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Optimizing the management of π-containers for Physical Internet

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Acronyms

ALICE	Alliance for Logistics Innovation through Collaboration in Europe
B	Billion
BPP	Bin Packing Problem
BFA	Best_Fit Algorithm
BTU	British Thermal Unit
CH4	Methane
CO2	Carbon Dioxide
COP	Combinatorial Optimization Problem
CRC	Collaborative Routing Centers
CSCMP	Council of Supply Chain Management Professionals
DC	Distribution Centers
DI	Digital Internet
FHWA	Federal Highway Administration
FMCG	Fast-moving Consumer Goods
GA	Genetic Algorithm
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GPS	Global Positioning System
HFC	Hydro-Fluorocarbon
i.e	That is to say
IoT	Internet of Things
IP	Internet Protocol
ISM	Institute for Supply Management
IT	Information Technology
Kg	Kilogram
LP	Linear Programming
m^3	Cubic Meters
MAC	Media Access Control
MCDM	Multiple Criteria Decision Making
MIT	Massachusetts Institute of Technology
MMT	Million Metric Tons
N2O	Nitrous Oxide
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
OSI	Open Source Initiative
OSS	Open Source Software
PI	Physical Internet
QB	Quarterback
RFID	Radio Frequency Identification
SCM	Supply Chain Management
T	Trillion
TAP	Traffic Assignment Problem
TCP	Transmission Control Protocol
TSP	Travelling Salesman Problem

UK	United Kingdom
US	United States
VM	Virtual Machine
WH	Warehouse
WSN	Wireless Sensor Network
3D	3 Dimensional

Global Introduction

In today's world, companies are faced with the inevitability to compete with each other as to ensure their survival and durability in the market of business, not only locally but internationally in particular. And as to be a hard player in the competition, a company is challenged with the need of innovation and amelioration of its organizational systems continuously and in such a flexible way that ensures the fulfillment of the customers' demands. The need of finding new tools and solutions to keep satisfying customers as to build their loyalty with the least possible expenses of making and delivering, is then rising and is more demanding than ever.

One of these organizational systems, not to say the most critical one, which should be continuously improved due to its heavy impact on the overall performance and the external image of the company, is the logistics' service. Logistics play a very important, not to say a decisive role in giving the lead and dominance to competing companies. And the thing that makes it hard to handle logistics easily, is the fact that the logistics networks architecture is designed and used in a non-optimal way, supported through numerous unsustainability symptoms that are outlined in our thesis.

Treating these symptoms, is then related to adopting new organizational concepts based on the entire collaboration of the whole actors in logistics networks, even competing companies, in the aim of correcting the flaws of the current logistics systems and contribute in creating optimized and well organized networks from different perspectives, whether economical as to unlock significant gains in global logistics, production, transportation, and business productivity, environmental as to reduce the global energy consumption, direct and indirect pollution including greenhouse gas emissions associated with logistics, production, and transportation, or even societal as to increase the quality of life of the logistic, production, and transportation workers especially drivers, as well as of the overall population by making the products much more accessible across the world where and when needed.

Decades ago, the world of digital information and telecommunications similarly faced the same challenges of unsustainability. It passed through a fast evolution from a world dominated by isolated large computers to a world filled with minicomputers and their workstations linked by private hyperconnected networks in such a transparent way to the user, allowing the transmission of formatted data packets as to be transited through heterogeneous equipment respecting the TCP/IP protocol [1] [2]. In the field of logistics, the networks already exist, but they are way far from being open and interconnectable. Each company has its own private mini network just like every individual has his own car. The clue here is to take advantage and get inspired from the open, hyperconnected and collective concept of the digital world, and project it on the way in which we do our logistics activities. That exactly what is known as the Physical Internet project.

This thesis is structured as follows. In chapter 1, we present an overview of our current logistics system and mention the different limitations and unsustainability symptoms facing it.

In chapter 2, we introduce the Physical internet, define its concept and characterize its structure and requirements, as well as its analogy to the famous Digital internet. This provides a good background for understanding the context of Physical internet. In chapter 3, we tackle a critical problem in the Physical internet, which is optimizing the selected number of Π-containers for shipping and how to arrange objects inside, in the aim of minimizing the total emptiness volume (converted into costs), using two different kind of reasoning methods, the first is an exact method using linear programing and the second is an approximate method using metaheuristics, we compare the performance of both methods after having interpreting their results. We conclude with a discussion of implications and future work.

1.
Current logistics system

1.1 Introduction

Logistics networks and supply chain processes are a major concern for the overall strategy of executive companies, they play a vital role in the success of the company's global manufacturing, marketing and total performance strategies [3]. In fact, logistics processes help companies operating in a global environment to gain a competitive advantage by delivering the right products in the right quantities at both the right time and price regardless of where the product is actually manufactured or marketed.

In this chapter, an overview of logistics networks and supply chains will be presented, all along with some statistical facts revealing the real picture of the state of the current logistics networks and the different symptoms of their unsustainability and non-efficiency.

1.2 Logistics and supply chain

1.2.1 Logistics definition

"Logistics" is a very old term that comes from the end of the 19th century from the French word "Logistique" meaning to lodge, which first appeared in the book "The Art of War" ("l'art de la guerre") by Baron Henri [4] who was the general in French army at the time of Napoleon. In other words, the term "logistics" was firstly used in the military, where it was applied to the process of maintenance, storage and transportation of army's persons and goods.

Others said that the term "logistics" is derived from the Greek word "λόγος" (LOGOSH), meaning reason, and "λογιστικός" (LOYISTIKOSH) meaning accountant or responsible for counting. [5]

With time, the term was borrowed and used in many fields, in specific industry where it was applied to the discipline known as "Business Logistics". [6]

In the pure context of industry, The Council of Logistics Management (1992) has defined logistics as "the process responsible for planning, implementing, and controlling the flow and storage of materials, goods, services, and information from origin to the consuming point." [7]

Another definition produced by Barros L (1997) was: "Industrial logistics include all activities which allow the physical flow of raw materials, intermediate and final goods and services from suppliers to producers to consumers within and across economic sectors". [8]

The person in charge of logistics is therefore not responsible for production tasks (materials handling within the factory), nor for marketing tasks (predicting the demand or evaluating the level of customer service), his role is actually to ensure the operation of establishing exterior linkages of people at all levels in the organization to the market place in both direct or indirect way. A graphic metaphor suggested by Barros L (1997), makes the idea pretty unambiguous; he represents an industrial company in the shape of a spider, such as the body of the spider represents the production unit, the feet represent the marketing unit and finally the logistics which is represented by the circulating flow through its legs that keeps it alive. Obviously, if there is no production, logistics is not necessary (the spider without its body cannot survive with only its legs. However, it will not work at best if the body is not supported by the whole eight legs). [8]

In today's highly competitive and increasingly globalized marketplace, manufacturing companies are facing the obligation to build a sustainable competitive advantage to keep their businesses alive while maintaining their reputation. Logistics is actually one of the most affective parameters of this competition. It truly represents the essential coordinating mechanism that enables manufacturing companies to successfully manage their global networks. As Daryl White, chief financial officer at Compaq Computer, has noted, "We have changed the way we develop products, manufacture, market, and advertise. The one piece of the puzzle we haven't addressed is logistics. It's the next source of competitive advantage". [9]

1.2.2 Supply chain definition

If any company sells an item to a customer, then it probably has a supply chain. And the latter affects almost every other business function in that company.

Many authors define supply chain as two or more parties linked by a flow of resources – typically material, information and money. Stevens G.C (1989), has defined the supply chain as "series of related activities concerned with planning, coordinating and controlling materials and goods from supplier to end user. It is concerned with both flows of material and information through the organization". [10] Another definition given by Eksioglu (2001); "The supply chain covers all efforts that are involved in producing and delivering a final product or service, from the supplier’s supplier to the customer’s customer ". [11]

Supply chain was also defined by Wilkinson J (2013), as "the path of goods and information from a first maker to an end user, allowing any business to turn product into sales. Involving either tangible or intangible goods or services. It represents the whole track that generates incomes for a company. As a result, a company must maintain a supply chain which efficiently transports important materials from one location to another". [12]

While Joel Sutherland, the Managing Director at Supply Chain Management Institute, School of Business Administration and University of San Diego, argues that there is in fact no universally accepted definition of the term "supply chain", because for some, it is simply another term for "logistics", while others claim that it encompasses purchasing, engineering, production, finance, marketing and related control activities. [13]

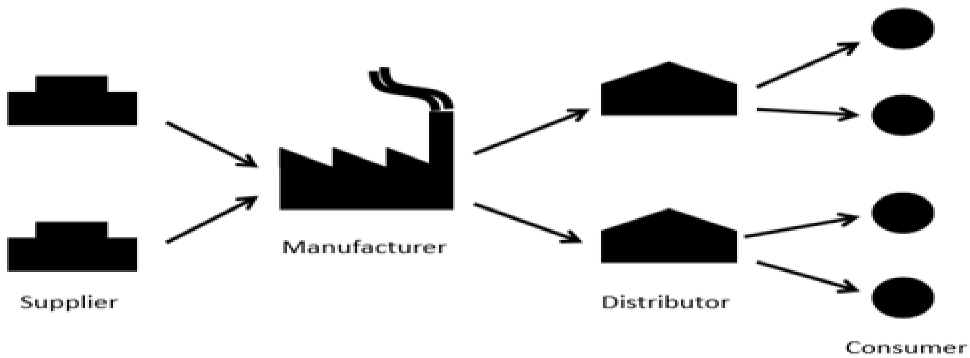


Figure 1.1 Supply chain network design [14]

In summary, any complete business comprises two major departments: marketing (or sales) and operations (figure 1.2), operations are another way of talking about supply chain including logistics. The supply chain therefore represents about almost the half (50%) of any business [12] and plays a key role in managing the flow of both information and materials smoothly across geographically dispersed members of the logistics network and reach by the end the global operational success of the company, hence it became an essential parameter in the global competition between manufacturing companies, as Harold Sirkin, of the Boston Consulting

Group, has noted : "As the economy changes, competition becomes more global, it's no longer company versus company but supply chain versus supply chain. [9]

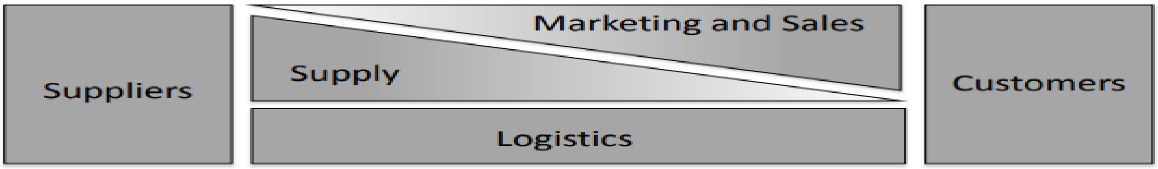


Figure 1.2 Integrated organizational structure between the activities of marketing and sales, supply and logistics

1.2.3 Are logistics and supply chain the same things?

Logistics and supply chain are not the same. The management of logistics and the supply chain management (SCM) differ by few points (table 1.1); the first is concerned with the flow of goods with a large emphasis on transportation using a combination of travel methods that includes ships, trucks, trains and airplanes, while supply chain management covers the many other areas already discussed in the previous definitions (accounting, handling, distribution, customer service, Information Technology (IT), developing new products and even security), in other words, Logistics focuses on transporting and storing goods while supply chain focuses on finished product and/or customers, but logistics is in fact an activity of supply chain, according to Council of Supply Chain Management Professionals (CSCMP), logistics the supply chain process part that plans, implements and controls the flow and storage of goods, services and related information between the origin and the consumer [15]. The Chief Executive Officer at the Institute for Supply Management (ISM); Thomas W. Derry, explained that "Procurement and logistics are responsible for getting the right thing (including quality and specifications) at the right total cost from the optimal source (s), while the supply chain is the implementation of this procurement strategy". [13]

The bottom line is that both logistics and supply chain are inseparable, thus they do not contradict but supplement each other. The Application Developer and Support Specialist at Ultra Ship TMS; Jasen Incidis, simulated the matter with American football, such as supply chain represents the football coach and logistics represents the quarterback (QB). They both provide guidance on how field assets should be located and positioned, but the coach provides the overall game plan and the quarter executes the moves while adjusting on the fly as needed. [13]

Table 1.1 Logistics management compared to supply chain management

BASIS FOR COMPARISON	LOGISTICS MANAGEMENT	SUPPLY CHAIN MANAGEMENT
Meaning	The flow and storage of goods inside and outside the firm	The coordination and management of the supply chain activities (product development, procurement, operations, logistics, demand/supply planning, and customer service management)
Objective	Customer Satisfaction	Competitive Advantage
Evolution	Earlier Concept	Modern Concept
How many organizations are involved?	Single	Multiple
One in another	Logistics Management is a fraction of Supply Chain Management.	Supply Chain Management is the new version of Logistics Management.

1.3 Limits of the current logistics network

1.3.1 Some facts and statistics

Numerous statistical reports have been compiled by national transport departments around the world, revealing the sad truth about the gaps and flaws generated by the current system of logistics. Few are mentioned down here.

1.3.1.1 From an economical perspective

Logistics expenditures represent a significant and relevant proportion of business costs. At the company level and for many products, 20% to 40% of total product costs are related to logistics [16] goods costs billions of dollars every year. According to Bowersox, R & Calantone, R, global business logistics system costed about $ 6,732 billion in the year of 2002, and corresponded back then to 13.8% of the world's Gross Domestic Product (GDP) [17]. It is good to keep in mind that GDP is the measure of overall market value of the whole final goods and services produced by a given country in a given year. [18]

The total logistics costs include all costs associated with logistical operations, which consists of six distinct components: transportation, warehousing, inventory carrying, administration, packaging and order processing costs (entry/customer service cost, tariffs and duties). The administration and order processing costs relate to the total volume being handled. However, for the same volume handled, transportation and warehousing costs will vary depending on the distribution strategies adopted**.** [19]

The United States (US) provides a striking example since being the world's largest economy [20], according to annual state of logistics report of the CSCMP [21], which measures total spending on transportation and Inventory by U.S. companies (Table 1.2, Figure 1.3), transportation accounted for about $965.5B (Billion). Operations including Storage, and other costs like logistics administration, are respectively about $428 B and $101.2 B. Thus the annual stakes easily amounted to $1.4947T (Trillion).

Table 1.2 Components of US total business logistics costs in 2017 [21]

	2017
TRANSPORTATION COSTS ($B)	
Full truckload	289.4
Less than truckload	62.4
Private or dedicated	289.6
Motor carriers	641.4
Parcel	99.0
Carload	59.0
Intermodal	21.4
Rail	80.5
Air freight	67.2
Water	41.0
Pipeline	36.4
SUBTOTAL	965.5
INVENTORY CARRYING COSTS ($B)	
Storage	148.0
Financial costs	151.6
Other	128.4
SUBTOTAL	428.0
OTHER COSTS ($B)	
Support activities	50.5
Administrative costs	50.7
SUBTOTAL	101.2
TOTAL US BUSINESS LOGISTICS COSTS	**1494.7** ($B)

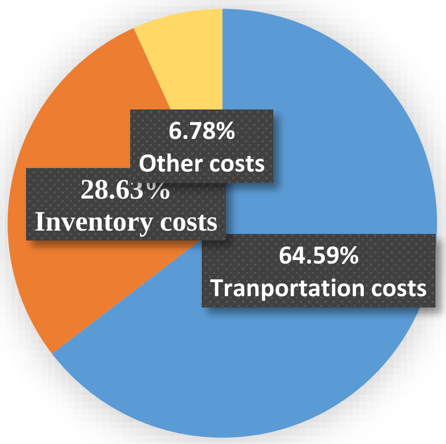


Figure 1.3 2017 US business logistics costs' components

Last year's CSCMP's annual report revealed that U.S total spending on logistics, after declining in 2016 for the first time since 2009, were on the rise again in 2017 (Table 1.3, Figure 1.4), thus they grew to a record of nearly $1.5T, up 6.2% from the year before, and about $250B more than companies spent on logistics in 2008, these expenses increased in the fourth quarter of 2017, suggesting an increase of the same amount for the year of 2018. [22]

Table 1.3 Total US business logistics costs [23]

YEAR	COSTS (T OF US$)
2008	1.25
2009	1.06
2010	1.13
2011	1.22
2012	1.27
2013	1.32
2014	1.40
2015	1.43
2016	1.41
2017	1.49

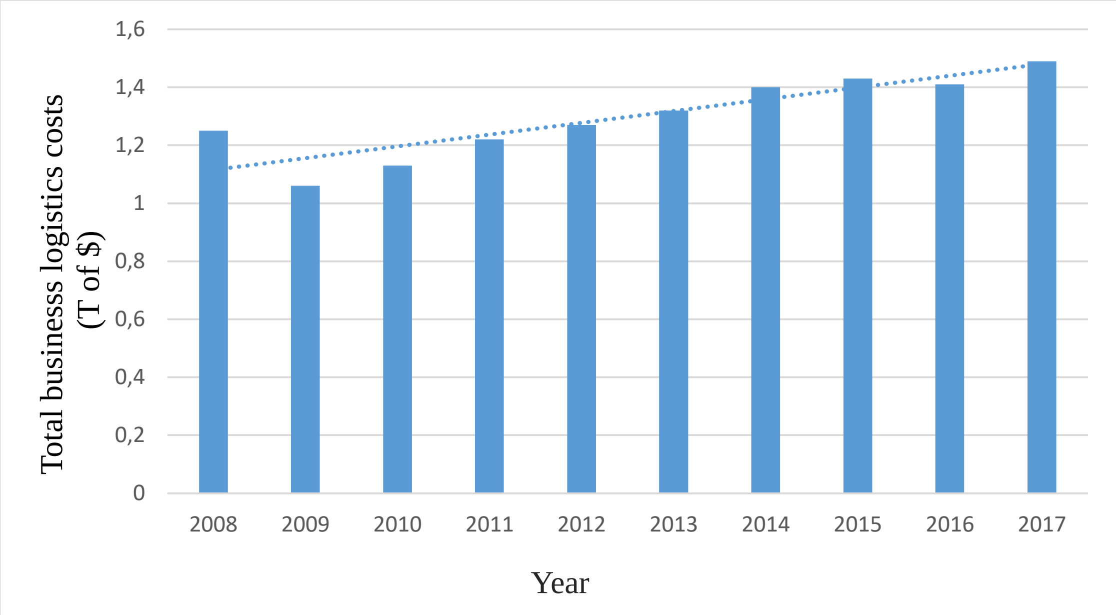


Figure 1.4 Graphic representation of the total US business logistics costs

In another sign of possible overheating, is the high share of logistics in overall economic output. Table 1.4 shows US logistics costs as a percentage of GDP over the past 10 years [24], the total costs in 2017 grew to 7.7% of GDP from 7.6% in 2016 and are expected to keep increasing for the upcoming years, and according to the US department of transportation, approximately 6 to 7% of these annual GDP rates are spent on freight transportation [25]

Table 1.4 US business Logistics costs as a percentage of GDP [24]

YEAR	NOMINAL GDP (%)
2008	8.5
2009	7.4
2010	7.5
2011	7.9
2012	7.9
2013	7.9
2014	8
2015	7.9
2016	7.6
2017	7.7

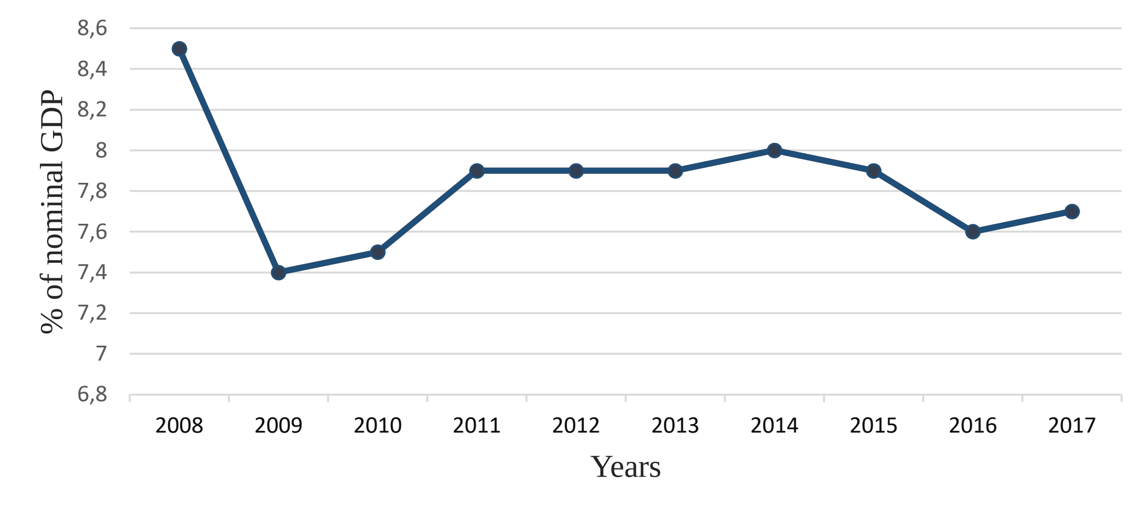


Figure 1.5 Graphic representation of US business Logistics costs as GDP percentages

In Europe, according to statistics from 2004, the logistics market was estimated at 8% of European total GDP representing about 710 billion euros. In France, it is estimated that the global logistics cost represents on average 11.9% of the net turnover of French companies in 2008, compared to 9.9% in 2005 [26]. So the economic weight of logistics cannot be ignored.

1.3.1.2 From an environmental perspective

In order to identify the environmental issues of logistics, more specifically, freight transportation, the given statistical analyzes will focus on two major interdependent issues: energy consumption and greenhouse gas (GHG) emissions.

