

Design of Supply Chain in Perishable Products

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A perishable product (PP) is defined as one that, by natural consequence, deteriorates in terms of its quality and/or organoleptic properties. The design of supply chains for products of all kinds is a classic problem of Industrial and Manufacturing Engineering as well as Cold Technology Engineering in order to provide the producer and customer with the optimal means for the manufacturing, packaging, loading, transport and download of the product with time windows.

cold chain

perishable food

fixed capacity routing problem

1. Introduction

A supply chain is defined as the set of activities required for the delivery of goods or services to the consumer ^{[1][2]}. In a manufacturing line, the activities related to the supply chain define the processes necessary to convert raw materials or components into finished products or services. An essential element in the supply chain is logistics. This activity consists of the process of planning and executing transport, the efficient storage of goods and the correct distribution of the products between customers and suppliers ^{[3][4]}. In this case, transport is the central problem for the design of the chain; this is where routes, loads, transport typology, operators, travel times, transport costs and time windows have to be defined. The importance of each of these issues is as described below:

- **Routes.** This considers the activity consisting of choosing the paths that the product distribution units must travel, considering distances, types of highways, their physical condition, highways, tolls, dirt roads, diversions, traffic regulations, assistance centers, routes for dairy (the milk road) and primary and secondary routes.
- **Volumetry.** This includes the calculation of areas and volumes available inside the transports, also considering the wasted spaces and the logistics of product accommodation inside it. Normally, the Last Input First Output (LIFO) discipline is used for the access and exit of containers in each transport, although this depends on the design of the vehicle, the container and the needs of the transport company, as well as the requirements of the clients.
- **Type of transport.** This concept includes land, sea, air, intermodal, river transport, pipeline transport and Ro-Ro transport (the acronym for "Roll on-Roll off" that refers to the system by which a ship transports cargo on wheels, mainly cars or trucks). In relation to land transport, it must be specified if the vehicle is a dry box, refrigerated dry box, wet cargo transport, platform, curtain, simple container, refrigerated container, heat truck or tank truck. In other types of transportation such as sea and air, there are other technological restrictions that must be addressed when shipping a load.
- **Operators.** This refers to the designation of the best transport driver based on his expertise, experience, knowledge of the route, travel times, rest time, time to eat and time to wash. The problem consists of assigning an operator to a route, a transport or a load.
- **Travel times.** This includes from the moment the vehicle forms in a port, bay or platform to receive the load until the moment its final point of travel arrives and the total load has been unloaded. This includes areas of spraying or primary

routes and the handling of secondary routes. The geographical place where the full load is divided into smaller loads to be distributed to the retail centers is called the shoveling zone. The route followed for this activity, using smaller vehicles, is usually called a secondary route. Similarly, a primary route is defined as the route that a transport with a large load capacity (usually more than one ton) must cover to take the product from the distribution center (DC) to the shoveling nodes. In both cases, not only is travel time important, but also the rest time, cleanliness of the vehicle operator and his food.

- Time window. This defines the interval that exists from the moment the transport load is made until the moment the product is delivered to the final customer; that is, the last link of the chain. This includes the times mentioned in the previous item. The time window helps determine the minimum time a carrier must take to deliver the product before it degrades. The product that must be transported with refrigeration in order to extend its lifetime deserves special mention.

2. Product Spoilage

A perishable product (PP) is defined as one that, by natural consequence, deteriorates in terms of its quality and/or organoleptic properties. This may be due to its biological and/or physical–chemical properties, for example, in the absence of adequate storage conditions. For this reason, packaging, loading, transportation and unloading, and where appropriate, refrigeration, must be performed under controlled conditions in order to minimize loss or damage. Examples of these products are fish, fruit, vegetables, potatoes, plants, bread, meat (of all types), hunted animals, butter, eggs, milk, cheese, birds, small animals, etc. Storage for these generally requires temperature control and proper treatment for transportation [5].

The concept of deterioration refers to the process of diminishing the quality, function and/or condition of the product in relation to its original attributes. As an example, damage to fruits and vegetables can occur in the form of rot, putrefaction, expiration, etc. In this case, the damage is due to the product continuing to metabolize and respire after harvest. Its loss is based on the fact that oxygen from the atmosphere is absorbed, producing heat, carbon dioxide and even ethylene gas. Here, the respiration rate is defined as the amount of O_2 consumed or CO_2 produced by the product, per mass unit and per time unit. In this case, the respiration rate has been identified as one of the indicators of physiological stress. Therefore, to keep products fresh and prolong their shelf life, the respiration rate must be reduced without affecting their organoleptic properties [6].

