2,48 \times 2,72$	
Load Capacity (Euro pallets of floor space)	33	
Maximum Load Weight (kg)	25000	

Storage

The packaging unit operates five days a week, from Monday to Friday, 24 hours a day. Shipment from the FPW to its customers is carried out from Monday to Friday, between 8:00 and 17:00.

Currently, storage is done using conventional shelving and block stacking. The merchandise is shipped at the warehouse docks, where semi-trailer trucks are loaded using pallet jacks and electric forklifts. All items are shipped on homogeneous full pallets, and the trucks are loaded to their maximum capacity.

The inventory level of each item as of March 21, 2021, is indicated in the file Dados.xlsx.

The responsibility for replenishing items in the FPW lies with the Packaging Unit based on sales, sales forecasts, and the commercial strategy. According to the company's expectations, overall demand is not expected to undergo significant changes in the coming years.

6.2 Problem Description

The company intends to determine the most suitable equipment and configuration for its warehouses. To achieve this objective, the task has been divided into 3 phases:

Determination of the packaging specifications for all items. This phase consists of carrying out at least the following activities:

- Define the type of pallet to be used for each item.
- Determine the quantities of primary packaging per pallet.
- Define the characteristics of the load pallet for each item.

Define the configuration of the storage area. This phase consists of carrying out at least the following activities:

- Determine the warehouse capacity.
- Define the storage systems.
- Define the handling equipment.
- Design performance levels and costs of the proposed solutions.

Define and develop a prototype of the warehouse management system. This phase consists of carrying out at least the following activities:

- Define the data model for the tool.
- Implement performance indicators.

Note: Whenever necessary information for problem-solving is not available, it should be obtained through research and/or assumptions. Both should be properly justified.