Freight transportation is a large contributor to emissions of GHG. The majority of these emissions are carbon dioxide (CO2) with a percentage of 23%, resulting from the combustion of petroleum-based products like gasoline, in addition to small amounts of methane (CH4), nitrous oxide (N2O) and hydro-fluorocarbon (HFC) representing approximately 15% of overall GHG emissions [27] And it is well known that these GHG emissions are naturally concerned by global warming and climate change problems.

Again, the United States, provides a striking example concerning the major issues related to the environment. In 2006, road transportation accounted for 8.8 million trucks traveling 263B miles a year. In 2007, truck and train freight transportation modes consumed about 42B gallons (158987294.928 m^3) of fuel which is a huge energy consumption. Figure 1.6 shows the expected future growth of freight transport energy consumption by mode from 2005 to 2030 in Trillion of British thermal unit Btu (1 Btu=1055 Joule). Much of this growth will occur in the truck mode, which is traditionally the most energy- and carbon-intensive mode of freight transport. [28]

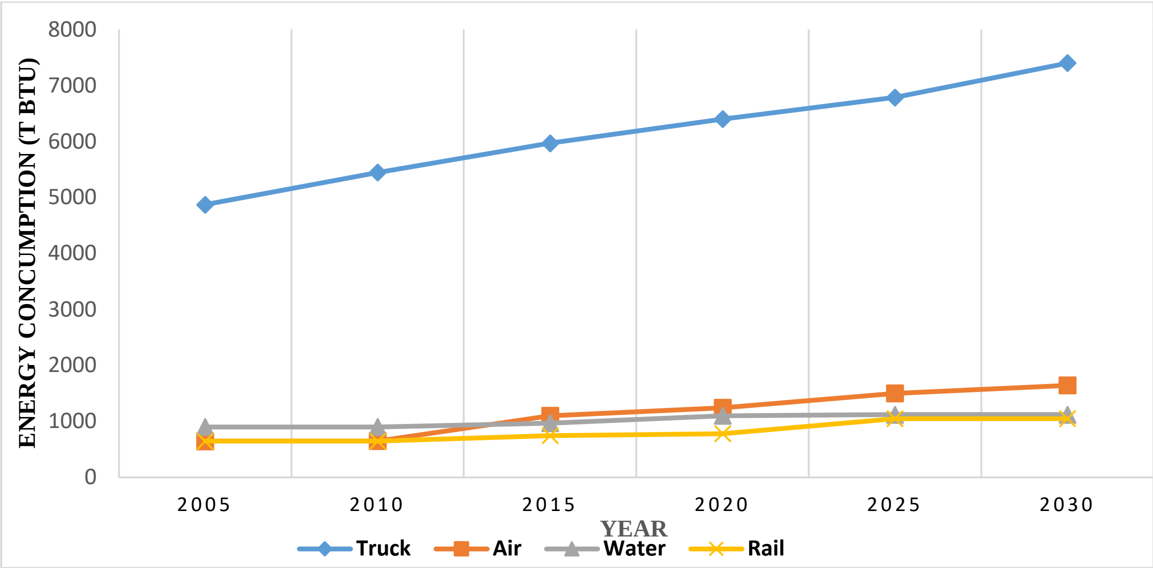


Figure 1.6 Expected energy consumption growth of US freight transport from 2005 to 2030 [28]

This bulky fuel consumption is also a primary source of both pollution and greenhouse gas emissions, freight transport (including rail, truck, air, and domestic and international shipping to the United States) is responsible for approximately 470 million metric tons (MMT) of CO2 per year in the United States, or approximately 7.8% of US total CO2 emissions [29] Table 1.5, represents the U.S. CO2 Emissions from Domestic Freight Transportation by Mode from 1990 to 2007. [30]

Table 1.5 U.S CO2 Emissions from Domestic Freight Transportation: 1990-2007

Freight transportation mode (MMT)	1990	1995	2000	2005	2006	2007
Truck	228.8	272.7	344.2	395.1	404.5	410.8
Rail	34.1	39.6	44.9	50.4	52.8	51.6
Ships and Boats	32.8	40.1	50.6	33.2	36.8	39.1
Commercial aircrafts	36.2	38.5	35.2	32.4	32.4	34.6
Pipelines	23.7	24.8	29	25.5	24.5	22.6
TOTAL	355.7	415.6	504.0	536.6	551.2	558.7

France is another typical example. Freight traffic has experienced and is forecast to experience rapid growth, in the order of 37% of tons-kilometers from 2005 to 2025. Freight transportation generates 14% of the GHG emissions in France, with annual growth rate of 23% from 1990 to 2006 while the country's objective is a major reduction of 20% targeted by 2020, and of 75% by 2050. [31]

1.3.1.3 From a societal perspective

Driver fatigue is probably the biggest threat to the safety of freight transportation and the leading cause of the accidents. This human factor is a widespread risk in most major transportation modes

The problem is so paramount that in the US, the Department of Transportation, the National Transportation Safety Board (NTSB) as well as the National Highway Traffic Safety Administration (NHTSA), have all invested millions of dollars in driver fatigue research and identified it as a priority. [32]

As an illustrative indication, The NHTSA stated that, drowsy drivers cause 100,000 crashes each year which result in more than 1,500 mortalities and 71,000 injuries [33]. These amounts are about 1.6% of all crashes and about 3.6% of fatal crashes.

In 1998, the Federal Highway Administration (FHWA) estimated that 0.53% to 1.3% of large truck crashes involving fatigue. The FHWA also concluded that more profound investigations produced higher percentages of fatigue-related accidents than those reported in police accident reports. [34]

The 1990 Safety Board study of 182 fatal heavy truck accidents for the driver, found that 31% of them were deemed to be fatigue and sleep deprivation related**.** [35], the Safety Board’s fatigue Accident numbers are more revealing, as its extensive investigations included alternative measures, such as 72-hour rest and duty periods, sleep duration over the last 24 hours and the regularity of working schedule.

1.3.2 The unsustainability symptoms

Beyond these global numbers and facts about the limits of the way logistics are currently managed, societal, environmental and economic unsustainability of Logistics on the planet can be comprehended through many symptoms. Below are thirteen of them.

1.3.2.1 Low rate of vehicle loading

Currently, loading freights tends to underestimate the true level of utilization of transport vehicles. Very few loads simultaneously reach the weight and volume limits of the vehicle, most filling the vehicle space before the weight limit is reached (Figure 1.7), leaving more of wasted space that could be used better. [36] In fact, trucks, wagons and containers are often half empty at departure, with a large part of the non-emptiness filled with packaging [37] .This fill rate is actually one of the factors indicating the efficacy of freight transportation sector in a given country, and it has recently been estimated that the global transport efficacy tends to be less than 10%. [38]

In the US, official statistics report that trailers are approximately 60% full when traveling loaded [39, 40]

In the UK (United Kingdom), an analysis of the food supply chain conducted in 2003, revealed that in terms of vehicle saturation, an average load factor of 70% at the surface and 53% by weight were found. Based on these results, the volume loading rate was approximately 50 %. [41]

And in 2004 in Germany, a study done with 50 German transport providers, obtained an average load capacity of 60% by volume and 44% by weight for all categories of vehicles studied. [42]

Figure 1.7 The emptiness rate inside of trucks [43]

1.3.2.2 High proportion of empty running

Another freight transport efficacy indicator is related to the proportion of truck distance travelled with empty trailers. Loaded vehicles and containers often return empty and get increasingly emptier as their route proceeds from delivery point to another. Empty running usually occurs when operators are unable to find a return load because of the fact that most of goods travel in only one direction unlike passengers, who usually return to their point of departure. [44]

In 2004 in the UK, the rate of empty driven trucks-kilometers was reported to be around 27% [45] In 2009 in the US, on average 20% of all miles were traveled with completely empty trailers and many more almost empty. [46] And in the same year in France, the pole of Economic Mutations Anticipation and the Conservatory of Arts and Crafts report, mentioned that "vehicles run on average 2/3 of load and that 20% of journeys are traveled empty" for freight transport at the national level. [47]

1.3.2.3 Unsteadiness of truck drivers personal and social life

Road based transportation represents the backbone of logistics sector and dominates the rest of the other means of continental transportation. [48] Which requires a high demand for truck drivers. For example, The American trucking association has estimated in 2008 that the driver shortage in the USA. Will grow to 111.000 by 2014 industries. [49, 50]

Despite this obvious importance of truck transport industry, the current way of moving goods creates a set of discomforts and risks for truck drivers, especially those driving for long distances. So many truckers are almost always on the road working for long hours, often away from home for long durations, exposed to high risk of injuries which makes them frustrated and compromises the stability of their family life, social life and health. [51]

In 2008, Spielholz et al. started exploring the level of injury risks associated with long distance truck driving [52]. Another research that paid attention to truck drivers' risks and injuries done by Johnson et al. (2009) revealed some sources of frustration that threaten the quality of life of long distance truck drivers, including being away from home, high fuel prices, lack of proper training and driving skills, government pressures and regulations and loading/unloading operations issues [53]. These observations corroborate with other findings like those of Shibuya et al. (2010) who quantified specific risks and analyzed accidents associated with activities of loading and unloading freights [54]**.** Another study adopted by

Williams and George (2013) revealed the following set of major deterrent factors frustrating truck drivers: boredom, poor job respect and stress resulting from long distance driving [55]

1.3.2.4 Unneeded storing and unavailability of products when and where needed

All manufacturers, distributors, retailers and users store products, often in large quantities through their extensive grid of warehouses and distribution centers. It has been reported that the average investment in all US business inventories amounted to $101B in 2005 [49]. Warehousing has been presented as a time-consuming and non-value adding activity, because storing goods and recovering them when needed, require both additional paperwork and time. [56] Yet many manufacturing and distribution companies need to build and operate warehouses to provide better customer service and quick response time to their needs. [49] Nike, for example, is a manufacturing company among the world leaders in sportswear. It has recently built a large distribution warehouse in Laakdal, Belgium with a total area of 1 million square feet. Nike has built this huge warehouse because one of its main goals is to serve 75% of its customers within 24 hours. Without proper storage facilities, it is impossible for Nike to achieve this objective because many of their manufacturing factories and suppliers are overseas. [56]

Despite these networks of warehouses spread all around the world, service levels and response times to local users remain constrained and unreliable. In fact, a significant portion of manufactured consumer products never reach the desired market in time, thus ending up unsold and unused at a given location, whereas they would have been needed elsewhere. Although reliable statistics are scarce on this sensitive issue, they are well known in the food and clothing industries, as well as very expensive products such as cars [57]. As an illustrative picture, it was estimated that Compaq Computer Company has lost between $ 500 and $ 1 billion in sales in 1994 because its best-selling laptops and desktops were not available where and when it was needed. [9]

1.3.2.5 Products poor reachability and hard intermodal transport

Infrastructure, capability and service levels of transportation and logistics directly affect the reachability of products for customers. In most of less developed countries, the established infrastructure is not resilient enough nor quickly adaptable, same thing for disaster areas where infrastructure and networks get totally or partially destroyed during crisis, making it difficult, costly and time-consuming to reach those in need in such parts of the world. [57] Intermodal transport interfaces, particularly related to container transport are another barrier to product accessibility [58]. They are badly designed and the overall Synchronization is poor, that intermodal transportation became inefficient, unprofitable and risky for the environment especially the fact that the less energy-efficient transportation modes are those used the most (trucks are largely used than trains even though that they emit twenty times more CO_2 than trains).

1.3.2.6 Flexible City logistics is hard to reach

Urban logistics or else named city logistics enables the mobility of urban freight through the transportation of goods taking place in an urban area. [59] The fact is that most cities are not well equipped for flexible transportation and warehousing of freight, the thing that creates a set of emerging Concerns for citizens such as Congestion and noise affecting especially their movements and social interactions, as well as the quality of life in the city beside other environmental concerns such as air pollution. Urban logistics is therefore becoming a major issue in urban sustainability especially in populated and old cities, the reason why several city logistics and urban mobility initiatives are being developed [60]

1.3.2.7 Excessive travel of Products across the world

Another phenomenon that has appeared in the world of logistics is the excessive and unnecessary mobility of products crisscrossing the world and traveling thousands of kilometers that could have been avoided by routing intelligently or by making the products much closer to their consuming point. Several factors explain this phenomenon, such as the outsourcing of products manufacturing in developing countries, hub-and-spoke networks and the few major distribution centers due to the current dominating concept of centralized production and distribution facilities.

1.3.2.8 Insecurity of the current logistics Networks

Logistics operations are not simply linear processes**.** [61] They are in fact complex systems of interlocking networks, in which goods move and travel along a narrow set of high-traffic routes and we call it the physical flow, but there is another important flow traveling along with goods which is the flow of information passing within and between a range of organizations and industries linked by these physical distribution networks and transport infrastructures. [62] This makes the logistics networks of many companies insecure and exposed to theft and terrorism acts and not robust to natural disasters and demand crises. Vulnerability, risk and resilience are increasingly critical issues facing logistic networks, which requires analysis to contribute to the design of policies to maintain or enhance security in existing logistics networks [63]

1.3.2.9 Smart technology is hard to justify and Innovation is strangulated

As mentioned before logistics include many operations like handling, storing and transporting goods, which means that all of the operational facilities belonging to the same logistic network, have to deal with many types of materials, shapes and unit loads with each deciding his material handling, storage and transport technology independently and locally. Automation in material flow system enables equipment or systems to run with little or no operator intervention. It improves safety, operational efficiency, consistency, and predictability, while increasing system responsiveness. Automation also decreases operating costs. [56] But the independency of operational facilities, makes it very difficult to justify intelligent connectivity technologies (like RFID and GPS), systemic handling, transport automation and smart collaborative piloting software as well. Not only smart automation is strangled but innovation as well because of the lack of systemic open infrastructures, generic protocols, transparency, and modularity in the existing networks, leading to limitation of breakthrough recently.

Table 1.6, relates the aforementioned symptoms to their economical, environmental and societal sustainability negative impacts. The whole symptoms combine to reveal the sad reality of the current unsustainability of existing logistics networks and highlight the significant need for change.

Table 1.6 The unsustainability symptoms of the current logistics network

	unsustainability symptoms	**economical**	**environmental**	**societal**
1	Low rate of vehicle loading	●	●	
2	High proportion of empty running	●	●	
3	Unsteadiness of truck drivers personal and social life	●		●
4	Unneeded storing and unavailability of products when and where needed	●	●	●
5	Products poor reachability and hard intermodal transport	●	●	●
6	Flexible City logistics is hard to reach	●	●	●
7	Excessive travel of products across the world	●	●	●
8	Insecurity of the current logistics Networks	●		●
9	Smart technology is hard to justify, and innovation is strangulated	●	●	●

1.4 Conclusion

Logistics operations, especially freight transportation is one of the most important and sensitive pillars and a basic component of the worldwide economy, which requires its ability to operate in a safe, secure, sustainable and efficient manner**.** Safe concerning its consequences on human health and the environment. Secure so that the focus is on events that could disrupt information, people, goods or infrastructure and efficient on the basis of the industry's ability to respond to customer demand with available supply in a fast, reliable and cost-effective manner. In the purpose of overcoming inefficiency symptoms (previously mentioned) that the current logistics are suffering from and reach the utmost safety, security, sustainability and efficiency of freight transportation system, the physical internet (PI) Initiative came into sight.

PI fundamentally targets to correct the classic logistics networks flaws, through the operation of open distribution centers, while deploying and delivering products through the interconnected web of mobility. The next chapter will be an overview of this new PI concept, where more details will be revealed.

2.
Introduction to the Physical Internet

2.1 Introduction

As mentioned earlier in the first chapter and based on the claim that, "the way physical objects are currently moved, handled, stored, realized, supplied and used throughout the world is unsustainable economically, environmentally and socially" [64], the current state of global logistics is not optimal, logistics networks are no longer efficient or sustainable, which requires a whole new concept of logistics organization able to meet the challenges of the current and future industrial practice from an operational, organizational and managerial aspect. The modern concept of Physical Internet could be the solution [65]**.**

In this chapter, we discover the context of the new concept "Physical Internet", or shortly PI, source of inspiration for its birth and its major elements. We also compare the physical internet to the famous digital internet and focus on its impact on logistics facilities. Finally, we end the chapter with some conclusive remarks and main challenges facing the process of installing a physical internet strategy.

2.2 Definition of the Physical Internet

In 2011, Ballot, Montreuil and Meller defined The PI as "a global logistics system that is based on the interconnection of logistics networks through a standardized set of collaboration protocols, modular containers and smart interfaces for the aim to increase efficiency and sustainability" [66]**.**

It proposes an efficient system in which the global logistics of the supply chain is made possible by an open and intermodal system (land, rail or sea) using standard, modular and reusable containers, real-time identification and coordinated routing via shared logistics facilities [67]**.** This means that the key principle of PI is about the full cooperation among all supply-chain stakeholders (manufacturers, transportation providers and retailers) and their full compatibility with all resources and solutions applied during operations, in other simplified terms, the Physical Internet targets a world where goods share warehouses, distribution centers and transportation means throughout their whole life cycle from production to final delivery, through fully open and connected smart logistics networks, in the aim of improving the overall performance in terms of efficiency and sustainability, economically, environmentally and societally.

2.3 The state of the art of the Physical Internet

2.3.1 The starting point of the very first sense of Physical Internet

The term "Physical Internet" was introduced for the first time as a big headline on the front page of The Economist magazine (Markillie 2006) [68], where the issue presented a survey of logistics practices. Even though it made the front page, there was no other mention of the term "Physical Internet" in any of the articles. This rose the author's _Professor Benoit Montreuil_ research interest and curiosity about what could be the potential meaning and significance of this new term of Physical Internet and the reasons why the world would need it anyway. And from that moment, the journey through the discovery of the revolutionary concept of PI has begun.

2.3.2 Main researchers and researches

Professor Benoit Montreuil (Laboratoire CIRRELT Université Laval Quebec) began the research journey by a manifesto presenting a global comprehensive vision of PI, the concept being presented in a list of thirteen characteristics that are supposed to meet the Great challenge of sustainable logistics (Montreuil 2009–2012) [64]. The essential points of this Manifesto were officially presented after as a newspaper article in 2011 [57]**.**

Professors Éric Ballot (Centre de Gestion Scientifique, Mines ParisTech, France) and Russell Meller (CELDI, U. Arkansas, U.S) were the first to join Professor Benoit Montreuil in 2009 to create a research team on PI by conducting high-impact research projects. Such as the project of Contribution to the conceptualization and realization of a PI rail-road hub in France in 2010 [69]. Professor Rémy Glardon joined them in 2011 to lead a France-Canada-Switzerland project, aimed to simulate PI's potential contribution to solving logistical problems by putting the focus on the application to fast freight logistics in France. In 2014, the team of Ballot, Montreuil, and Meller published a book to disseminate knowledge about PI [66].

Most of the researches were developed in Europe, thus it became a fertile ground for PI research and innovation. The first PI project has been submitted to the 7th Framework Program of the European Commission thanks to the pioneering initiative of Sergio Barbarino (Procter & Gamble's supply Network Innovation Center), who teamed up with Professors Ballot, Meller and Montreuil. The project led to multi-million dollar funding by the commission [70]. Another successful large-scale project focused on the consumer goods industry called the Modulushca project involved many industry and academic partners from Europe and Canada [71]. The success of this project combined with the growing recognition by the industry of PI, has lead the European Technology Platform on Logistics to make the PI the vision of Central Europe to the 2030-2050 horizon for logistics and supply chains, and propose a complete roadmap for its implementation and wide -scale adoption [72].

The U.S was also a research ground for PI. In 2012, Professors Meller, Kim Ellis (Virginia Tech), Bill Ferrell (Clemson U.) and Phil Kaminsky (UC Berkeley) collaborated on a research project to assess PI potential in North America [73]. And in 2014, Professors Meller and Montreuil led a project focused on PI facilities in the US [74].

2.4 The concept of the Physical Internet

The concept of PI, was first introduced by Professor Benoit Montreuil of Laval University (Quebec, Canada). PI is inspired by the Digital Internet (DI). However, the purpose of PI is not to copy the DI, but to exploit the DI metaphor and the way information packets are distributed to develop a PI vision and transfer that mindset to the real world in the way we move, store, handle, realize, supply and use physical objects all around the world [75].

PI is about shipping freight just like information flows over the DI. For example, when we send an e-mail, we rely on the DI to securely deliver it to the receiver. The DI deals with standard data packets called datagrams, so that email is first divided into small data components, each encapsulated in a set of datagrams according to a universal format and protocol. These datagrams do not travel directly from source to destination, they travel through a series of routers and cables to arrive to their final destination, where they are reconstituted to a readable full email. The Physical Internet intends to do it similarly but with physical objects. To ship goods, physical internet uses what is known as the network of hubs (figure 2.1). The hub sends and receives products, the products may cross several hubs and the final delivery leaves from the closest hub to the receiver. Products moving over this open and interconnected network, belong to many different parties, what they have in common is that they are users of the Physical internet. The Physical internet therefore aims to rethink the current closed dedicated logistics operational networks into a universally opened interconnected system just like the DI [65]. Based on this PI principle of open and connected Networks, the participants who want to ship freight, can look each time at what is the best modality to choose, what the best location to store products is..., when a shipper wants to send a shipment of a group of containers, a decision is taken in the network as to what is the best compilation, which containers travel together, which transport modality is chosen as it could be his own but perhaps the freight could best be shipped with someone else's freight and at what moment it will arrive at the selected destination.