On the other hand, there are two factors of great importance to consider in the PP supply chain. The first one is the economic factor associated with the harvest, storage and transport of the product from its origin to the final consumer. Secondly, there is the environmental impact derived from the management of the supply chain associated with its distribution process. More generally, the abuse of temperature in the Food Cold Chain (FCC) is a problem of crucial interest for the production and the logistics [7], as well as the systematization of the management of the delivery process of perishable cargo and the development of new methods to improve its efficiency.

The transport of PPs requires greater attention to maintain the quality of the cargo. This is achieved through careful preparation and strict adherence to numerous requirements for loading, location, packaging, delivery time, etc. The foregoing requires high demands on the transport organization process in terms of the coherence and coordination of the actions of the actors involved. In addition, it requires compliance with standards and quality planning of both the process and the delivery [8]. Finally, the strict regulation of quality in the supply chain and its logistics process, as well as its economic indicators, are given in the SCOR model (Supply Chain Operations Reference) [9]. In this reference, the main standards that producers, carriers, warehouses, sales and distribution centers must comply with are defined.

2.1. The Environmental Impact of PPs

The useful life, overproduction, storage and especially the transport of PPs are factors that have a strong effect on the environment. Therefore, there is a requirement to integrate sustainability with the design of the supply network. PPs generally have a short useful life, and their storage must be constantly controlled to prevent expired waste and its impact on the environment [\[10\]](#). The importance of good design in the supply chain affects economic action and environmental pollution. Some aspects related to pollution are discussed in detail below.

The design of the PP supply chain must consider its expiration time. Therefore, the time windows play an important role in the topology of the product distribution network. Some of the most relevant factors associated with the environmental contamination generated by the use of transport and the handling and cryopreservation of PPs are the following:

- Emission by polluting particles from the combustion of transportation engines and greenhouse gas (GGE) emissions.
- Contamination generated by the refrigeration systems in the plant and during handling.
- Contamination generated by packaging.
- Pollution generated by the expired product.

In general, environmental impact is defined as the direct effect of socioeconomic activities and the natural consequences on the components of the environment. It can be said that, for the most part, it is due to the activities of the human being. In [\[11\]](#), it is recognized that this phenomenon has three components:

- The environmental stressor: the pollution and noise that can be measured in terms of tons of transported product divided by tons of pollutants emitted into the atmosphere.
- The spatial pattern of the distribution of transported goods: The mode of transport and the total amount of stress placed on the environment. This depends on the volume of the products transported and the distance traveled.
- The environmental impact: the nature of the environment; for example, the characteristics of the physical ecosystem and human density.

Regarding the previous list, the air pollution generated by transport is the main cause of its poor quality and directly affects the health of living beings. Pollutants that cause poor air quality include particulate matter, nitrogen oxides (NO_x

) and volatile organic compounds (VOC). In general, the transport sector is responsible for the emission of approximately the following figures of pollutants [\[12\]](#):

- More than 55% of NO_x emissions.
- Less than 10% of VOC emissions.
- Less than 10% of emissions of very small particles (organic chemicals, dust, soot and metals) suspended in the air that have a diameter of less than 2.5 microns. Also, there are small solid or liquid particles of dust, ashes, soot, metal, cement or pollen, whose aerodynamic diameter is less than 10 micrometers.

The following percentages show the distribution of greenhouse gas emissions worldwide during the year 2018 [\[13\]](#):

- Electric power generation: 32%.
- Transport: 17%.
- Manufacturing and construction industry: 13%.
- Agriculture: 12%.
- Industrial processes: 5.9%.
- Fugitive emissions (spurious leaks in industrial areas and/or clusters of companies such as gases used in refrigeration systems and others that come from equipment such as valves, pumps, pipes, etc.): 5.9%.
- Residential areas: 5.9%.
- Waste of all kinds: 3.3%.
- Other combustion sources: 3%.
- Land use, land use change and forestry: 2.8%.

The above amounts show only part of the environmental pollution problem generated by the emission of gases and particles from transportation. As a consequence, pollution in the US alone is to blame for approximately 40,000 premature deaths, 34,000 hospitalizations and 4.8 million lost work days. Therefore, the US Environmental Protection Agency (EPA) expects that emissions of hazardous air pollutants from mobile sources will be reduced by 80% by the year 2030.