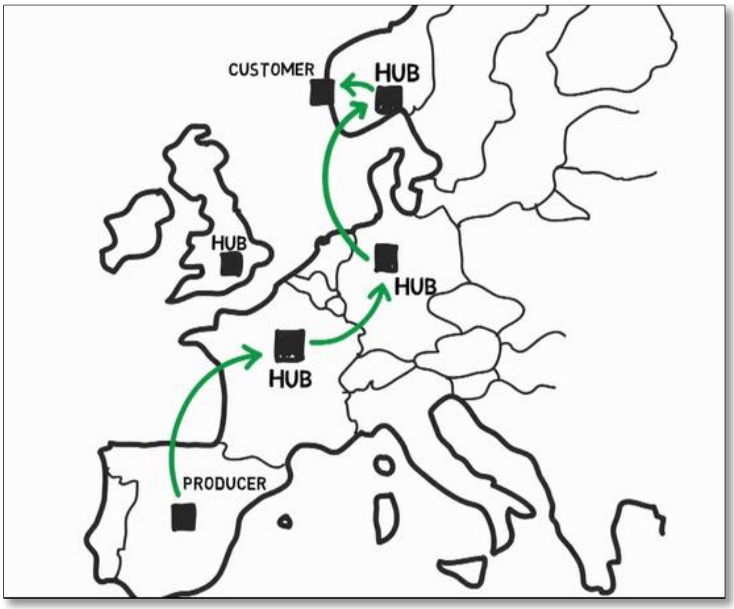


Figure 2.1 An illustration of a hub- network [73]

2.5 Similarities and Differences between Digital Internet and Physical Internet

2.5.1 Similarities

Since the PI network is inspired by the DI network, some of the distinct attributes of the PI can be traced to their counterparts in the DI. The major similarity attribute is that both of them represent network of Networks. DI is the Universal interconnection of Routers Networks (figure 2.2) while PI is the interconnection of hubs Networks. The role of routers in case of DI is to dispatch and/or reconsolidate datagrams while in case of PI, the hubs dispatch, compose/decompose and/or load/unload of containerized objects [76].

Another attribute is the collaboration between the different parties building the network. In both DI and PI network, all types of information are transferred to the entire network, from the sending to the reception of datagrams in case of DI and of containers in case of PI, beside the Share of services like transportation and warehousing in PI network.

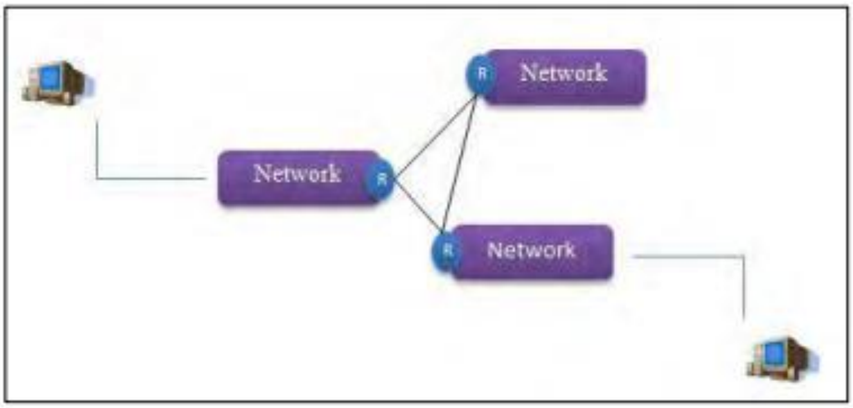


Figure 2.2 Interconnection of networks via the routers [76]

2.5.2 Differences

Although the PI is considered as an analogue of the DI, they are two completely different things. In fact, the complexity of the PI is considerably greater than that of the DI, because When sharing information; it's easy to save it, double it and send thousands of copies, but when moving goods, costs must be paid each time , not to mention the [77]. Beside that the PI not only needs to solve the reachability problem that exists in the DI, i.e., routing from A to B, but also must face the problem of optimality, i.e., optimizing the logistics metrics such as costs and time for the physical distribution activities. Transporting physical objects instead of transmitting digital signals, therefore, requires additional efforts in terms of physical distribution.

The table below summarizes the major differences in a set of logistics parameters between the DI and the PI.

Table 2.1 Main differences between DI and PI [78]

	DI	**PI**
Flow	Digital signals (0/1) in standardized packets (datagrams)	Physical objects in standardized containers
Speed	Near light transmission speed	Lead time Subject to transportation modes, availability of labor, handing time in the warehouses, etc.
Schedule	Transmission of digital information is almost instantaneous	Dynamic flow and potentially problematic process subject to the real-time status of the PI. (For example, if congestion arises or a vehicle breaks down, new routings may need to be implemented that lead to delayed deliveries**)**

Cost	Trivial variable cost linked to electricity consumption	Substantial variable costs linked to transportation modes, packing and unpacking, loading and unloading in distribution centers
Networking problems	**The reachability problem** : how to transmit from A to B	**The reachability problem** : how to ship from A to B **The Optimality problem** : how to optimize cost , lead time , etc. dynamically

2.6 The components of the Physical Internet

The PI requires three main elements in order to be implemented. These elements are π-containers, π-nodes and π-movers. The prefix π is used because it corresponds to the Greek letter pi, which corresponds to the abbreviation of the Physical Internet [65]**.**

2.6.1 Π-containers

While the DI deals with standard data packets, the PI deals with goods encapsulated in standard modular containers called Π-containers [79]**.**

2.6.1.1 Definition of ∏-containers

Π-containers are the basic unit loads that are moved, handled and stored via the PI network. They act as packets in the DI, but unlike these digital packets, the π-containers have a structure and a physical content rather than being purely informative. They protect the encapsulated goods and provide a private space in an openly interconnected logistics network [65]**.**

2.6.1.2 Description of ∏-containers

2.6.1.2.1 Physical description

From a physical perspective, π-containers must be designed to facilitate their handling, storage, transport, hanging on a structure, interlocking together, loading, unloading, building and dismantling. They may contain individual physical goods, as well as π-containers of lesser sizes, or yet other smaller private objects not designed for the Physical Internet.

Π-containers must be standardized worldwide and defined according to open norms. They come in modular dimensions expressed in height, width and depth, through combinations of the following dimensions: 0.12m, 0.24m, 0.36m, 0.48m, 0.6m, 1.2m, 2.4m, 3.6m, 4.8m, 6m, 12m and 18m. This dimensional modularity allow the easy composition of composite π-containers from sets of smaller π-containers (figure 2.3). The composite π-containers can later be easily decomposed so as to allow the individualized treatment of its constituent π-containers.

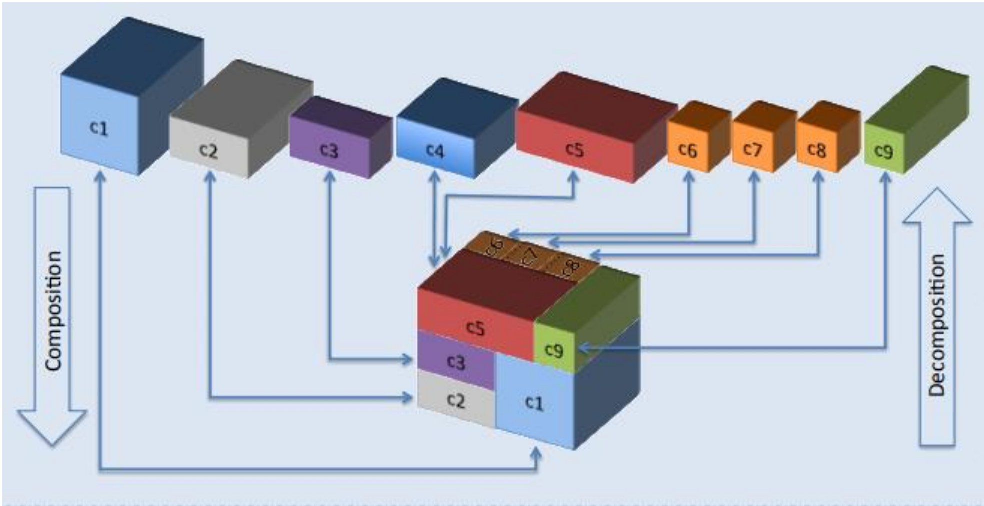


Figure 2.3 Standardized Modular π-containers [65]

The π-containers must also be as environment friendly as possible, reusable and/or recyclable, adaptable to the weight and characteristics of the loads contained while being as light as possible and have a minimal off-service footprint, allowing their on-demand dismantling and assembling. They also can have conditioning capabilities such as temperature, humidity and vibration control (figure 2.4) [65]**.**

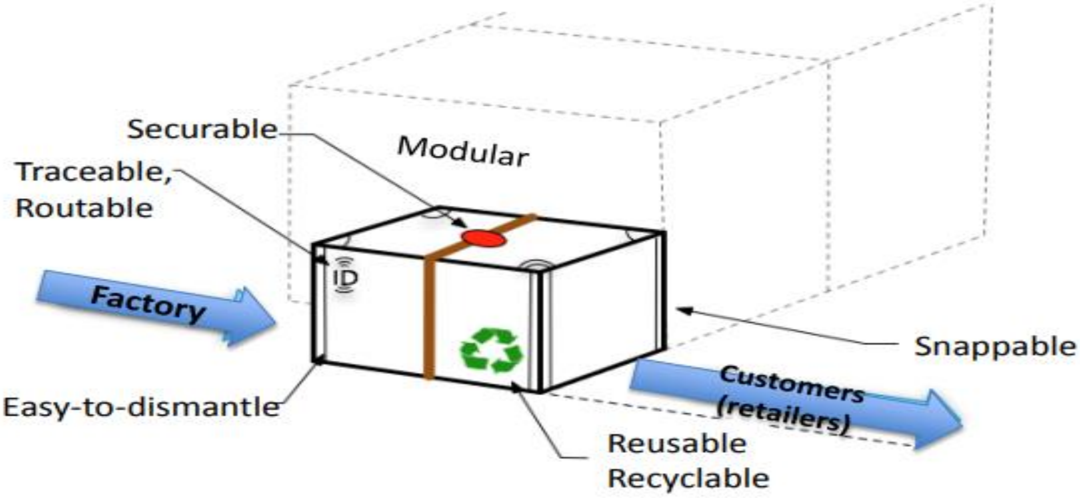


Figure 2.4 key characteristics of the π-containers [80]

2.6.1.2.2 Informational description

Each π-container has a unique identifier, such as the MAC address in the Ethernet network and the DI [81]. This identifier can be represented in the form of a smart tag attached to each π-container and helping to ensure the identification, integrity, routing, conditioning requirements, monitoring, traceability and security of the π-container through the PI. In order to deal adequately with privacy and competitiveness concerns within the PI, the smart tag of a π-container strictly limits access to the information of the pertinent parties. The informational contents of π-container tags are protected by an encryption/decryption key for security purposes. Only the information needed to route π-containers through the PI are accessible without this key [65].

2.6.2 Π movers

In the PI, π-containers are generically moved around by π-movers, and moving here is equivalent to transporting, conveying, handling and lifting. The main types of π-movers are π-transporters, π-conveyors and π-handlers [65].

The set of π-transporters includes π-vehicles and π-carriers, which are specifically designed for enabling easy, secure and efficient moving of π-containers. Π-vehicles are self-propelled while π-carriers have to be pushed or pulled by π-vehicles or by π-handlers which are humans that are qualified for moving π-containers. The set of π-vehicles notably includes π-trucks, π-locomotives, π-boats, π-planes, π-lifts (figure 2.5) and π-robots, while the set of π-carriers includes notably π-trailers, π-carts, π-barges and π-wagons

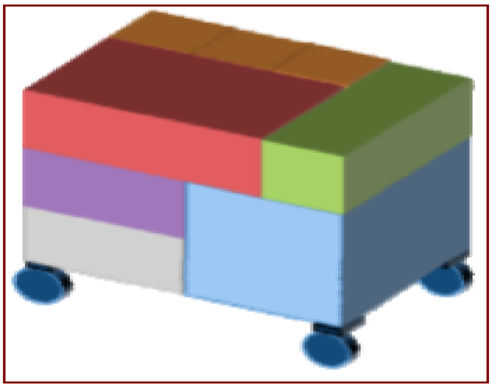


Figure 2.5 π-lift-truck lifting a composite π-container [65]

Complementary to π-vehicles, the π-conveyors (figure 2.6) are conveyors specialized in the continuous flowing of π-containers along determined paths without using π-vehicles and π-carriers. As they are explicitly designed for π-containers, π-conveyors may well differ from contemporary conveyors by not having rollers nor belts, the π-containers simply clipping themselves to the π-conveyor gears so as to be towed. [65].

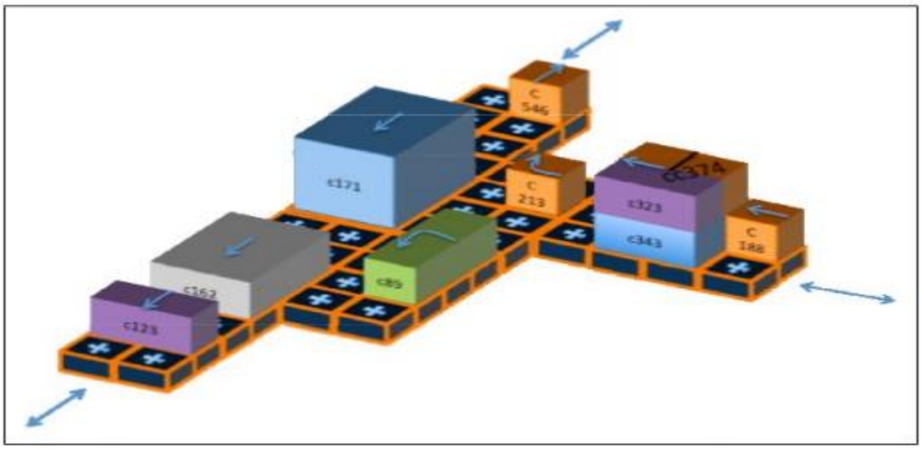


Figure 2.6 π-conveyor grid composed of flexible conveying pi-cells [65]

2.6.3 Π nodes

Π-nodes correspond to the site, facilities and locations designed to perform logistics activities and operations on π-containers, such as receiving, testing, moving, routing, sorting, handling, placing, storing, picking, monitoring, labeling, paneling, folding, assembling and disassembling, snapping and unsnapping, composing and decomposing and finally shipping the π-containers. Π-nodes are divided into seven types: π -transits, π -switches and π-bridges, π-hubs, π-sorters, π-composers, π-stores, π-gateways [65].

2.6.3.1 Π-transit

A π-transit can be as simple as a π-site located near the intersection of two highways, where π-trucks carrying π-trailers record their arrival, unhook their π-trailer at a given location, then either leave or pick up another assigned π-trailer parked at a location in the π-transit. In general, π-transits are often unimodal. There can be multi-modal π-transits. For example, π-trailers can be transited from π-trucks to either π-trains or π-boats, and vice-versa [65].

2.6.3.2 Π-switch and Π-bridge

A π-switch is a π-node whose mission is to enable and carry out the unimodal transfer of π-containers from an incoming π-mover to a departing π-mover. Examples include rail-rail π-switches and conveyor-conveyor π-switches. Whereas a P-bridge is a π-node having a mission of the same type as a π-switch, specialized in the one-to-one multimodal transfer of π-containers not involving any multiplexing. An example is a rail-route π-bridge [65].

The main tasks of a π-switch and a π-bridge are double. From a physical perspective, their main role is to transfer π-containers from one π-mover to another in an efficient, safe, secure and reliable way. From an informational perspective, their main role is to ensure that the receiving π-mover is ready before the transfer of the π-container, that all parties are informed of the transfer and that the contracts are terminated and activated respectively for the incoming π-mover and the departing π-mover [65].

2.6.3.3 Π-hub

The π-hubs are π-nodes having for mission to enable the transfer of π-containers from incoming π-movers to outgoing π-movers. Their mission is similar to the mission of π-transits, but dealing with π-containers themselves rather than dealing with the π-carriers. They enable unimodal π-container cross docking operations. Furthermore, π-hubs will be at the core of fast, efficient and reliable multimodal transportation, by allowing ease of transfer of π-containers between combinations of road, rail, water and air transportation [65].

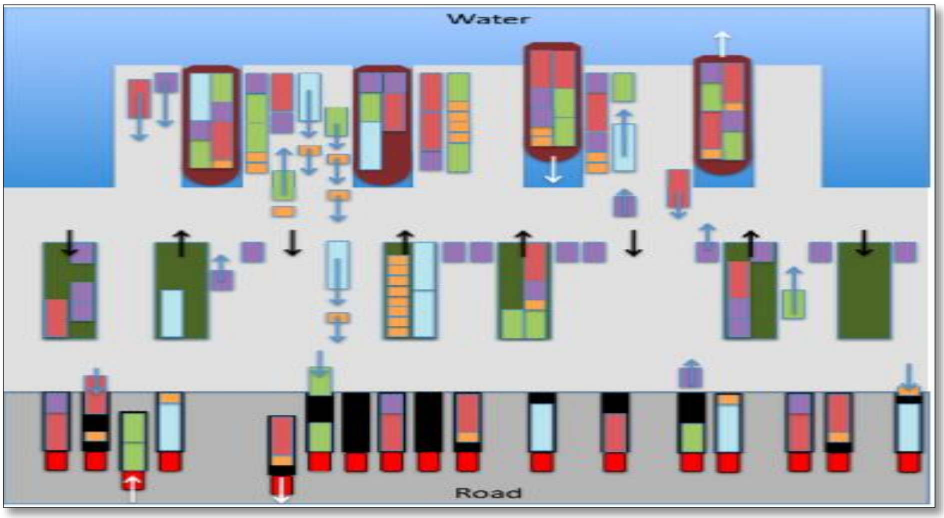


Figure 2.7 Illustrative water-road π-hub [65]

2.6.3.4 Π-sorter

A π-sorter is a π-node that receives π-containers from one or multiple entry points and sorting them so as to ship each container from a specified exit point, potentially in a specified order. A π-sorter may incorporate a network of π-conveyors and/or other embedded π-sorters to achieve its mission. The π-sorters are typically embedded within more complex π-nodes, such as π-hubs [65].

2.6.3.5 Π-composer

Constructing composite π-containers from specified sets of smaller π-containers, usually according to a specified 3D layout, and/or dismantling composite π-containers into a number of π-containers that may be either smaller unitary or composite π-containers [65].

2.6.3.6 Π-store

A π-store is a π-node whose mission to enable and achieve for its clients the storage of π-containers during a certain time. π-stores differ from contemporary warehouses and storage systems in two main points. First, they focus strictly on π-containers: they can stack them, interlock them, snap them to a rack, and so on (figure 2.8). Secondly, they do not deal with products as stock-keeping units, but instead focus on π-containers, each being individually contracted, tracked and managed to ensure both quality and reliability of the service [65].

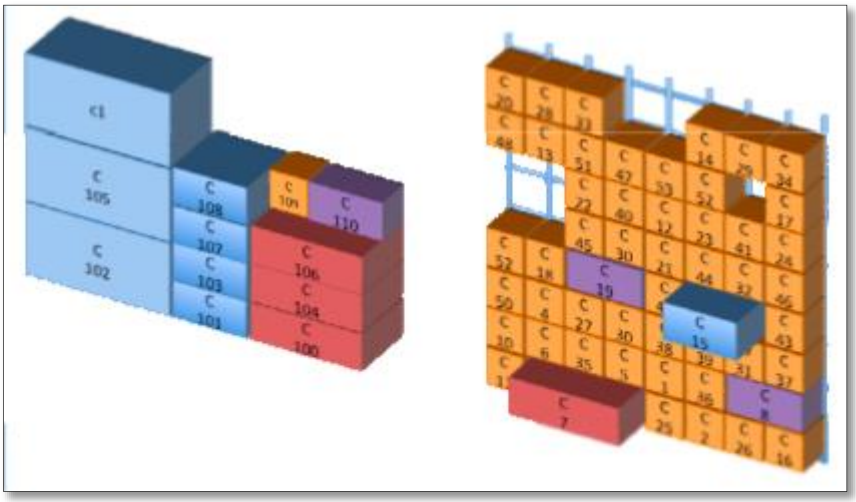


Figure 2.8 Illustrating stacking and snapping functionalities of a π-store [65]

2.6.3.7 Π-gateway

The π-gateways are π-nodes that either receive π-containers and release them so they and their content can be accessed in a private network not part of the PI, or receive π-containers from a private network out of the PI and register them into the PI, directing them toward their first destination along their journey across the PI [65].

2.7 Simple network model of the Physical Internet

While the DI network includes the following elements: cables, hosts and routers, the PI network faces a more complex reality in terms of elements. A PI model should integrate: a large number of participants organized in a network with a topology. A PI network can be presented graphically with nodes (logistics centers including distribution centers (DCs), hubs, warehouses (WHs), factories, etc.) and arcs defining transport connections (by road, rail, maritime services, etc.) (Figure 2.9) [82]**.** A shipper **s** among the network participants, sends his containerized merchandise to a neighboring node that handles it, stores it and sends it to another node to do the same job and so on, until it arrives at the receipt **r** after having traveled in one of the many accessible logistics plans of the entire network.

Each node and arc is associated with a weight vector W. The elements of the weight vector represent the logistics parameters or criteria, such as the cost, lead time, etc. As noted earlier, a PI network faces two major problems; the reachability which consists of finding a path to ship freight from the sender **s** to the receiver **r**, while the second more complex problem is that of optimality, which is to solve the reachability problem with a minimization of the total logistics cost and lead time which are subject to dynamic constraints in all or part of the PI network, such as network topology, delays in the network flow due to capacity related issues, etc.