Other important factors associated with pollution are the following:

- Operational oil contamination.
- Solid waste disposal.
- Accidental spills.
- The construction and maintenance of ports and canals.
- Pollutants from the aeronautical and railway industries, due to the use of ducts and pipes.

With respect to the contamination generated by the refrigeration systems in the plant and during handling, the effect of air and water pollution on industrial refrigeration systems has been well documented. Air contamination reduces the efficiency of the refrigeration system and increases electrical costs due to the increased compressor discharge pressure caused by the presence of air.

The problem with the use of refrigerants is that they are known to have a negative effect on the environment. The above is due to its contribution to global warming and the depletion of the ozone layer by what are called greenhouse gases (GHGs). These, like carbon dioxide and emissions from other types of refrigerants, contribute to global warming by absorbing infrared radiation and retaining it in the atmosphere. For example, Chlorofluorocarbons (CFC), Hydrochlorofluorocarbons (HCFC) and HFC Hydrochlorofluorocarbons (compounds made up of hydrogen, fluorine and carbon).

The impact of air conditioning and refrigeration systems on stratospheric ozone is mainly related to the release of refrigerants that deplete it. This is one of the main causes of global warming since it contributes through the release of refrigerants and GHGs. In this case, the electrical energy necessary to operate the refrigeration systems also has a significantly greater warming impact. Hence, the importance of phasing out Hydro-Fluoro-Carbon (HFC)-based refrigerants with less efficient options will increase net GHG emissions; the same conclusion applies to Per-Fluoro-Carbons (PFC), although they are used less frequently as refrigerants [\[14\]](#).

The increase in atmospheric concentrations of CFC has accounted for about 24% of the direct increase in the radiative forcing of greenhouse gases during the last decade. A decrease in the amount of stratospheric ozone has been observed and is believed to be related to the increase in stratospheric chlorine from CFCs (and, to a lesser extent, from other man-made compounds containing chlorine and bromine) [\[15\]](#).

The food distribution process using refrigerated systems is responsible for a significant loss of quality in perishable products and a huge source of environmental pollution in addition to waste from cooling systems (air conditioners, freezers, refrigerators, chillers and dehumidifiers) [\[16\]](#). Due to the above, one of the main lines of current research in the area of Engineering in Cold Technology (ECT) consists of the search for new ideal refrigerants that are less harmful to ozone; that is, compounds that are free of these problems but that, in turn, provide safety, stability, compatibility, cost and similar burdens. Some of these trends incorporate CO_2

as new refrigerant possibilities associated with thermoelectric and ejector-compression cooling system technologies; see, for example, [\[17\]](#).

Waste from cooling systems (air conditioners, freezers, refrigerators, chillers, dehumidifiers, etc.) is another major source of air pollution. In the case of a refrigerator or freezer, they generate an environmental impact made up of the following compounds: insulating foam (9 kg), refrigerant gas (125 g), contaminated oil (250 g), mercury (above 2 g), plastics, metals and glass (76.5 kg) and carbon dioxide (above 2.5 tons) [\[18\]](#). In relation to the operation in processing plants, aerosols are also common sources of pollution after industrial processes such as the pasteurization of dairy products. Little is known about the degree to which biological aerosols contaminate pasteurized products and the environment in general; however, evidence indicates that the air within a packaging area is a critical control point for both pathogens and spoilage microorganisms.

Regarding the manufacturing of dairy products, the microorganisms involved in the product are often damaged due to the stresses of the aerosol state and consequently may not grow on selective media; for example, in cheese production, yogurt, etc. Aerosols are generated within the dairy by worker activity, sink and floor drains, water spray and air conditioning systems [\[19\]](#). Similar situations are experienced in processing plants for meat products and their derivatives, the bread industry, sausages, etc. The effect caused by the oil used in the systems of refrigeration relates to its use as hydraulic control, functional fluid and lubricating oil in refrigeration compressors under the influence of a refrigerant. Cooling systems are of two types: synthetic oil and mineral oil. The first one has more duration, and the second one is used in industrial applications such as air conditioning units for commercial buildings [\[20\]](#).

Relating to the contamination generated by packaging, this is the wrapping or bottling of the products to protect them from being damaged during handling, transport and storage. Its function is to keep them safe and marketable by also helping to identify, describe and promote them. The most common materials used in product packaging are the following:

- Rigid plastic containers or PET (polyethylene terephthalate) or high-density polyethylene plastic (HDDE).
- Paper.

- Cardboard.
- Cardboard/Fiberboard.
- Aluminum.
- Glass.
- Expandable polystyrene (styrofoam).
- Flexible plastic containers.

Polyethylene terephthalate (PET) is a polymer not classified as a dangerous substance according to Regulation (EC) No 1272/2008 (CLP). PET is not classified as persistent, bioaccumulative or toxic (PBT). However, its use generates serious problems for its disposal since its recycling requires large amounts of energy with conventional sources, which depletes natural resources and generates environmental degradation [21]. PET plastic is the most widely used in the production of single-use plastic-based water containers. It does not contain BPA, but PET is also associated with many of the same health risks, including delayed growth, reproductive problems, low energy levels, body balance problems and an inability to process stress [22]. An interesting figure is that single-use plastic bags take approximately two decades to degrade. In contrast, plastic water bottles made with polyethylene terephthalate are estimated to take approximately 450 years to fully decompose.

For its part, paper alone represents approximately 40% of all waste around the world. That adds up to around 71.6 million tons per year in the US alone. Paper waste is a huge problem in terms of the devastating impact on the world due to deforestation. Paper production uses up to 40% of all the world's wood. The process of paper manufacturing releases nitrogen dioxide, sulfur dioxide and carbon dioxide into the air, contributing to pollution such as acid rain and greenhouse gases [23].

Cardboard is a heavy, stiff paper used to make boxes used for packaging. It is made of several layers of thick paper to increase its rigidity and strength in order to protect the items to be stored. Cardboard drums are even used to transport dangerous chemicals, products pharmaceuticals and hazardous waste. Cardboard is biodegradable, produces methane (a GHG) as it breaks down and typically ends up in a landfill, increasing the amount of methane released into the atmosphere.

The contamination produced by aluminum occurs mainly during its extraction process. Some toxic pollutants produced during this are dioxins, furans, hexafluoroethane, tetrafluoromethane, fluoride (gases and particles), hydrocarbons polycyclic aromatics (PAHs), mercury and benzopyrene.

Expanded polystyrene (EPS) is a white foam plastic material produced from solid beads of polystyrene. It is mainly used for packaging, insulation, etc. It is a closed-cell rigid foam material produced from (a) styrene—which forms the cellular structure and (b) pentane, which is used as a blowing agent. Plastic can be degraded into microparticles (MP) < 5000 nanometers in diameter and then into nanoparticles (NP) < 100 nanometers in diameter. NP have been detected in air, soil, water and sludge. The use and handling of this substance entails health risks; for example, polystyrene nanoparticles can penetrate organisms, accumulate throughout the food chain and are also surrounded by a crown of proteins that allows them to penetrate membranes and are highly toxic.

Depending on the cell type, NP can be transported via pinocytosis, phagocytosis or passively transported. Currently, there are no studies indicating the carcinogenic potential of NP. On the other hand, the PS (styrene) monomer was classified by the International Agency for Research on Cancer (IARC) as a potentially carcinogenic substance (carcinogenicity class B2) [24].

Finally, the contamination generated by the expired product is considered from cosmetics to food. In the second case, food and ingredient manufacturers often include production dates, best-before dates and/or spoilage information. Foodborne contamination is generally defined as food that spoils or is contaminated because it contains microorganisms, such as bacteria or parasites, or toxic substances that make it unsuitable for consumption. A food contaminant can be biological, chemical or physical in nature, the former being the most common. The four main types of contamination considered in this document are chemical, microbial, physical and allergenic. All foods are at risk of contamination with these four types. Even canned foods expire; for example, canned foods with a high acid content, such as tomatoes and fruits, can expire after 12 to 18 months. Low-acid canned foods, such as meats and vegetables, can stay fresh for 2 to 5 years. However, if the containers are rusty, dented, swollen or otherwise damaged, they indicate that the food is unsafe or may be contaminated. In relation to frozen foods, they do not expire.

When food expires, the vast majority of it is thrown away. This is not just an obvious problem for food safety: it is a huge environmental problem. In addition to the amount of land and water required to produce all the food that is never used, the Food and Agriculture Organization of the United Nations has estimated that the carbon footprint associated with food waste worldwide each year is more than 3 billion tons of carbon dioxide equivalent. The FAO reported that around 1.6 billion tonnes of food is wasted globally each year, thanks to a variety of reasons at points along the supply chain. In the US, research has suggested that up to 40% of the nation's food supply could end up wasting away [25]. Other PPs that deserve special attention due to their environmental impact are cigarettes, food wrappers/containers, beverage bottles, plastic bags, caps/lids, cups, plates, forks, knives, spoons, straws/stirrers, glass beverage bottles, beverage cans, paper bags, etc. [26][27].