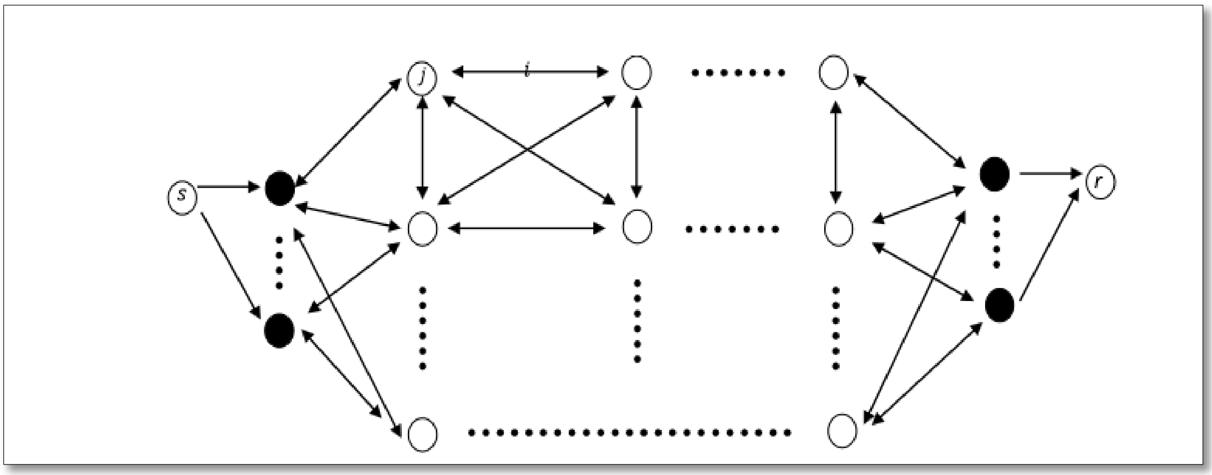


Figure 2.9 A simple network model for the PI [82]

If only the cost criteria is taken into account, the mathematical structure of the PI problem will be similar to that of the classic Travelling Salesman Problem (TSP) which is to search for a feasible route between the origin **s** and the destination **r**, ensuring the minimum possible overall cost. And if only the total routing time is considered, the mathematical structure will be similar to that of the classic Traffic Assignment Problem (TAP), which deals with traffic flows delay problems in a network with a limited capacity by determining all possible routes and traffic mobility expectations on each route. However, even the most sophisticated algorithms developed to solve these TSP and TAP problems would not function in the case of a PI network, since PI needs to dynamically consider both cost and time, and it encompasses an extensive collaborative network of which the problem size is considerably larger than any of all the TSP or TAP problems studied so far.

C. Dong and R. Franklin [82], have proposed an algorithm (figure 2.10) based on dividing the complex problem of PI model into two sub-problems: the reachability and optimality problems. The solution is divided into two iterative steps. In the first step, the reachability problem is solved by finding all walks from the current node to the receiving node r. Then comes the second step, which to find a compromise between cost and time. The optimality of the total logistics cost is therefore subject to lead time constraint or the opposite.

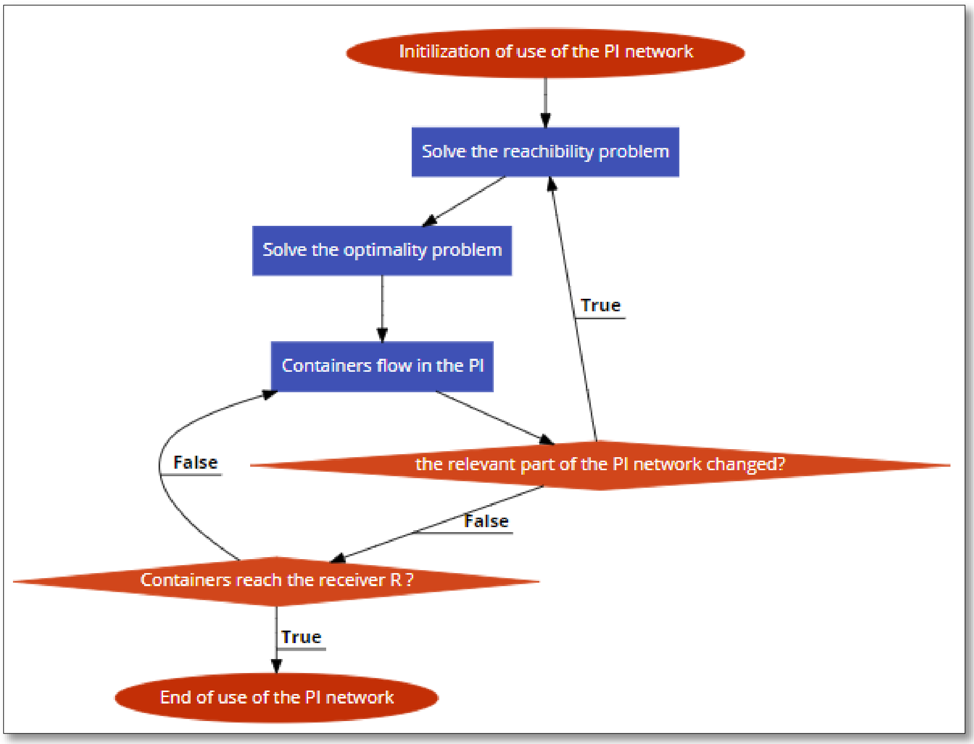


Figure 2.10 The flowchart of the PI [82]

2.8 Physical Internet and Internet of Things

2.8.1 Internet of things

The term "Internet of Things (IoT)" was introduced for the first time in 1999 by Kevin Ashton of the Massachusetts Institute of Technology (MIT), combining two words, the Internet which refers to an idea of network and virtual space, and Things that focuses on physical objects. IoT is an integrated part of the Internet of the future and could be defined as “a world in which physical objects are seamlessly integrated into the information network, and physical objects can become active participants in business processes. Services as well, are available to interact with these “smart objects” over the Internet, query their status and all information associated with them, taking into account security and privacy issues” [83]. The first research of IoT was based on RFID technology. However, with the application and features being developed, IoT is currently taking place in a wide range of sectors such as transportation, energy, healthcare, pharmaceuticals, retail, manufacturing, recycling and food traceability…, and it is predicted that the number of connected devices will reach 50 billion by 2020. IoT has become an important asset in terms of creating business opportunities and gaining a competitive advantage in the marketplace thanks to its transparency, traceability, adaptability, scalability, and flexibility [84].

2.8.2 Internet of Things applications in the Physical Internet

As previously introduced, PI aims to revolutionize logistics by improving its efficiency and reducing its operational costs. Technology is therefore needed to achieve this goal and the integration of IoT technologies into such a logistics paradigm can be an accelerator and a potential solution to improve the performance of this process [85] and enhance the PI roadmap towards a more sustainable logistics network by using several applications such as: real-time product status tracking, inventory and delivery management, simplification of interactions between objects, self-organization, improvement of logistics flow, automation and machine decision making [84].

The main application of IoT technologies to PI is for containers encapsulating goods. Containers in a PI approach should be uniquely identified, integrated, routed, monitored, secured and tracked at all times. Current IoT technologies such as Radio Frequency Identification (RFID), Global positioning system (GPS), Wireless Sensor Network (WSN), can be the appropriate tools to realize these smart features of containers as they track items, dynamically manage assets and goods in real time, reduce risks and increase reliability and security.

In fact, both of the PI and IoT systems have the same occupation, which is to connect between the virtual world and the real world by linking the things with the information concerning them (identification, location, status…). Their applications are similar in the industry (optimization of production, logistics…) but their utilities are different. IoT integrates the real world into a virtual network (smartphone, tablet…), while PI runs a physical global network of logistics with monitoring of virtual operations [86].

2.9 Current logistics compared to the Physical Internet vision

2.9.1 Point to point transport in contrast to Physical Internet enabled distributed multi-segment transport

The Current logistics is dominated by the Point to point transport mode, which means that Truck drivers need to drive for long distances and are away from home for various durations in order to transport their trailer from the shipping point to the destination point. This mode of transporting goods is therefore inefficient and extremely discomforttable for the drivers.

In the PI strategy, another potential mode is used which is the distributed transport where the driver, or even better the driver-duo, would be transporting goods for only few hours instead of many hours or days, unloading the trailer in a ∏-transit, then loading another trailer as to deliver it back to its origin destination. Figure illustrates the difference between the two modes point to point transport and PI enabled distributed transport.

A shipper wants to transport containers from Quebec in Canada to Los Angeles in the US (figure 2.11). According to the current way, the driver will have to drive all the way for a 120 hours trip to arrive to Los Angeles and once having delivered the trailer, the driver will move the truck to the nearest possible location to pick up a new trailer returning to Quebec, which makes the total round trip at least 240 hours long.

In the PI strategy, the scenario is different. A first driver will drive for few hours to bring the trailer from Quebec to Montreal where there will be a switch, the driver would deposit the trailer in a ∏-transit or ∏-hub then go back to Quebec city with another new trailer, a second driver would pick up the trailer from Montreal and transport it to the next point, and so on until the trailer arrives to Los Angeles. In this way, the drivers would be going back home every day and the trailers would get to Los Angeles twice as fast as the point to point transport, because there will be no need for drivers to take sleep or eating breaks. Which means that the proposed PI distributed transporting system is beneficial for the drivers as well for the efficiency of transportation.

Figure 2.11 Contrasting current point-to-point transport and PI enabled distributed transport [57]

2.9.2 Transformation from dedicated networks towards Hyper connected System

2.9.2.1 Dedicated networks

In the current logistics organization, producers, distributors and retailers rely mainly on private supply networks, consisting of the production and distribution centers of their companies and those of their partners. Figure 2.12 illustrates the situation, suppliers represented by squares, send their products to privately-owned WHs represented by triangles, which then forwards them to regional DCs owned by the retailers who then send the goods to their final destinations represented by circles. It is clear that the current system does not create much space for intelligent and efficient transportation. The limitations of using private networks are clear because the range of options depends on the amount of WHs and DCs available. The current model only allows for strategic decisions such as the timing of the goods shipment and their quantity [57]**.**

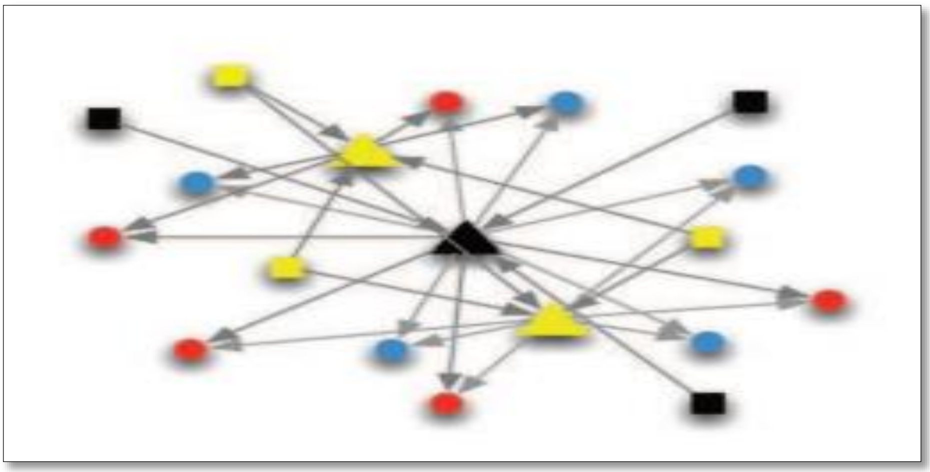


Figure 2.12 Dedicated logistics network [87]

2.9.2.2 Hyper connected networks

The scenario under the PI perspective is different. Instead of dedicated and fragmented supply networks, PI makes it possible to develop a global interconnected network where suppliers have many different options of where to send goods and can push them towards the demand in a more efficient way, outsourcing part of the inventory, thanks to the suggested open logistic web and open available WHs and DCs or ∏-Hubs. At the same time, retailers can reduce lead time and stock by sourcing from all the open available DCs, this way creating an interconnected network [57]**.** As shown in Figure 2.13, each supplier, represented by a square, directly sends the goods which are containerized and each container thus filled will be charged to the factory and shipped to its target destination represented by a circle via transits through open network hubs.

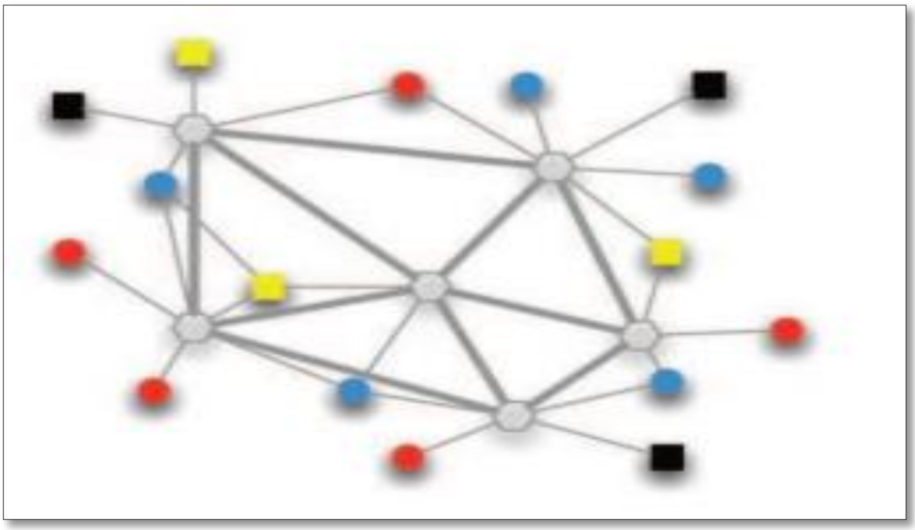


Figure 2.13 Hyper connected logistics network [87]

Dedicated Networks are optimized for each player and are not a globally optimal networks, while the Hyper connected Networks are optimized globally by increasing proximity to demand locations and improving capacity utilization of WHs and DCs. Figure 2.14 illustrates the difference between the current topology of dedicated networks (left-hand diagram) and that corresponding to an interconnection of logistics networks (right-hand diagram) for the same volume of flows sent in France. If we consider that the various logistic centers (factories, warehouses, distribution centers, etc.) are connected through an open network, we see that we end up with a less complex network and therefore with flows easier to optimize [80]**.**

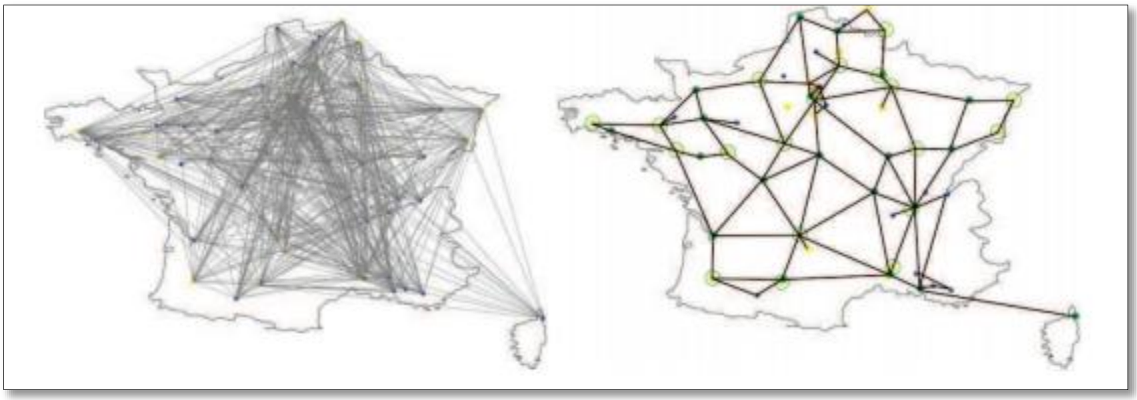


Figure 2.14 Example of switching from a dedicated service network (left) to an interconnected network (right) [87]

2.9.3 Main differentiation Elements between current logistics and the Physical Internet

As noted in the different previous sections, PI is a highly scalable cooperative approach based on open universal interconnection, with the aim of tackling the main sustainability challenges facing the current logistics. Table 2.2 highlight the main differences between the PI approach and the current way of doing logistics.

Table 2.2 Main elements of differentiation between the current logistics and the PI. [88]

Function	Current Logistics	Physical Internet
Shipping	Goods	Containers
Network	Specific services	Network of open and shared networks
Path	Logistics scheme	Dynamic routing
Information system	Proprietary	Internet of Things Cloud Service Platforms (Cloud)
Standard	Breaking standards	Agreement on interfaces, identification and protocols
Storage	Punctual (centralized)	Deployment logic
Capacity management	Private	Publication

2.10 The contribution and Predictable consequences of the Physical Internet

PI has been introduced as a way of addressing the great challenge of improving the efficiency and sustainability of logistics [73] Recent studies have assessed the enormous potential for PI across a wide range of sectors. Estimations predict economic gains of at least 30%, environmental gains of 30 to 60% in GHG emissions, and social gains such as reduced truck turnover about 75% for roads based transportation coupled with lower prices and faster supply chains [73, 87].

PI has recently been highlighted in the US Roadmap on Material Handling and Logistics as an essential contribution to the future of logistics and material [89]. thus in a 2013 study done by engineers at the University of Arkansas and Virginia Tech University, it was found that “if 25 percent of the U.S. supply chain operated with the physical internet system, profits for participating companies would increase by $100 billion, carbon dioxide emissions from road freight transportation would decrease by at least 33 percent and consumers would pay less for goods" [90].

In short terms, PI aims to contribute to the creation of an open, global, interconnected and sustainable logistics system in which these benefits are introduced:

- Maximum loading capacity of transportation means (boats, trucks, trains…).
- Better utilization of equipments.
- Minimal operational costs (handling, inventory, transport …).
- Lower inventory level in warehouses.
- Minimum delivery time.
- Minimum fuel consumption and GHG emissions, in particular of CO2.
- Maximum efficiency of logistics operations.
- Maximum interconnectivity and collaborative economy (where possession is less important than the whole network efficiency).
- Better customer service and reduction in prices paid by the consumer.
- Lower driver turnover rates.

2.11 Main challenges facing the implementation of the Physical Internet

The PI could be a potential framework for enabling more consistent approaches for solving logistics issues. However the implementation of such a smart network is confronted to a set of challenges and large requirements, the thing that made the researchers determine the year of 2050 as an horizon for spreading the PI concept widely. These challenges could be divided on three levels: physical, informational and business level.

2.11.1 Physical level

PI requires major changes in the physical infrastructure, common tools and elements need to be defined and designed such as π-movers, π-nodes and π-containers. Beside both tools and time are required to codify places and shipments standardized worldwide and make the connection to move from one provider to another, rather than doing everything with one solution.

2.11.2 Information level

Since PI is an intelligent open network of networks, the major challenge is how to make the physical objects especially π-containers, smart and interconnected at most efficient way. Therefor the development of researches on strategic role of communications and information technology is required.

2.11.3 Business level

The PI redefines the logistics configuration and value-creation patterns which requires the creation of new business models [91]. These business models should be based on the concept of collaborative economy and engage strategic partnerships, which is not easy and requires time since the fact that until now warehouses and distribution centers are still privately owned, every provider has made his own tools, his own modes of operations, therefore, the implementation of a shared network does not come directly to mind and it takes a whole change of mindset [92]. In a recent study, it was revealed that 88% of companies believe in collaboration and see benefits including increasing the profit margin, reducing the cost of charges to the shipper, less inventories and carbon footprint, better customer service, etc. But only 10 to 30% of them use a certain form of collaboration on the real plan while many report "failed collaboration projects" [93, 94].

2.12 Conclusion

PI represents a technological breakthrough in transportation and a powerful paradigm towards more sustainable, efficient, adaptable and resilient logistics web [57]**.** Several trials in their early stage are currently experimenting with the use of the PI such as the CRC project (Collaborative Routing Centers) in France, ALICE project (Alliance for Logistics Innovation through Collaboration in Europe) [72], the Modulushca project that proposes to exploit the PI on fast-moving consumer goods (FMCG) logistics [71] and the ATROPINE project about business models designs which supports the idea of a sharing economy) [95].Theoretically, adopting the PI approach requires a critical mass of participants to create a huge interconnected network. And as to diffuse such a new technology, expenses could often prevail over the benefits generated by the network users. Thus, government funding can play a significant role for the diffusion of the PI. Finally, there is a significant research required on the transformation of the current sets of containers, movers, systems, facilities, sites and protocols along a roadmap from the current paradigm towards a full implementation of the PI [65]**.**

After having giving a general overview of the PI, in the next chapter we tackle our selection and arrangement problem and suggest two resolution methods whose results are interpreted at the end.

3.
Π-containers selection and objects ranking problem

3.1 Introduction

In this chapter, we are going to tackle a major sophisticated problem in the Π-network that has not been treated yet since the appearance of the PI context, which is the optimization of the management of Π-containers. This main problem includes the selection of an optimum number of Π-containers to ship a precise number of objects. The questions here are, which Π-containers to use and how to arrange the objects inside of each selected Π-container, in a certain way that assures having the least possible emptiness rate.

In fact, optimizing the Π-containers management, would help significantly in solving the unsustainability symptoms already mentioned in the chapter number one. Minimizing the empty volume inside of Π-containers, means that the shipping expenses including the void and the empty runnings costs would decrease, also the fact of minimizing the number of used Π-containers would reduce the iterations number of the transport operations, which means a fast products delivery and more stable life for drivers.

3.2 The definition of the problem

given a set of n objects of various weights (WeiO1,WeiO2,WeiO3,...,WeiOn) and of various volumes (VO1,VO2,VO3,...,Von) these objects must be packed into a limited number of m Π-containers having different load capacities (MAXC1, MAXC2, MAXC3,…,MAXCm) and volumes (VC1, VC2, VC3,…,VCm). The main objective of this problem is to minimize the total emptiness rate by selecting an optimum number of used Π-containers and arrange the objects in a way that assures filling as much as possible the available volume of selected Π-containers, while respecting the limits of their loading capacity and their volume. The cost of emptiness inside of a Π-container is directly proportional to the rate of its empty volume. In this case minimizing the empty volume for the Π-container would bring great benefits on the economic side for the shipper.

This problem is NP-hard optimization problem which means that it is not possible to find an efficient algorithm to optimally solve large size instances in reasonable computational time. To solve this problem, we adapt two types of programming, the first is a linear program (LP) by using a linear mathematical model and the second is a meta-heuristic programming using a Genetic algorithm or shortly GA.

Our problem can be taken as a particular case in the famous 3D Bin Packing Problem (BPP), in which items of different volumes must be packed into a finite number of identical bins, in a way that minimizes the number of bins used, respecting the capacity. It is a combinatorial NP-hard problem. The decision problem which consists of deciding whether objects will fit into a definite number of bins or not, is NP-complete. The difference between the 3D BPP and our problem is the fact that the Π-containers are not similar and they are dimensionally standardized in a careful practical way, while in case of Bin Packing; the bins are identical and have the same volumes and capacities beside that the objective is to minimize the total number of the selected bins, while in our problem we focus more on minimizing the emptiness volume inside of each selected Π-container. That's why the heuristics used for solving the BPP like the Best-Fit Algorithm (BFA), do not best fit our problem.

3.3 The resolution of the problem

3.3.1 Linear programing

3.3.1.1 Formulation of the problem

Given a set of different parallelepiped-shaped objects and each object I is characterized by length (LOi), width (WOi) and height (HOi), hence a volume (VOi) and a certain weight (WeiOi). Our target is to find out the optimum set of Π-containers that could pack all the objects and make sure that the objects are well arranged inside of each used Π-container in a way that provides a minimum emptiness rate. Each object can be arranged according to one of six possible positions or orientations that are relative to the parallelism to the Π-container dimensional axes (length LC_j, WC_j width, HC_j height). The six positions are shown in the table below

Table 3.1 The six possible positions of an object inside of a Π-container

Position number	Axis parallel to LC_j	Axis parallel to WC_j	Axis parallel to HC_j
1	Object length LO_i	Object Width WO_i	Object Height HO_i
2	Object width WO_i	Object Length LO_i	Object Height HO_i
3	Object Width WO_i	Object Height HO_i	Object Length LO_i
4	Object Length LO_i	Object Height HO_i	Object Width WO_i
5	Object Height HO_i	Object Width WO_i	Object Length LO_i
6	Object height HO_i	Object length LO_i	Object width WO_i

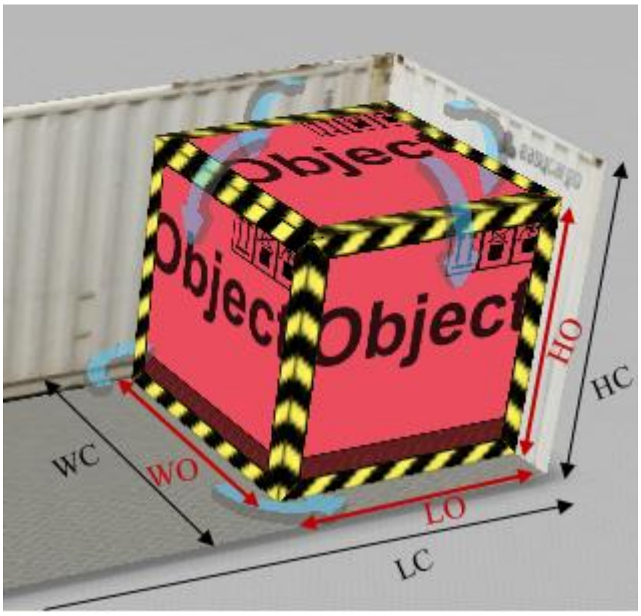


Figure 3.1 Illustration of the six possible positions of a containerized object

Based on the descriptions of the problem, the mathematical formulation is presented as follow

Sets

O set of Objects I, ranging from 1 to n

C set of Π-containers j, ranging from 1 to m

P set of Positions k, ranging from 1 to 6

Parameters

n Number of objects to be loaded;

m Number of available Π-containers;

$LO_i, WO_i, HO_i, VO_i, WeiO_i$:Length, width, height, volume and weight of object i

$LC_j, WC_j, HC_j, VC_j, MaxC_j$:Length, width, height, volume and maximum load capacity of Π-container j

Decision Variables

X_j Binary variable which indicates if container j was selected. It is equal to 1 if Π-container j was selected and 0 otherwise;

$Y_{i,j,k}$ Binary variable which is equal to 1 if object i is loaded in the Π-container j with the position k and 0 otherwise;

Objective Function

Our objective is to reduce the unoccupied volume in the Π-containers selected for the shipping. The total unoccupied volume is calculated as the total volume of the selected Π-containers minus the total volume of the objects placed in each selected Π-container.

$$\text{Min} \sum_{j=1}^{m} \left(VC_j * X_j - \sum_{i=1}^{n} \sum_{k=1}^{6} (VO_i * Y_{I,j,k}) \right)$$

Contraints

$$\left[\sum_{i=1}^{n} (LO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (WO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (WO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (LO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (HO_i * Y_{i,j,k}) + \sum_{i=1}^{6} (HO_i * Y_{i,j,k})\right] \le LC_j * X_j \dots \forall j \in m \quad \dots(1)$$

$$\left[\sum_{i=1}^{n} (WO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (LO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (HO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (HO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (WO_i * Y_{i,j,k}) + \sum_{i=1}^{6} (LO_i * Y_{i,j,k})\right] \le WC_j * X_j \dots \forall j \in m \quad \dots(2)$$

$$\left[\sum_{i=1}^{n} (HO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (HO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (LO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (WO_i * Y_{i,j,k}) + \sum_{i=1}^{n} (LO_i * Y_{i,j,k}) + \sum_{i=1}^{6} (WO_i * Y_{i,j,k})\right] \le HC_j * X_j \dots \forall j \in m \quad \dots(3)$$

$$\sum_{i=1}^{n} \sum_{k=1}^{6} (WeiO_i * Y_{i,j,k}) \le MaxC_j * X_j \dots \forall j \in m \quad \dots(4)$$

$\sum_{i=1}^{n}\sum_{k=1}^{6}(VO_i * Y_{i,j,k}) \leq VC_j * X_j$ ……………………………………………………………… $\forall j \in m$ ……..(5)

$\sum_{j=1}^{m}\sum_{k=1}^{6} Y_{i,j,k} = 1$ ……………………………………………………………………………… $\forall i \in n$…….........(6)

$Y_{i,j,k} \leq X_j$ ………………………………………………………………………………… $\forall i, \forall j, \forall k$……(7)

$X_j \in \{0,1\}$ ………………………………………………………………………………… $\forall j \in m$………(8)

$Y_{i,j,k} \in \{0,1\}$ ……………………………………………………………………………… $\forall i, \forall j, \forall k$………..(9)

Constraints (1) to (3) allow to check the Π-container size simultaneously along the length axis LC_j, the width axis WC_j and the height axis HC_j.

Constraint (4) ensures that the total weight of the loaded objects do not exceed the maximum loading capacity of the selected Π-container.

Constraint (5) ensures that the total volume of the loaded objects do not exceed the volume of the selected Π-container.

Constraint (6) ensures that each object must be placed in only one Π-container and according to only one position among the six available positions.

Constraint (7) allow the objects to share the same Π-container.

Constraint (8) and (9) define the binary variables of the model.

3.3.1.2 Numerical simulation

We implemented the previous mathematical linear model on Lingo solver. Lingo is a simple tool for utilizing the power of linear and nonlinear optimization to formulate large problems concisely, solve them, and analyze the solutions. [96]

The Π-containers Data used in the implementation are as follow:

We have 12 Π-containers which dimensions are standardized through combinations of the following dimensions: 0.12, 0.24, 0.36, 0.48, 0.6, 1.2, 2.4, 3.6, 4.8, 6, 12 and 18. [71]

N.B: all dimensions used are in meters (m), volumes are in meters cube (m^3) and Capacities/ weights are in Kilograms (Kg).

Table 3.2 The Data of the Π-containers used

Π-container ID	**Length LC_j**	**Width WC_j**	**Height HC_j**	**Volume VC_j**	**Maximum Capacity $MaxC_j$**
C1	1,24	1,20	1,20	1,79	1,46
C2	2,40	3,60	2,40	20,74	17,66
C3	4,80	2,40	2,40	27,65	23,55
C4	6,00	6,00	4,80	172,80	147,15
C5	12,00	3,60	2,40	103,68	88,89
C6	18,00	4,80	4,80	414,72	353,17
C7	6,00	4,80	1,20	34,56	66,22
C8	3,60	3,60	4,80	62,21	52,98
C9	12,00	6,00	6,00	432,00	360,22
C10	6,00	4,80	3,60	103,68	88,89
C11	4,80	3,60	2,40	41,47	17,66
C12	6,00	4,80	4,80	138,24	117,72

Case 01:

We first tested the attitude of the program using only one object to containerize, called "object_ test". The dimensions of the object are:

Table 3.3 The Data of the object used in case one

	Length LO_i	**Width WO_i**	**Height HO_i**	**Volume VO_i**	**Weight $WeiO_i$**
Object_ test	2,50	1,60	1,40	5,6	9,00

After running the program, we obtained the following results:

Table 3.4 The Π-containers selected in case one

Π-containers	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Selection and Object positioning	0	**(1,6)**	0	0	0	0	0	0	0	0	0	0
Selection rate %	0	**100**	0	0	0	0	0	0	0	0	0	0

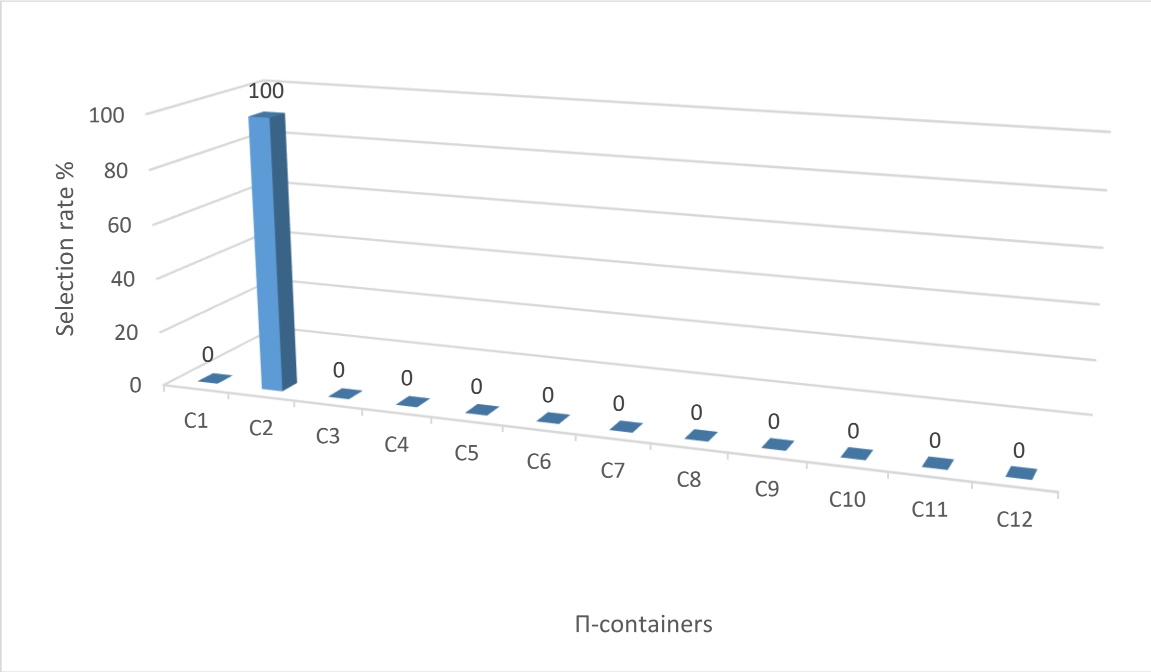


Figure 3.2 Selection rates of Π-containers in case one

The Π-container selected for shipping the object_test is then C2 with a volume of 20.74 m^3 according to the sixth position. In this case, the value of the objective function which is the emptiness volume inside of C2, equals to 15.14 m^3 as shown in figure 3.3, after having completing 842 iteration according to Branch and Bound algorithm.

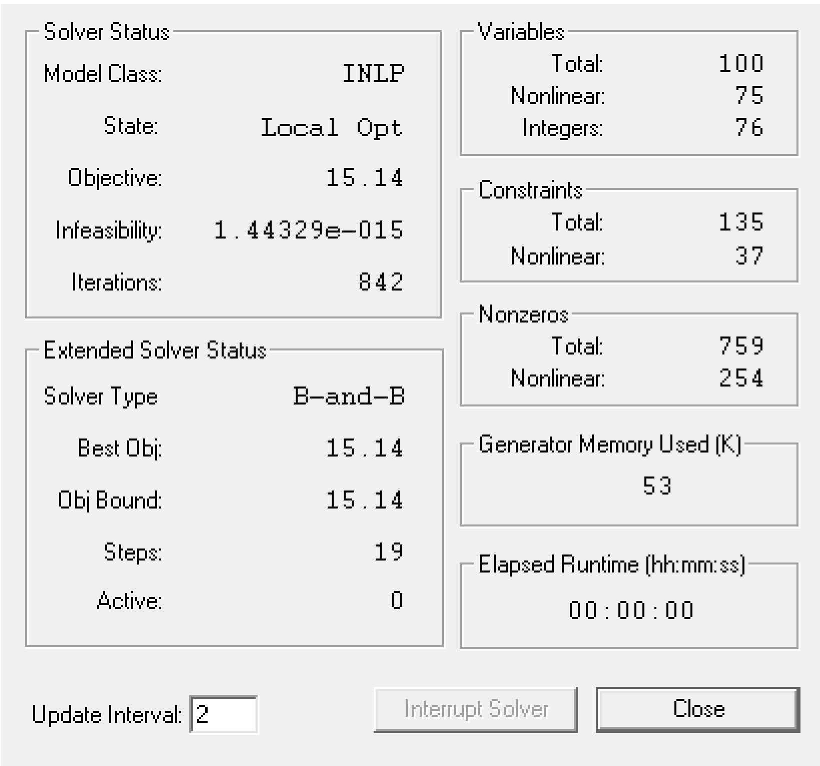


Figure 3.3 Case one Lingo solver's results

According to the objective function value, the emptiness rate of the Π-container C2 is 73%, while the used volume rate is equal to 27%. The emptiness rate here is very large because we only have one object to containerize in the system.

Figure 3.4 represents a simple simulation of the obtained results, using EasyCargo software. Easy Cargo is a 3D truck and container load planning software, it can create load plans for over 10 000 items of 250 different types in one shipment and illustrate the results in an interactive 3D image, but it can only plan for one shipment, i,e., loading one container at once. [97]

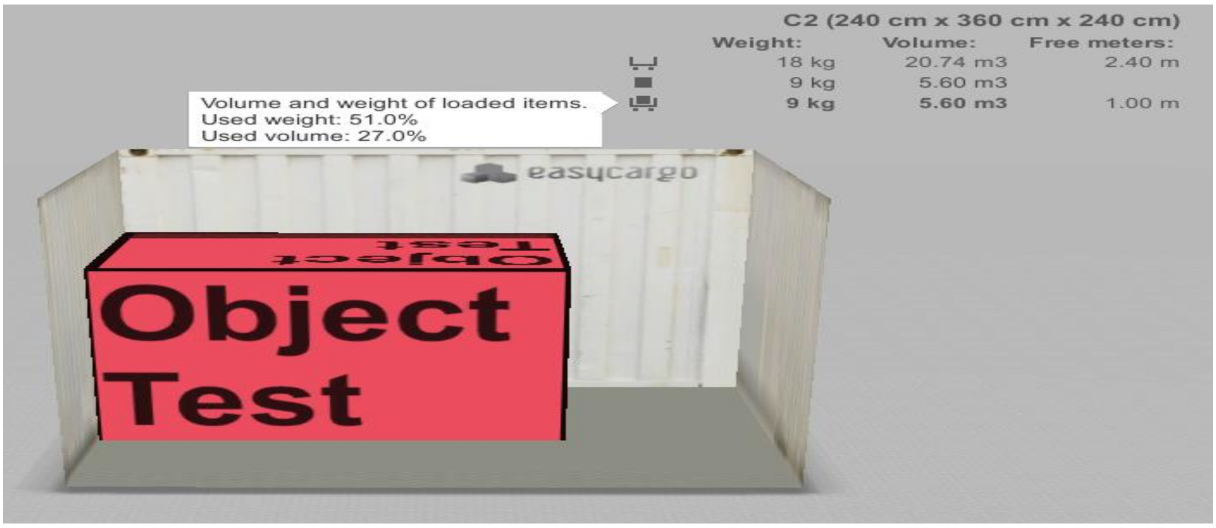


Figure 3.4 EasyCargo simulation of the arrangement of object_test in case 01

Case 02:

Now, we run the program again but using this time 8 different objects chose stochastically, whose DATA are given in the table below

Table 3.5 The Data of the objects used in case two

Object ID	Length LO_i	Width WO_i	Height HO_i	Volume VO_i	Weight $WeiO_i$
O1	1,50	1,20	1,40	2,52	9,00
O2	0,80	3,60	1,60	4,61	1,50
O3	2,40	1,10	1,60	4,22	1,30
O4	2,50	2,20	1,20	6,60	6,20
O5	2,50	0,85	1,30	2,76	5,00
O6	0,90	2,50	1,20	2,70	5,80
O7	1,00	3,50	0,50	1,75	2,00
O8	0,50	2,50	1,00	1,25	1,50

After running the program, we obtained the following results:

Table 3.6 The Π-containers selected in case two

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
O1	0	0	0	0	0	0	**(1,5)**	0	0	0	0	0
O2	0	0	0	0	0	0	**(1,5)**	0	0	0	0	0
O3	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O4	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O5	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O6	0	0	0	0	0	0	**(1,5)**	0	0	0	0	0
O7	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O8	0	0	0	0	0	0	**(1,6)**	0	0	0	0	0
Selection rate %	0	0	0	0	0	0	**100**	0	0	0	0	0

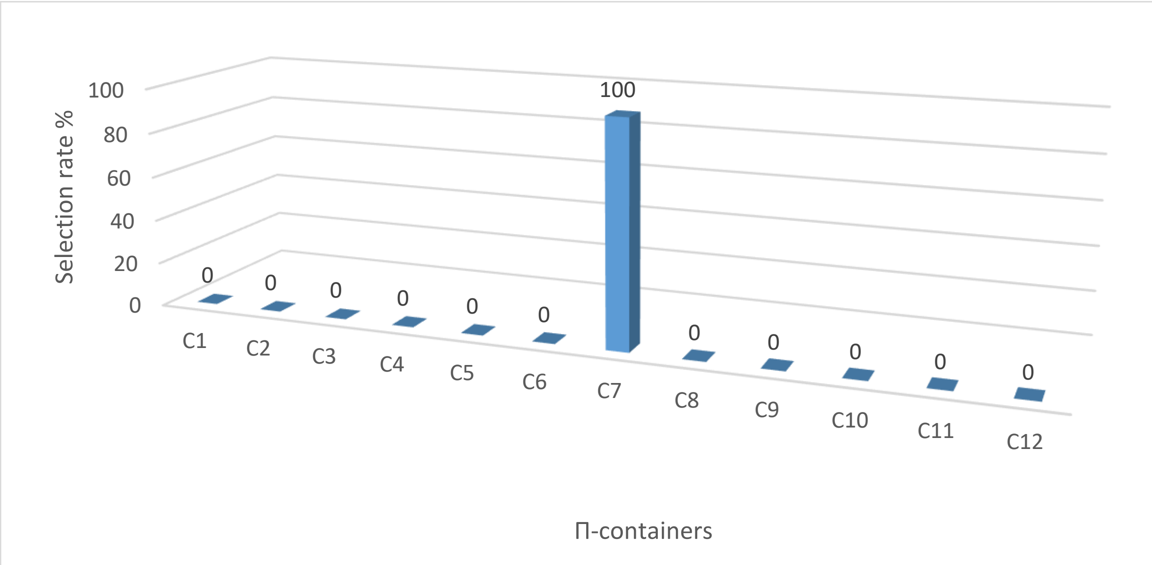


Figure 3.5 Selection rates of Π-containers in case two

The only Π-container selected is then C7 with a selection rate of 100%. The objects are ranked in the following way: O1, O2 and O6 according to the fifth position, O3, O4, O5 and O7 according to the first position and finally O8 according to the sixth position. The emptiness volume in this case is equal to only 8.16m^3 found in 843 iteration run in 1 second, as shown in figure 3.6.

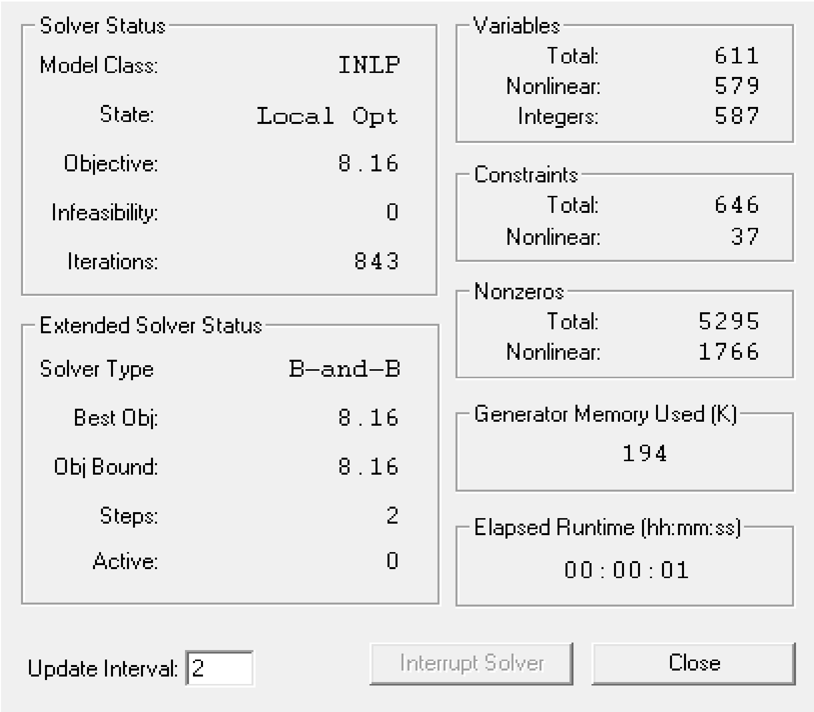


Figure 3.6 Case two Lingo solver’s results

The fullness rate of the Π-container C7 is then equal to 76.4%, while the emptiness rate equals only 23.6%.