2.2. The Design of the Supply Chain in Perishable Products: A Short Bibliography Review

The design of supply chains for products of all kinds is a classic problem of Industrial and Manufacturing Engineering as well as Cold Technology Engineering in order to provide the producer and customer with the optimal means for the manufacturing, packaging, loading, transport and download of the product with time windows. The concept of optimality refers to the delivery time of the product (lead time) in the quantity and quality requested and fully complying with the regulations established by the SCOR model, which is the reference framework for supply-chain operations. Design problems also involve the macro- and microlocation of manufacturing centers, storage, spraying areas, loading and unloading areas and delivery criteria in cities, ports and other terminals where the product must be stored. This includes some of the characteristics of transport, routes and packaging systems involving, in addition, the refrigeration requirements. Practical applications of these models can be seen in [28][29].

The literature in this regard is abundant in terms of information related to models for the design and operation of supply chains. Little attention has been paid to the models associated with perishable food and even less attention has been paid to products that require cryopreservation. Regarding production planning and the logistics of perishable products, the investigation is scarcer, in particular under the approach in which this point of view is related to time windows, which will be addressed. For example, in [30], an integrated location-inventory-routing model for perishable products in an emerging market is developed. The analysis includes the cost, freshness and carbon-emission factors. The authors propose a multitarget planning model and set constraints based on real location-inventory-routing situations.

In [31], approximation methods are applied to estimate and compare the total logistics cost of supply-network designs under various business conditions, such as variations in demand, changes in costs and changes in production policies. The model is applied in a real case and evaluates the trade-offs between five different network designs for the supply of highly perishable foods from a single regional supplier. Similarly, in [32] a multi-objective mathematical programming model is developed to optimize the cost, energy consumption and traffic congestion associated with supply chain operations. In [33], the authors elaborate a systematic literature review of articles focused on sustainable supply-chain management in global supply chains.

In [34], a new idea is developed to study the use of environmental indicators to measure profitability. The objective of the authors was to understand the impact of a group of categories (on the installation, location and capacity of the installation, selection of suppliers, technology used, definition of the transport network, supply planning and product recovery) in the decisions of the chain. The model was applied to a real case study.

In the case of systems with refrigeration, in [32], the authors develop a multiobjective mathematical programming model to optimize the cost, energy consumption and traffic congestion associated with the operations of a supply chain. The important contribution of the model is very close to the objective of the researchers' development since the researchers analyze the useful life of the product through a Weibull-type random variable assuming that the expiration date of the food is affected by the use of the vehicle's refrigerator, which is considered a decision variable. The model includes different classes of vehicles and multiple types of products. A dairy-supply-chain case is investigated and sustainability interrelationships are studied. A similar study is the work presented in [35]. Here, the degradation process of perishable foods is studied and the optimal temperature of the food chain is determined, as well as the optimal price to maximize the benefit of the channel. The optimum temperature is correlated with the profit proposed for its sale.

An interesting investigation is found in [36]. This article aims to determine the principles of the sustainable distribution of perishable goods and examine the current state and plans for the application of its principles in business practice on the example of port cold storage. The authors propose market research to identify the main directions of activities carried out by port cold stores in the field of the sustainable distribution of perishable foods.

In the field of mathematical modeling similar to the one developed here, there are important contributions in this regard; for example, in [37], a methodology is proposed for the rapid loading of products in an electric vehicle assisted by a service vehicle (drone). In [38], the authors address the stochastic dynamic vehicle routing (SDVR) problem inherent to urban logistics and from a theoretical perspective, and ref. [39] addresses the problem of the minimum spanning tree, a fundamental tool in the analysis and construction of clusters in logistics engineering.

A very important contribution to the topic is found in [40]: a vehicle-routing problem with time windows (VRPTW) with compatibility matching constraints and the total completion time as the objective function is proposed, with applications in home healthcare routing and scheduling. An approach close to ours is found in [41]. Here, the problem of recycling waste products through closed-loop logistics networks is analyzed by using a fuzzy programming model to minimize the total network cost and the sum of carbon rewards and penalties when selecting recycling locations, facilities and transportation routes among network nodes. Other representative models of the cold-supply-chain-management problem are given in [42][43][44].

Despite the technological advances applied to solving stochastic models, there are still several areas of opportunity to be addressed in future research. For a comprehensive review of the methods and models associated with the routing model, see [45].

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