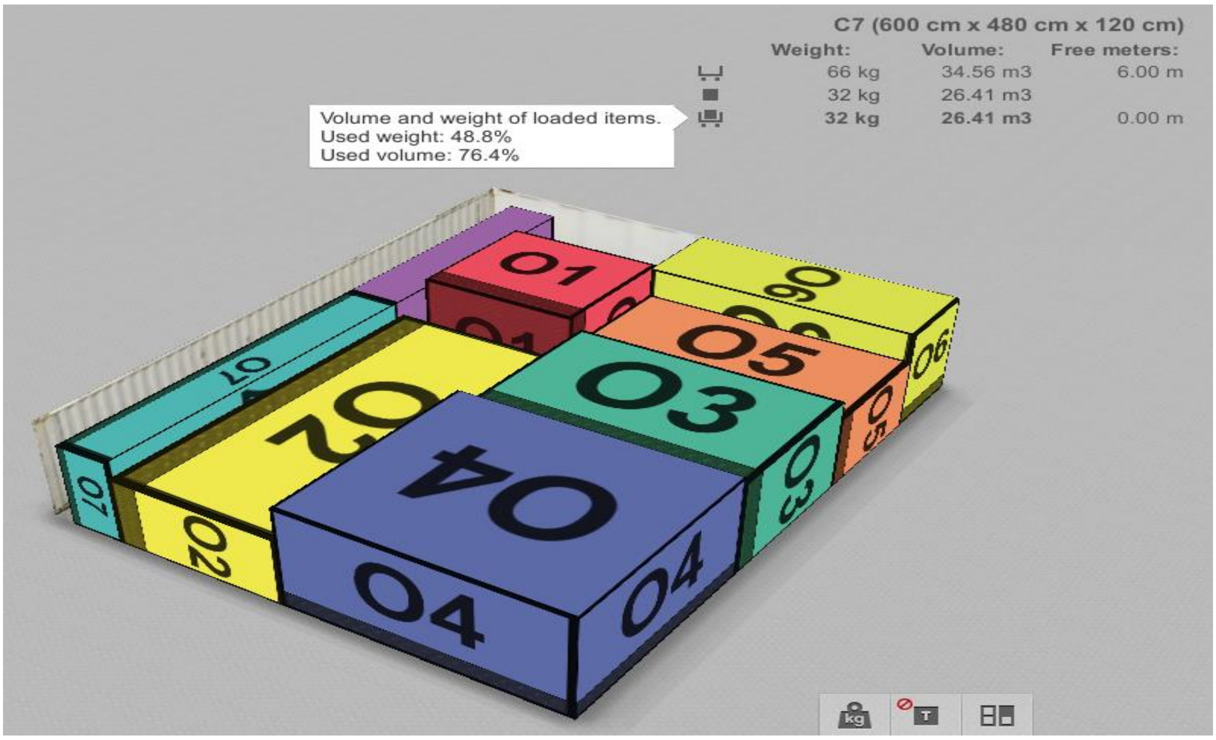


Figure 3.7 EasyCargo simulation of the objects arrangement in case 02

Case 03:

In this case we will be shipping 10 different objects, the previous 8 objects, in addition to another two, whose dimensions are:

Table 3.7 The data of the additional objects in case three

Object ID	Length LO_i	Width WO_i	Height HO_i	Volume VO_i	Weight $WeiO_i$
O9	4,40	0,65	2,85	8,15	9,20
O10	2,50	1,50	1,00	3,75	6,30

The size of the program in this case exceeds Lingo's capacity, so we use instead CPLEX optimizer in its latest version 12.9.

IBM ILOG CPLEX Optimizer is a powerful tool for solving various types of optimization problems including: Linear programming problems, Integer and mixed integer programming problems and Quadratic programming problems. It was created by Robert E. Bixby using C language in 1987 and was bought and commercialized by ILOG since 1997. It is used by many air companies (Delta, Continental…) and 95% of papers mentioning solver, state CPLEX. [98]

The results obtained after running the program, are shown in the table below

Table 3.8 The Π-containers selected in case three

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
O1	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O2	0	0	0	0	0	0	**(1,1)**	0	0	0	0	0
O3	0	0	0	0	0	0	**(1,2)**	0	0	0	0	0
O4	0	**(1,4)**	0	0	0	0	0	0	0	0	0	0
O5	0	0	0	0	0	0	**(1,2)**	0	0	0	0	0
O6	0	0	0	0	0	0	**(1,5)**	0	0	0	0	0
O7	0	0	0	0	0	0	**(1,3)**	0	0	0	0	0
O8	0	0	0	0	0	0	**(1,6)**	0	0	0	0	0
O9	0	**(1,2)**	0	0	0	0	0	0	0	0	0	0
O10	0	0	0	0	0	0	**(1,3)**	0	0	0	0	0
Selection rate %	0	**20**	0	0	0	0	**80**	0	0	0	0	0

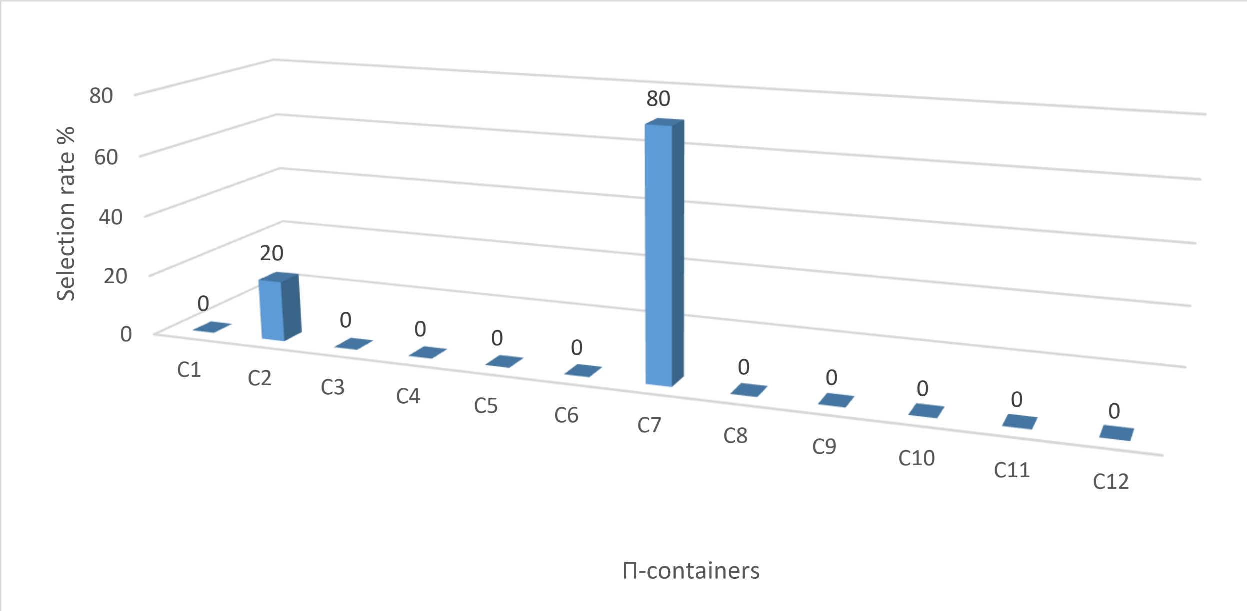


Figure 3.8 Selection rates of Π-containers in case three

The Π-containers selected are then C2 and C7 with selection rates of 20% and 80% simultaneously. The total emptiness volume in this case is equal to 16.85 m^3 generated in only 125 iteration using Simplex algorithm in a computational time of 0.72 seconds, as presented in figure 3.9

Statistique	Valeur
Cplex	solution (optimal) with objective 16.85
Constraints	754
Variables	732
Binary	732
Non-zero coefficients	3624
MIP	
Objective	16,85
Incumbent	16,85
Nodes	0
Remaining nodes	0
Iterations	125
Solution pool	
Count	5
Mean objective	332,31

Figure 3.9 Case three Cplex optimizer's results

Based on these results, the total fullness rate of the Π-containers selected is then equal to 69.5%, while the total emptiness rate equals 30.5%.

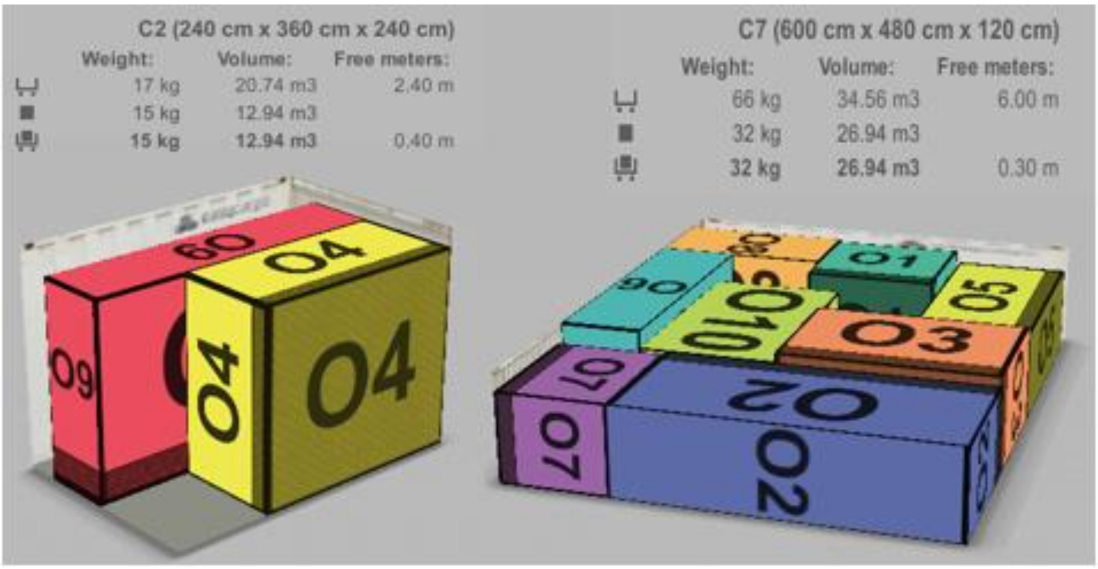


Figure 3.10 EasyCargo simulation of the objects arrangement in case 03

Case 04:

In this case we enlarge more the size of the problem by using a total number of 30 different stochastic objects. The previous 10 and another 20 whose dimensions are:

Table 3.9 The data of the additional objects in case four

Object ID	Length LO_i	Width WO_i	Height HO_i	Volume VO_i	Weight $WeiO_i$
O11	3,90	1,00	0,34	1,33	2,40
O12	4,40	0,65	0,29	0,83	0,78
O13	4,18	2,14	2,90	25,94	4,75
O14	4,44	1,32	0,35	2,05	3,15
O15	3,51	2,03	2,00	14,25	2,80
O16	2,85	3,45	2,60	25,56	9,20
O17	4,43	3,98	1,00	17,63	7,10
O18	6,00	0,95	2,00	11,40	11,23
O19	0,60	3,95	4,00	9,48	10,80
O20	0,70	5,40	4,80	18,14	12,58
O21	5,00	0,48	3,50	8,40	11,10
O22	2,50	1,50	1,00	3,75	0,90
O23	3,30	1,40	1,60	7,39	3,20
O24	3,48	1,70	3,30	19,52	4,15
O25	2,80	1,80	0,60	3,02	2,50
O26	3,60	2,30	1,10	9,11	9,25
O27	2,95	1,65	2,75	13,39	10,75
O28	4,50	2,90	1,50	19,58	4,70
O29	2,90	1,90	1,20	6,61	2,75
O30	0,42	1,60	2,80	1,88	2,20

The results obtained after running the program, are shown in the table below

Table 3.10 The Π-containers selected in case four

	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C6	**(1,2)**	**(1,2)**	**(1,4)**	**(1,2)**	**(1,1)**	**(1,4)**	**(1,3)**	**(1,5)**	**(1,1)**	**(1,6)**	**(1,1)**	**(1,3)**	**(1,1)**	**(1,3)**	**(1,3)**
C7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	O16	O17	O18	O19	O20	O21	O22	O23	O24	O25	O26	O27	O28	O29	O30
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C6	**(1,1)**	**(1,4)**	**(1,1)**	**(1,2)**	**(1,2)**	**(1,1)**	**(1,6)**	**(1,2)**	**(1,1)**	**(1,1)**	**(1,1)**	**(1,1)**	**(1,4)**	**(1,2)**	**(1,4)**
C7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.11 Π-containers selection rates in case four

Π-containers	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Loaded Objects number	0	0	0	0	0	**30**	0	0	0	0	0	0
Selection rates %	0	0	0	0	0	**100**	0	0	0	0	0	0

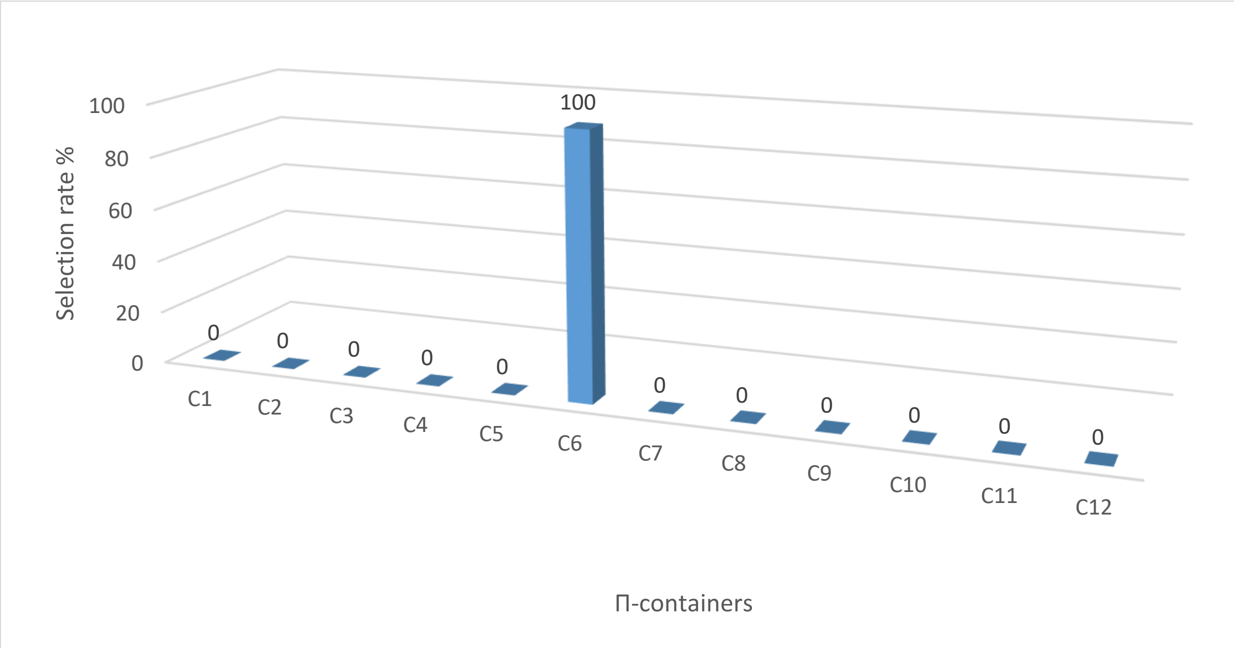


Figure 3.11 Selection rates of Π-containers in case four

The only Π-container selected for this case is C6 which is the Π-container with the second largest size. The selection rates of C6 is then 100%. The total emptiness volume in this case is equal to 157.01m^3 found in a number of 299 computational iteration in a time of 0.89 seconds, as presented in figures 3.13

Statistique	Valeur
Cplex	solution (optimal) with objective 157.01
Constraints	2214
Variables	2172
Binary	2172
Non-zero coefficients	10824
MIP	
Objective	157,01
Incumbent	157,01
Nodes	0
Remaining nodes	0
Iterations	299
Solution pool	
Count	2
Mean objective	485,89

Figure 3.12 Case three Cplex optimizer's results

Based on these results, the total fullness rate of the Π-containers selected equals then to almost 62 %, while the total emptiness rate is equal to 37.86%.

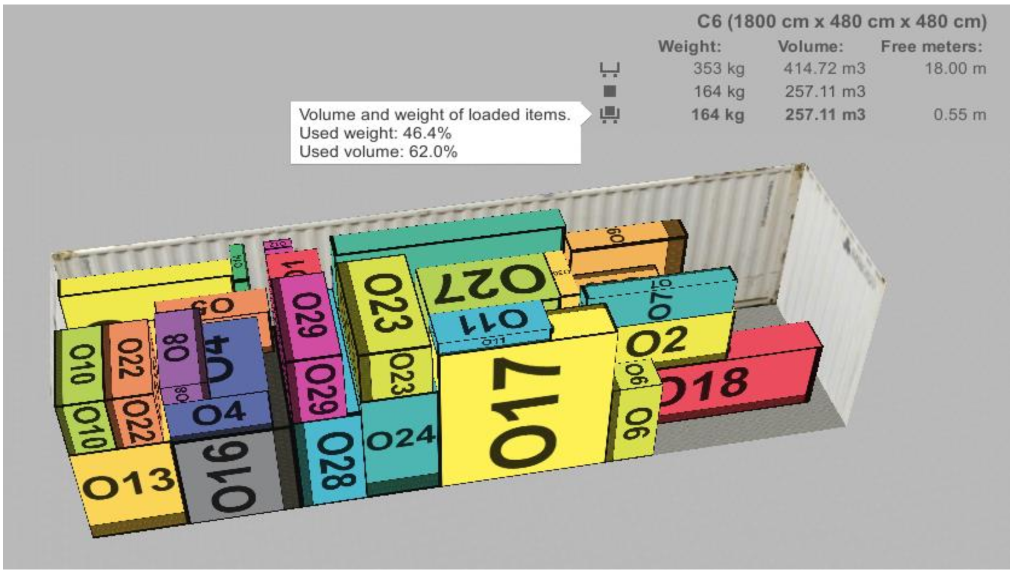


Figure 3.13 EasyCargo simulation of the objects arrangement in case 04

3.3.1.3 Results interpretation:

Case 01: The program chose C2 because it has the second least volume after C1 which was not chosen because the volume of the object_test is larger than the volume of the Π-container C1. Choosing the Π-container with the least volume that can fit the object loaded, provides the best minimum possible of emptiness among all the Π-containers available in the system.

Case 02: C7 has been chosen, because it is the Π-container with the least volume that can containerize all the objects, assuring the best minimum possible of emptiness volume, compared to the other non-selected Π-containers.

Case 03: based on the given results, we notice that two Π-containers among the containers having the least sizes with the capability of containerizing the objects to load, have been chosen (C2 and C7). Such a combination assures maintaining an equilibrium between the two factors of free volume and loading capacity; thus the Π-containers selected would be able to load a good number of objects without allowing a large free space in the inside. A maximum number of objects has been ranked in the Π-container with the largest volume among these two selected (C7), which is fairly logical, since a container with a large volume can load numerous objects than another with a least volume.

Case 04: The results indicate that, a combination of three Π-containers with the largest volumes (C6, C4, C12) and two with the smallest (C11 and C7) among the overall set of available Π-containers, has been chosen to rank the amount of objects we dispose, such that the majority of objects were loaded in the large sized Π-containers, which is logical enough because the bigger is the container, the much it can load.

Excluding case 01 that represents a particular case since there's only one object to ship, which is mostly far from the reality, it is noticed that the emptiness rate does never exceed 50% for the Π-containers selected, which indicates the performance of the program in testing the emptiness volume for each candidate Π-container in every iteration; if the emptiness rate is less than 50%, the Π-container is taken into consideration, if not the Π-container is then replaced with another one whose volume is less bigger and so on, until it ends up with selecting the Π-container that best fits the objects to containerize. The dimensional standardization of the Π-containers is a key reason behind this performance since it permits to create different but compatible and dimensionally proportional combinations that make the Π-containers selection and loading less complicated. This modularity in dimensions also favors the possibility of gathering the selected Π-containers to create composite Π-containers as previously mentioned in chapter two.

3.3.2 Programing using metaheuristics

Our problem is NP hard combinatorial optimization problem (COP), for which it is impractical to find an optimal solution. For such kind of problems, the only reasonable way is to search for a coherent metaheuristics algorithms, which can be defined as higher level procedures or heuristics designed to find, generate or select heuristics that may produce sufficiently approximate good, although not necessarily exact optimum, solutions to a given optimization problem.

3.3.2.1 Reasons for choosing the Genetic algorithm

We chose to work with GA as a type of metaheuristics to resolve our problem, for the reason that the concept of GA is easy to understand compared to other algorithms which do the same job. It guarantees a wide range of high quality solutions by relying on bio-inspired operators such as mutation, crossover and selection, it is also robust to local minima/maxima. It’s becoming more widely used in many areas such as business, scientific and engineering disciplines to solve NP-hard optimization problems and work well on both discrete and continuous problems.

3.3.2.2 Overview of Genetic algorithm

The GA starts with initial set of random chromosomes offering a solution for the problem, by applying the evolution operators, a new generation is formed by firstly applying tournament selection operator which considers the fitness of the parents, and rejection of the others so as to keep the population size constant. To perform it, new chromosomes are formed by merging two parents from the current generation using the crossover operator and modifying a chromosome using a uniform mutation operation, the best chromosome is selected to be transferred in the new population using elitism in GA. After some generations, the algorithm converges to the best chromosome which represents the optimum solution for the problem. Two stopping criteria could be used, the first is the achievement of the optimal fitness value and the second is reaching a limited set of iterations. The table below represents the pseudo-code of GA.

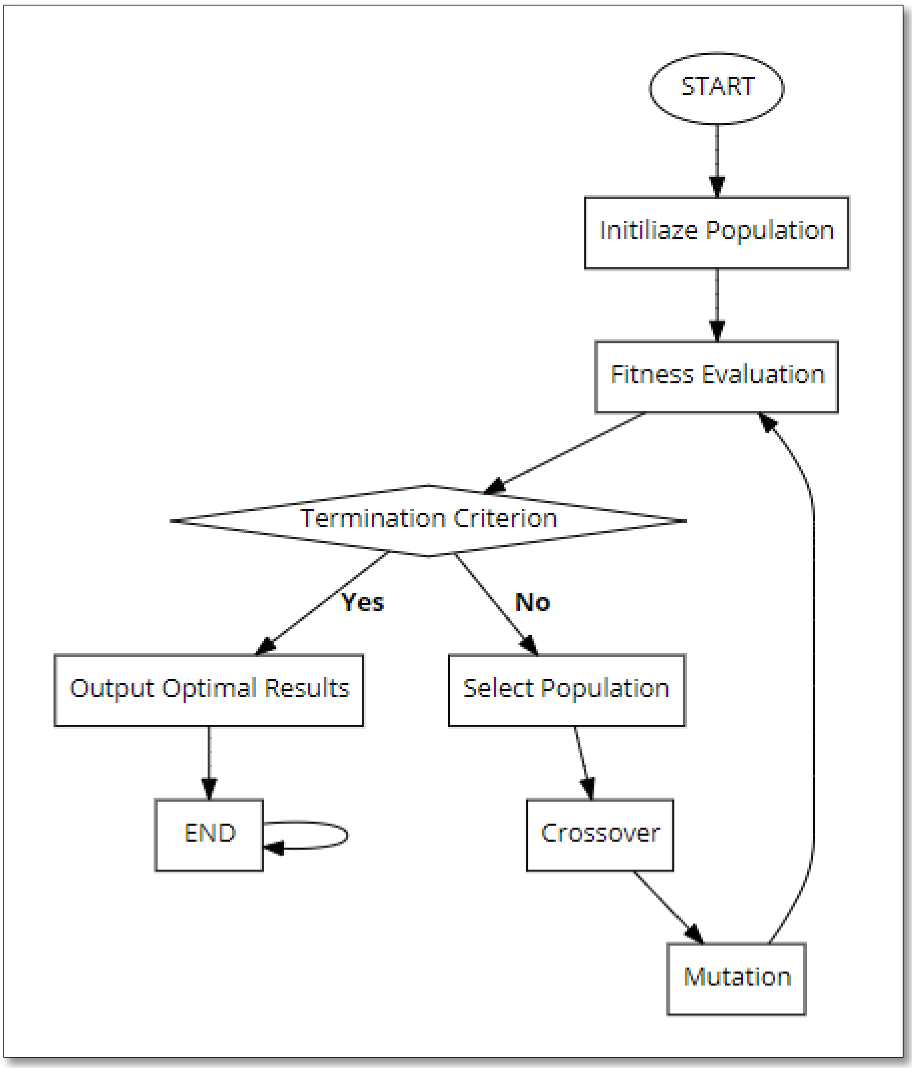


Figure 3.14 Flow chart of Genetic Algorithm

3.3.2.3 Genetic algorithm implementation

3.3.2.3.1 Parameters and operators of the Genetic algorithm of our problem

Essential elements are required to implement the GA, which consist of chromosomes encoding, crossover, mutation and selection

a. Chromosomes encoding

We call a possible solution an individual, and by possible, we mean a solution that belongs to the search space of our problem that is limited by constraints of dimensions, volume and weight. The individuals are also called Chromosomes.

Designing suitable chromosomes representing the candidate solutions is a key issue for a successful GA implementation. The representation of a chromosome in this problem is illustrated in Figure 3.17. Each chromosome is partitioned into n zones, where n is the number of objects. And each object zone is divided into m parts, where m represents the number of Π-containers. Each Π-container part is subdivided into six spots that we call genes representing the six possible positions in each Π-container. The total number of genes per chromosome is then equal to $n * m * 6$.

The encoding is binary, which means that the genes values are either 0 or 1. Below is an example of a suggested solution, with n = 2 and m = 3, which means a total number of $2 * 3 * 6 = 36$ gene.

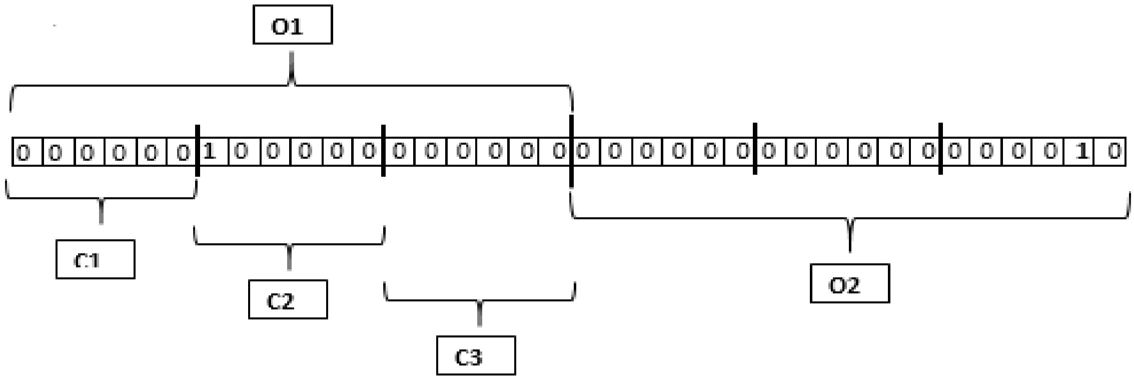


Figure 3.15 Example of an individual

In this example, Object one (O1) is containerized in Π-container two (C2) according to the first position. While Object two (O2) is containerized in Π-container three (C3) according to the position number five.

Now, taking in consideration the previous four cases in linear programming, the generated individuals would be as follow:

Case 01: For a number of Containers equal to 12 and a number of objects equals 1, the length of each generated chromosome is equal to $1 * 12 * 6 = 72$ genes.

Case 02: For a number of Containers equal to 12 and a number of objects equals 8, the length of each generated chromosome is equal to $8 * 12 * 6 = 576$ gene.

Case 03: For a number of Containers equal to 12 and a number of objects equals 10, the length of each generated chromosome is equal to $10 * 12 * 6 = 720$ gene.

Case 04: For a number of Containers equal to 12 and a number of objects equals 30, the length of each generated chromosome is equal to $30 * 12 * 6 = 2160$ gene.

b. Selection

A generation consists of a certain number of chromosomes. They are sorted in ascending fitness order. The fitness of a chromosome is given by the calculation of the emptiness space volume corresponding to the sequence it refers to. Chromosomes with the better fitness (smaller one) are selected as elitism which directly proceed into the next generation.

c. Crossover

Binary encoding structure facilitates simple crossover operations like one-point crossover where gene sequences are simply exchanged with single cut point. A cutting point is randomly selected for the gene sequence provided that it comes always between the objects and not containers nor positions sequence, as to avoid multiplying the containers selection variable which means ranking a same object in more than one container. Parents represented by chromosomes C1 and C2 will generate two children represented by the off_ springs O1 and O2. O1's genes sequence s1 is the same sequence as S1 of C1 and the sequence s2 is the same as the sequence S2 of C2. O2's genes sequences can be obtained in the same manner. What we are actually doing is sweeping between C1 and C2 circularly starting from i till the end of S2.

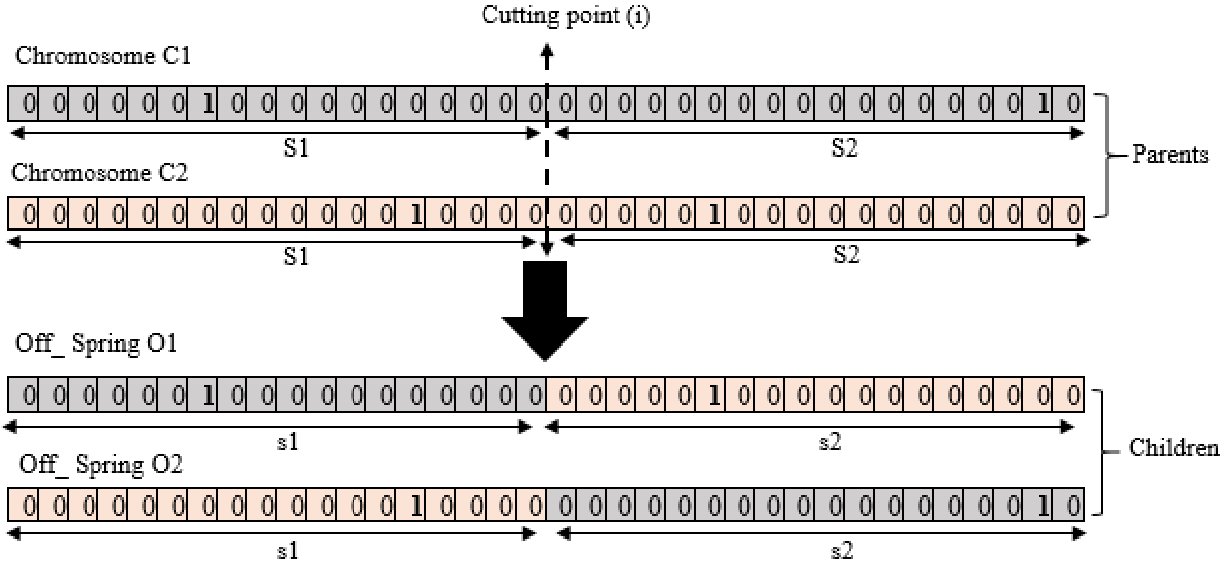


Figure 3.16 Illustration of single point crossover

d. Mutation

Mutation is conducted on each newly generated off_ spring with a certain probability Pm. For each gene sequence, two positions from the same object sequence are randomly selected and the genes on these positions are swapped, this type of mutation is called order changing. We could not use the famous Bit inversion mutation because it would be very frequent to fall in the case where an object is ranked in more than one container or arranged according to more than one position.

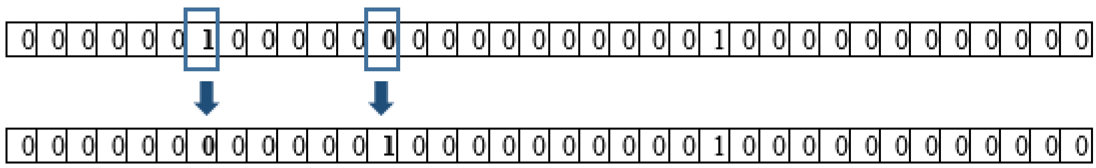


Figure 3.17 Illustration of order changing mutation

3.3.2.3.2 Computational experiments

We implemented the GA of our problem on Eclipse IDE-Java 4.8 (Photon). This version is the latest of the Eclipse IDE released by the Eclipse Foundation. It is an Open Source Initiative (OSI) Certified Open Source Software (OSS), developed on Java SE 8 VMs. [99]

We used the same number of containers, and same number of objects in the previous four cases in the LP. Besides using another large-sized two, to test the GA performance, we call them case 05 and case 06. The data of the added objects used are given in the next two tables (3.12 and 3.13).

Table 3.12 The data of the additional objects in case five

Object ID	Length LO_i	Width WO_i	Height HO_i	Volume VO_i	Weight $WeiO_i$
O31	2,30	1,50	2,35	8,11	1,50
O32	1,00	3,60	1,45	5,22	4,50
O33	3,60	2,30	1,06	8,78	1,64
O34	2,80	2,10	0,80	4,70	1,20
O35	2,90	2,10	0,50	3,05	2,14
O36	2,90	2,60	0,90	6,79	11,20
O37	0,43	3,20	1,40	1,93	4,02
O38	0,46	0,29	1,50	0,20	5,10
O39	0,43	2,90	1,26	1,57	12,75
O40	2,40	1,60	2,45	9,41	9,00
O41	0,90	0,80	2,00	1,44	23,15
O42	0,90	0,90	2,00	1,62	27,80
O43	4,00	0,90	2,00	7,20	21,75
O44	7,00	1,60	2,00	22,40	30,80
O45	6,00	1,60	2,00	19,20	30,80
O46	2,00	1,60	2,00	6,40	32,25
O47	2,00	1,60	2,00	6,40	32,25
O48	2,00	1,80	2,00	7,20	35,10
O49	0,55	2,00	4,37	4,81	16,70
O50	0,70	4,50	1,20	3,78	19,50

Table 3.13 The data of the additional objects in case six

Object ID	Length LO_i	Width WO_i	Height HO_i	Volume VO_i	Weight $WeiO_i$
O51	2,30	1,70	1,40	5,47	30,50
O52	0,80	1,00	2,30	1,84	5,12
O53	2,35	1,80	3,90	16,50	26,75
O54	5,00	1,00	1,95	9,75	9,70
O55	3,55	3,70	2,90	38,09	31,92
O56	3,78	2,55	1,70	16,39	25,40
O57	2,18	2,75	2,96	17,75	29,34
O58	1,45	1,40	3,33	6,76	6,75
O59	3,45	2,65	2,73	24,96	17,20
O60	3,75	0,86	1,80	5,81	1,50
O61	2,20	0,65	1,35	1,93	2,86
O62	3,90	1,35	0,75	3,95	1,95
O63	1,00	2,90	2,95	8,56	2,33
O64	2,75	0,72	2,75	5,45	3,10
O65	1,06	2,50	1,40	3,71	2,70
O66	2,30	2,20	0,81	4,10	2,85

O67	1,30	1,55	0,86	1,73	0,92
O68	1,50	0,65	1,65	1,61	1,20
O69	3,50	1,80	1,85	11,66	23,41
O70	0,75	0,46	0,87	0,30	0,25
O71	2,88	1,00	1,00	2,88	0,75
O72	1,75	1,47	2,70	6,95	3,17
O73	0,85	1,40	0,32	0,38	0,27
O74	2,00	0,40	1,10	0,88	0,68
O75	1,80	0,81	0,67	0,98	1,20
O76	3,00	0,60	1,40	2,52	2,10
O77	1,18	1,25	0,30	0,44	0,68
O78	1,75	2,45	2,60	11,15	23,12
O79	2,55	1,05	0,71	1,90	2,00
O80	3,60	0,70	1,95	4,91	6,10
O81	1,60	1,40	1,17	2,62	3,15
O82	2,70	1,35	1,81	6,60	3,25
O83	0,95	3,70	1,84	6,47	2,98
O84	0,40	0,39	0,41	0,06	0,15
O85	1,05	3,20	4,10	13,78	25,23
O86	2,30	1,00	1,00	2,30	3,20
O87	2,15	1,25	0,40	1,08	0,87
O88	4,00	0,85	0,75	2,55	2,55
O89	1,15	0,85	1,25	1,22	0,92
O90	0,65	0,45	0,80	0,23	0,50
O91	1,25	0,40	0,65	0,33	0,75
O92	0,75	0,45	0,40	0,12	0,64
O93	3,00	1,05	0,45	0,61	1,20
O94	0,65	0,45	1,55	1,06	4,73
O95	1,55	1,33	2,00	1,40	3,78
O96	2,50	1,60	2,50	8,31	9,20
O97	0,80	1,40	0,70	0,90	1,25
O98	1,60	1,60	0,52	1,16	2,33
O99	1,30	2,25	1,00	2,08	2,56
O100	0,40	1,35	1,45	1,31	4,10

The GA parameters on the run are:

Table 3.14 Parameters used in the GA implementation

Parameter	Value/Type
Population size	10 Chromosomes
Crossover type	Single point
Crossover probability	0.8
Mutation size	2 genes
Mutation type	Order changing
Mutation probability	0.01
Number of off springs to produce	8
Chromosomes to replace	2
Replacement type	Replace worst
Fitness sorting	Minimization
Stop criterion type	Fitness change
Stop criterion depth	425 iterations

Figure 3.20 illustrates the different results obtained after running the GA program of our problem and for all the six studied cases.

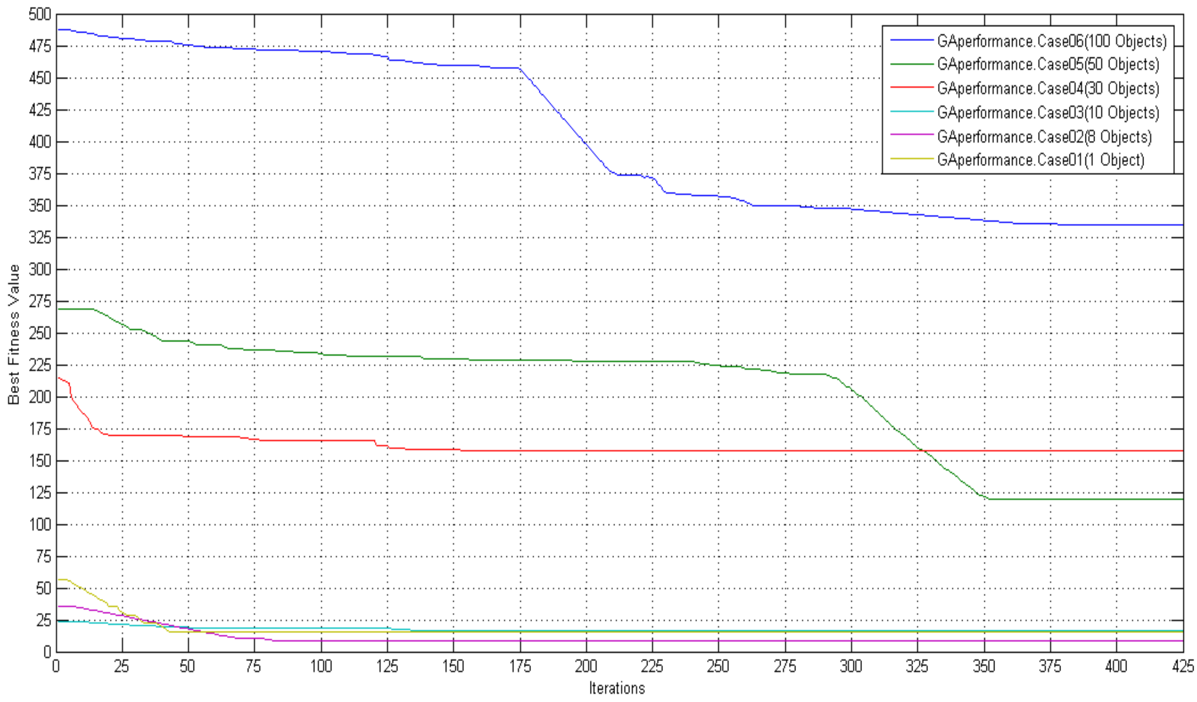


Figure 3.18 GA performance for the six studied cases

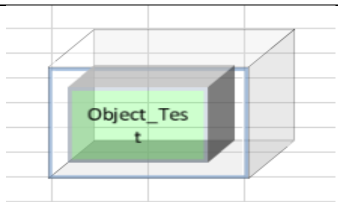
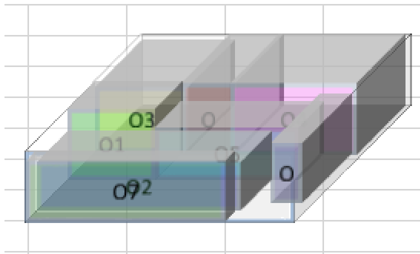
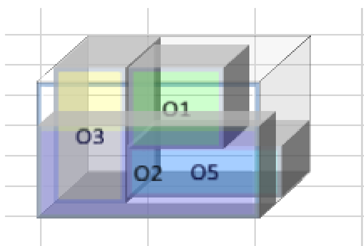
The above figure illustrates the evolutionary attitude of the GA resolution process of our problem. All the aforementioned six cases are represented. It is easy to capture that the largest sized is the system, the more iterations number are needed to arrive to the global minima. Each case's fitness value get better (smaller in our problem) by the succession of the computational iterations until it arrives to a certain constant value which represents the global minimum of the problem for that particular case. The set of the best performing solutions responsible on producing these global minima represent what we call “the hall of fame”. The intervals of each case’s Hall of fame are represented in table 3.15

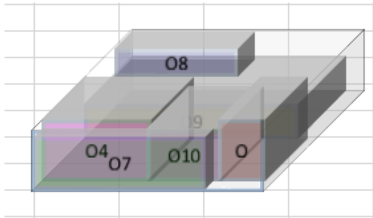
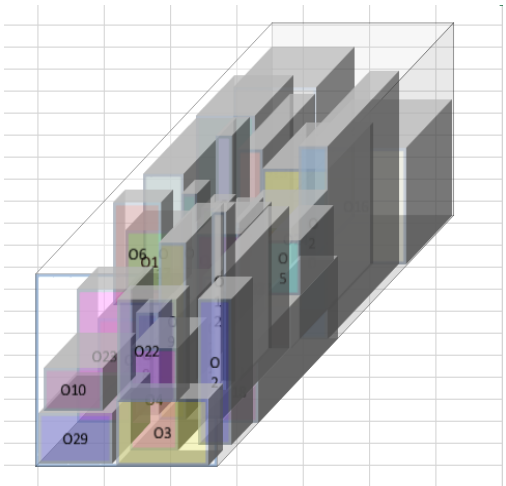
Table 3.15 Hall of fame interval per case number

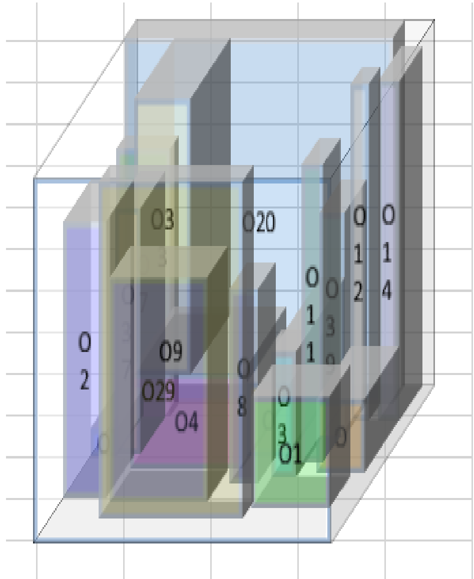
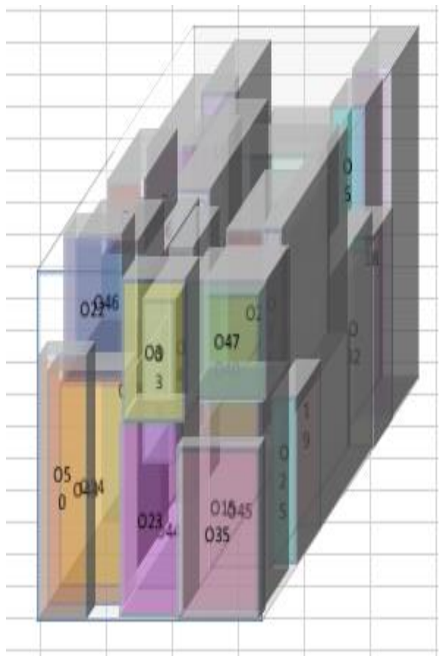
# Case	Hall of fame interval
01	[44,425]
02	[84,425]
03	[134,425]
04	[152,425]
05	[353,425]
06	[379,425]

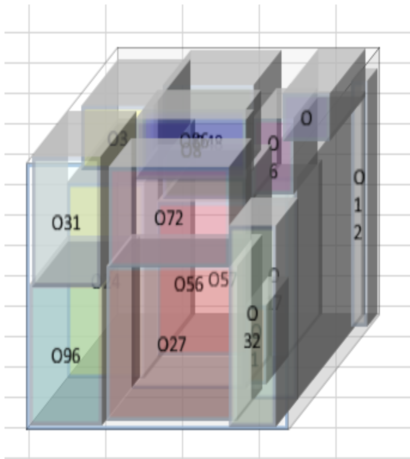
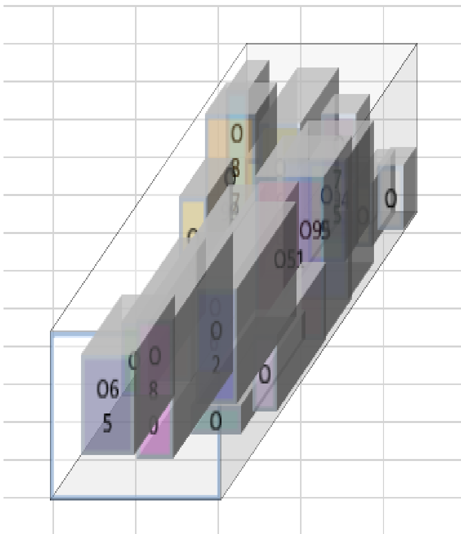
But since our secondary goal is to minimize the total number of Π-containers used, we only picked the solutions with the best fitness value coupled with the least Π-containers number demanding. These solutions and there performance are given in table 3.16.

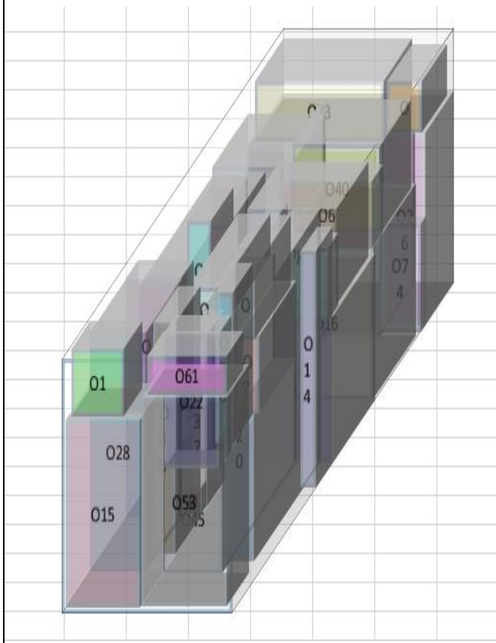
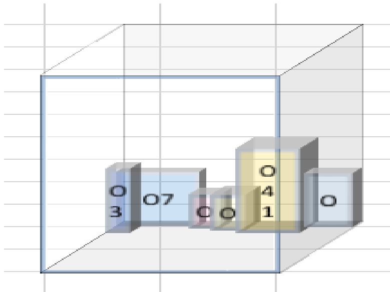
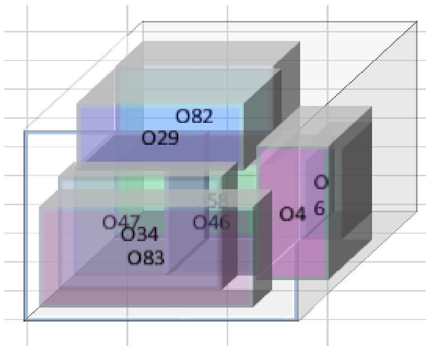
Table 3.16 GA performance for the six studied cases

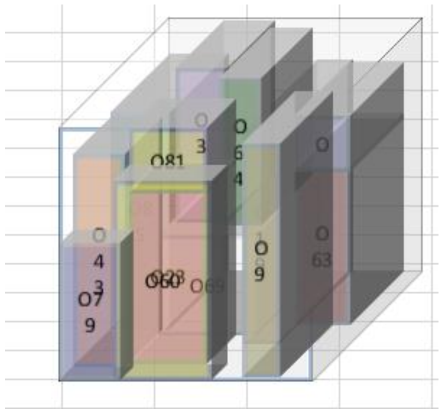
# Case	Containers selected And Objects arrangement #Container	 #Position	Best fitness	Best fitness (%)	Solution visualization
01	C2 Object_ test	 6	**15.44**	**73%**	
02	C7 O1 O2 O3 O4 O5 O6 O7 O8	 6 3 4 1 4 6 5 1	**8.15**	**23.85%**	
03	C2 O2 O3 O4 C7 O1 O5 O6 O7 O8 O9	 1 5 6 1 6 2 2 3 4	**16.99**	**30.72%**	

	O10 1			
04	C6 O1 5 O2 6 O3 2 O4 3 O5 1 O6 4 O7 4 O8 6 O9 5 O10 1 O11 3 O12 3 O13 5 O14 3 O15 1 O16 3 O17 3 O18 1 O19 2 O20 2 O21 1 O22 5 O23 5 O24 5 O25 3 O26 3 O27 5 O28 3 O29 1 O30 2	**157.14**	**37.89%**	

05	C4 O1 6 O2 6 O4 6 O7 6 O8 6 O9 3 O11 3 O12 6 O14 5 O20 1 O29 3 O30 1 O33 5 O37 4 O38 4 O39 4 O41 2 O42 1 C9 O3 3 O5 5 O6 2 O10 3 O13 1 O15 5 O16 2 O17 4 O18 5 O19 2 O21 1 O22 5 O23 3 O24 5 O25 3 O26 4 O27 1 O28 3 O31 2 O32 6 O34 3 O35 5 O36 3 O40 1 O43 3 O44 1 O45 1 O46 1 O47 2	**119.59**	**23.57%**	 

	O48 2 O49 2 O50 4			
06	C4 O3 4 O8 1 O12 3 O17 4 O24 5 O27 2 O31 5 O32 6 O48 2 O52 5 O56 5 O57 4 O67 3 O72 3 O86 6 O96 5 O100 6 C5 O2 2 O7 3 O11 1 O50 2 O51 3 O62 4 O65 2 O66 4 O70 1 O73 3 O75 3 O80 1 O87 3 O89 5 O93 4 O94 3 O95 1 O97 4 O98 3 O99 4 C6 O1 4 O5 2 O6 1 O10 5	**334.09**	**33.57%**	 

	O13	5			
	O14	3			
	O15	5			
	O16	3			
	O18	1			
	O20	2			
	O21	1			
	O22	5			
	O25	3			
	O26	3			
	O28	3			
	O30	2			
	O33	2			
	O35	4			
	O37	6			
	O39	2			
	O40	4			
	O42	5			
	O44	1			
	O45	1			
	O49	2			
	O53	2			
	O54	1			
	O55	5			
	O59	1			
	O61	6			
	O74	3			
	O76	1			
	O78	5			
	O84	1			
	O88	1			
	C8				
	O38	1			
	O41	2			
	O77	6			
	O90	1			
	O91	3			
	O92	3			
	C10				
	O4	3			
	O29	2			
	O34	6			
	O46	1			
	O47	5			
	O58	4			
	O68	1			
	O82	2			
	O83	1			

	C12				
	O9	5			
	O19	2			
	O23	5			
	O36	3			
	O43	5			
	O60	3			
	O63	2			
	O64	1			
	O69	1			
	O71	1			
	O79	5			
	O81	1			
	O85	2			

3.3.2.4 Results interpretation

Case 01: just like explained when using the LP, having only one object to load, creates a large wasted space that could be minimized only by using the least possible Π-container size that could containerize the object which is C2 in our problem. Selecting C2 generated 72% of unused volume which is the smallest rate that could be found for this case.

Case 02: to ship the eight objects, the GA suggests the same solution offered by LP which is selecting C7 as a loading Π-container. C7 ensures containerizing the overall set of objects since its volume can contain their dimensional sum and guarantees wasting only a minimum space that is equivalent to less than 25%.

Case 03: the two Π-containers selected for this case (C2 and C7) are the ones with the least volumes that can containerize the ten concerned objects. This selecting attitude ensures using the maximum possible of Π-containers inner space which directly refers to a small average of emptiness rate in the order of 30.72%.

Case 04: the only Π-container selected for loading this case's objects is C6. C6 is the second largest Π-container in the system, which means that it can containerize the whole set of thirty objects while ensuring a high space utilization ratio and a low emptiness rate that is found to be less than 38%.

Case 05: unlike the other cases where the generated solutions are as the same performant as in the LP method, this case was a proof of the advantage of metaheuristics in dealing with large sized systems. Two Π-containers were selected which are C4 and C9, they are among the largest sized Π-containers in the system which ensures containerizing the full number of objects and since their number is high; the percentage of used volume (76.43%) dominates the percentage of empty volume (23.57%).

Case 06: in the same resolution approach used in the previous case, 6 Π-containers among 12 were selected to ensure containerizing the overall high number of objects. These selected Π-containers (C4, C5, C6, C8, C10, and C12) are the Π-containers with the largest volumes in the system, which guarantees a maximum rate of utilization (66.43%) or in another way a minimum rate of emptiness equals to only 33.57%.

3.3.3 Performance comparison between linear programming and Genetics algorithm

We make a comparison of the performance of the GA with the previous LP performance. Table 3.17 summarizes the computational results. The column “#Objects” and “#Π-containers” indicate the size of the system with the number of objects and the number of containers used in each case. Column “CT” reports the computational time in seconds, used for finding the optimum. The column “ES%” reports the percentage of empty space in the found solution. Because the objective is to minimize the percentage of emptiness, therefore the lower ES% value is, the better the solution is.

Table 3.17 LP and GA performance comparison

#Case	#Objects	# Π-containers	LP		GA	
			CT	ES%	CT	ES%
01	1	12	•	73%	•	73%
02	8	12	1.00	23.60%	1.55	23.58%
03	10	12	72/100	30.50%	2.42	30.72%
04	30	12	89/100	37.88%	6.08	37.89%
05	50	12	-	-	61.11	23.57%
06	100	12	-	-	62.9	33.57%

- No feasible solution is found in 3600 seconds
- • Fractions of seconds

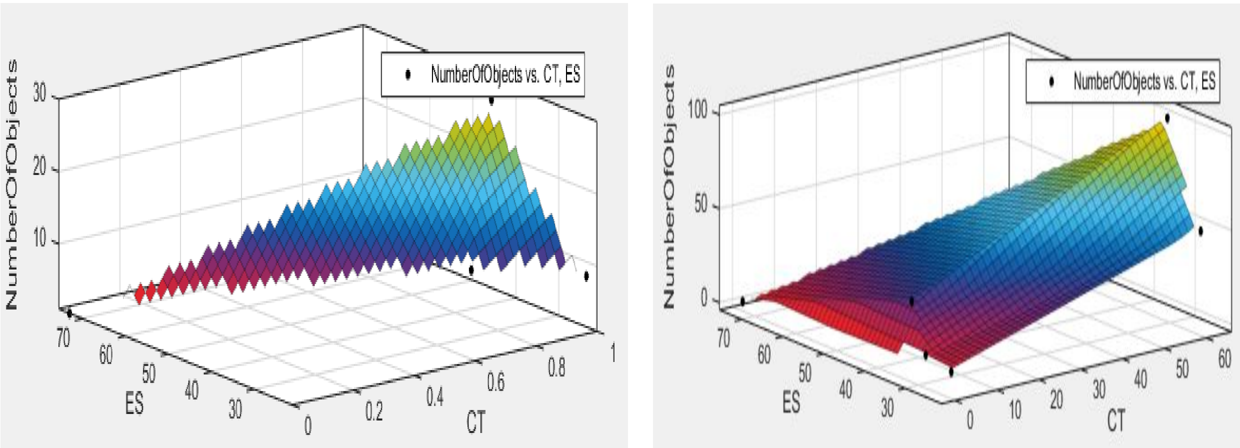


Figure 3.19 3D interpolation and Surface Plotting of LP (left) and GA (right) global performance in function of CT, ES% and objects number

As remarkable from the table’s results, both LP and GA do well when the size of the system is relatively small (0 object < size < 30 object); with a slight advantage to the LP method, thus they afforded very closed almost to the same rates of emptiness in matter of small converging computation instances. Once the system’s size get larger (size > 30 object); GA dominates LP in its ability to generate good-enough solutions in a short time frame.

3.3.4 Explanation

For many of the available LP algorithms, the computational time increases in general exponentially with increasing instance size. Which means that the computational time towards finding the optimum solution, is directly linked to the size of the system we are working on. The larger are the dimensions of the system, the longer is the process of resolution Because of the fact that LP functions with exact algorithms that search for the exact optimal solution, just like Branch and Bound algorithm in case of Lingo solver, or Simplex algorithm in case of Cplex optimizer. Beside that LP models requires a linear simplified behavior of the system parameters which lead to a situation where complex behaviors and nonlinear nature of certain technologies and dynamics phenomena cannot be modelled for example the inner temperature controlling and tracking system that is subject to thermodynamics nonlinear laws, other complex supervision tasks like humidity degree, container ship motions subject to nonlinear forces when sailing in moderate to heavy head seas, and many unpredictable behaviors during the transportation process etc.

Metaheuristics generally or GA in specific, have shown significant success in achieving near-optimal (and often optimal) solutions to difficult COPs. They can adapt with the size of the system parameters, because of the fact that they are flexible tools that search for satisfying the global system requirements by finding an approximate solution that can handle the problem not enforced in the best way ever, but stills in a good acceptable way.

However, disadvantages of metaheuristics are that they cannot prove optimality for the approximate generated solutions, and they cannot reduce the size of the search space, particularly when the system get more complex like in the case of evolving more constraints about objects to objects relations and interactions flows.

It is then fair enough to say that, LP and metaheuristics approaches each have their particular advantages and disadvantages. Therefore, a combination between these two distinct technics could create powerful problems solving strategies.

3.4 Conclusion

In this chapter, we treated the major problem of selection of PI containers and arrangement of the objects inside. We used two different resolution methods, the first was a linear mathematical programming and the second was the utilization of Genetics Algorithm, we interpreted the results of both methods and compared them between their each other to select the most adaptable and flexible method, which was the Genetics algorithm programming, that gave a better performance in a least time. These results reinforce the fact that metaheuristics still a powerful efficient tool to treat the NP hard optimization problem.

Global Conclusion

In this paper, we tackled a new and innovative area of research which is the Physical Internet. We have introduced the concept as a potential solution to help us better manage our logistics by ensuring sustainability and efficiency. We tried to solve one of the many problems that a Physical Internet network could face, this problem of selection and ranking is very common and frequent in the world of industry. We have only managed to take one step forward many others are needed to find the right answers and solutions to the rest of the critical situations that may be encountered during the process of implementing the physical Internet.

Just like any other academic work, ours is not perfect, we could select an optimal number of Π-containers to ship a given amount of products and figure out how to arrange it indoors according to a certain orientation, but yet the things get complicated once the size of the system becomes larger, programs may take a long computational time that can stretch for hours. Thus, for future work, we aim to use a combination of hybrid metaheuristics to solve the same problem, for a reduced computational time and better solutions quality, besides using them to solve the problem of reachability and optimality problem of a Π-network. We are also looking forward to working on the management of Π-hubs, which are another important ingredients of the Physical Internet, in order to optimize their number and ensure their good localization throughout the network, using Multiple Criteria Decision Making technics (MCDM). And complete these primary goals with a critical study to analyze the performance of any given Physical Internet network after having optimizing the managements of hubs and Π-containers building the network.

To conclude this work, and as highlighted in the chapters one and two, we would like to mention again that the Physical Internet is still in its early stage and there is a long way for it as to be fully implemented, it is a fertile ground for research and innovation for both academia and industry, whose efforts and forces should be combined together as to develop the Physical Internet and provide it with tools to continue evolving into a sustainable and efficient open global logistics network.

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ملخص

على الرغم من أن البنية التحتية الأساسية للأنظمة اللوجستية وشبكات التوزيع الحالية ضخمة وتنتشر على نطاق واسع في جميع أنحاء العالم ، ويتم استخدام وسائل مختلفة للمرافق والنقل والتخزين ، الا ان حقيقة الترابط الضعيف والخصوصية المغلقة لهذه الشبكات تعمل على الحد من الأداء الكلي وخلق حالة من عدم الاستدامة ونقص الكفاءة في الطريقة التي نتعامل بها مع أنشطتنا اللوجستية من بداية صنع المنتج الى غاية تسليمه النهائي إلى العميل ، على الصعيد الاقتصادي، البيئي و الاجتماعي.

فيما يتعلق بمعالجة هذه الحالة الحرجة لأنظمتنا اللوجستية الحالية ، فقد اقترح مؤخراً تطوير شبكة لوجستية عالمية مفتوحة مستدامة وفعالة ، من خلال استعارة الإنترنت الرقمية. المشروع يسمى بالإنترنت المادي.

نظرًا لأن الإنترنت المادي مفهوم جديد ومبتكر ، فيجب حل العديد من التحديات ومشاكل التحسين في طريق تنفيذها. تتمثل إحدى هذه المشكلات في كيفية ترتيب أنواع واحجام مختلفة من المنتجات داخل عدد محدد من الحاويات الخاصة بالإنترنت المادي و التي تُسمى حاويات-باي لنستفيد من حيث المساحة والتكلفة. في هذه الأطروحة ، نقترح حل المشكلة التي تم تناولها باستخدام البرمجة الخطية و الميتا-أوريستيكس المستندة إلى الخوارزمية الجينية.

الكلمات المفتاحية: الإنترنت المادي ، الاستدامة اللوجستية العالمية ، حاويات-باي ، التوصيل البيني ، الشبكات الموزعة ، البنى التحتية اللوجستية المفتوحة

Abstract

Even though, the basic infrastructures of the current logistics systems and distribution networks are huge and widely spread all over the world and different means of facilities, transportation and storage are being used, yet the fact of the poor interconnectivity and closed privacy of these networks, is limiting the overall performance and creating a state of unsustainability and a lack of efficiency in the way we are handling our logistics activities from the very first phase of making the product until its final delivery to the customer, at the economical, environmental and societal level.

As to address this critical state of our current logistics, it was proposed recently to develop a sustainable and efficient open global logistics network, through the metaphor of the Digital Internet. The project was called the Physical Internet.

Since the Physical Internet is a new and innovative concept, many challenges and optimization problems should be solved in the way of its implementation. One of these problems is how to arrange different kind and size of products inside of an optimum selected number of Physical Internet special containers called Π-containers as to gain in terms of space and cost. In this thesis, we propose to solve the addressed problem using linear programming and Genetic Algorithm based metaheuristics.

Keywords: Physical Internet; Global logistics sustainability; Π-containers; interconnectivity; Distributed networks; Open logistics infrastructures.

Résumé

Bien que les infrastructures de base des systèmes logistiques et des réseaux de distribution actuels sont énormes et largement répandus dans le monde entier et que différents moyens d'installation, de transport et de stockage sont utilisés, le faible niveau d'interconnectivité et la confidentialité de leur réseaux, limitent la performance globale et créent un état de non durabilité et un manque d'efficacité dans la gestion de nos activités logistiques de la toute première phase de fabrication du produit jusqu'à sa livraison finale au client, sur le niveau économique, environnemental et même sociétal.

Pour répondre à cet état critique de notre logistique actuelle, il a été proposé récemment de développer un réseau logistique mondial ouvert, durable et efficace, à travers la métaphore de l'Internet numérique. Le projet s'appelait Internet Physique.

L'Internet Physique étant un concept nouveau et innovant, de nombreux difficultés et problèmes d'optimisation doivent être résolus lors de sa mise en œuvre. L'un de ces problèmes est de savoir comment arranger des différents types et tailles de produits dans un nombre optimal de conteneurs dédiés à l'Internet physique appelés Π-conteneurs, afin de gagner du temps et de l'argent. Dans cette thèse, nous proposons de résoudre le problème abordé en utilisant la programmation linéaire et les métaheuristiques basées sur l'algorithme génétique.

Mots-clés: Internet physique, durabilité logistique globale, Π-conteneurs, interconnectivité, réseaux distribués, infrastructures logistiques ouvertes.