Sustainable Supply Chain Management of COVID-19 Vaccines for Vaccination Delivery based on Routing Algorithms

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Abstract: - Covid-19 pandemic has changed daily life in the city of Athens where vaccines are exploited with supply chain technology potentiality. Vaccines are tracked at the city's airport till their delivery to vaccination centers. Due to the sensitivity of vaccines to the warm climate inherent in the city, delivery is assigned to a fleet of trucks. Specifically, two use cases, i.e., UC-I and UC-II, are proposed, which are based on global and local routing algorithms to exploit trucks' load COVID-19 vaccine delivery from the airport and transport it to vaccination centers. In this paper, we focus on the supply chain routing algorithm technology of collecting COVID-19 vaccines from the airport and delivering them to vaccination centers in the smart city of Athens, Greece. Concretely, the purpose and the objectives of the research effort are in the areas of: (1) describing in deep detail the proposed supply chain system, (2) exploiting the adopted architecture based on certain separate use cases for system experimentation, (3) adopting specific vaccination routing algorithms to support vaccination distribution, and (4) evaluating experimentally the proposed supply chain system architecture with regards to the adopted use cases' routing algorithms.

Key-Words: - Supply chain management, routing algorithms, covid-19 vaccination delivery

Received: May 15, 2023. Revised: October 23, 2023. Accepted: November 7, 2023. Published: November 17, 2023.

1 Introduction

This Covid-19 era changed rapidly the social interaction of citizens in smart cities, [1]. Although, smart cities are the future of earth habitation, according to the Cities 2.0 paradigm, where 67 percent of the human population will live in vast cities, such a habitation concept has been challenged due to the coronavirus pandemic in the last couple of years, [2]. Internet of Things (IoT) and contemporary technologies, such as artificial intelligence, edge computing, data science, global and local scheduling, and global and local routing, are incorporated to make feasible the establishment of smart cities due to high-quality technological advancements in the area of smart devices, such as sensors and actuators, and remake the way we make things, [3]. However, technology by itself is not adequate to preserve the healthcare and safety of the smart cities' population, [4]. Covid-19 emerged with new challenges, which should be undertaken to face current threatening reality, [5]. Lockdown, mask protection, and vaccination services were used to face the pandemic in real-time, [6]. Regarding vaccination supply chain management of stock COVID-19 vaccines, it should be considered certain healthcare parameters to ensure vaccinations are performed correctly and in time according to a certain schedule, [7]. In the case of Greece, COVID-

19 vaccines have entered the country through the smart city of Athens airport. When airplane flights come into the city there is a supply chain management process, that is responsible for storing vaccine stock in certain warehouses in the airport area. Warehouses are specially designed to keep vaccines frozen at the same temperature they had during the flight. Accordingly, there is a process, which uses trucks to collect vaccines from the airport's warehouse and distribute them to vaccination centers in the city of Athens.

To further analyze the significance of the examined research area, in, [8], the authors perform an analysis focusing on the impact relational governance has on designing performance improvements in the area of cultural intelligence of smart cities. Such a system is based on Structural Equation Modelling (SEM), which aims to provide manufacturing firms with the theoretical tools to reconfigure emerging social knowledge. A particular type of knowledge can support and build a learning capability to treat efficiently social infrastructure inefficiencies in vast cities. Concretely, in, [9], the authors propose a buyer-supplier relationship system, that focuses on social performance improvement. Such a system performs an extensive survey of adequate methods aiming to face social performance. Results indicate that fundamental elements of commitment and relational governance should be combined to produce a viable green ecosystem in smart cities.

It should be noted that Athens is a smart city in Greece based on research proposed in, [10], where it is presented a system, that incorporates sustainable strategies for smart city services. In addition, research proposed in, [11], analyses the importance of collecting various data sources from the smart city of Athens to support advanced municipality green solutions for the citizens. Subsequently, the authors in, [12], propose innovative sustainable planning for the smart city of Athens focusing on the economic role required to support an integrated strategy for a green environment.

In this paper, we focus on the green and sustainable supply chain management technology of collecting COVID-19 vaccine stock from the airport and delivering it with the incorporation of trucks to vaccination centers in the area of the smart city of Athens Greece. Such a system focuses mainly on the adoption of sustainable supply chain management to efficiently face time critical operations, which need to be treated in real-time in case of an emergency. Such a sensitive situation might emerge from a COVID-19 incident, which requires instant health treatment. The proposed system faces both citizens' quality of life as well as the technical maturity of the adopted infrastructural operations. Since vaccines are sensitive to high temperatures, which is a common climate condition in Athens, a truck should provide refrigerator services during the transportation of the vaccines. In addition, to optimize the distribution process vaccination centers should record their stock of available vaccines and order new vaccines on time from the system. There is proposed a system, that faces the population needs to be vaccinated. Concretely, certain use cases are performed, namely UC-I and UC-II, to treat the vaccination distribution process. Supply chain technology is assessed by incorporating certain evaluation parameters for both use cases, such as spatial and temporal distance, fuel consumption, cost of routes in Euros, and efficiency of sustainable global and local routing algorithms to assist the vaccination delivery process with regard to algorithms' time complexity. Both use cases have strengths and weaknesses, which are addressed and it is proposed that the smart city's headquarters' control center should balance between the strengths and the weaknesses to choose which use case covers its requirements for an integrated supply chain management of vaccination process service.

1.1 Impact of the Research Effort

The proposed research effort has an innovative and methodological impact in the areas of:

- Performing analytical exploitation of state-of-the-art contemporary research in the domain,
- Describing in deep detail the proposed supply chain system,
- Exploiting the adopted architecture based on two separate use cases for system experimentation,
- Presenting the system parameters used to input supported infrastructure,
- Adopting two vaccination routing algorithms, namely global and local, to support vaccination distribution in the smart city of Athens,
- Evaluating experimentally the proposed supply chain system architecture with regards to the adopted use cases' routing algorithms,
- Performing in-depth discussion on the observed results of the research effort, and
- Proposing future research work required by the domain experts to be ready to face an emerging pandemic in the near future.

The rest of the paper is structured as follows. In Section II related work is provided. Section III describes the supply chain system architecture along with the two use cases, UC-I and UC-II. In Section IV there are presented certain system parameters. Section V proposes the separate use cases of global and local routing algorithms. In Section VI proposed use cases are evaluated experimentally providing certain results. Section VII discusses the observed results, while Section VIII concludes the paper and proposes research work for an upcoming future pandemic.

2 Related Work

Contemporary research against covid-19 pandemic during the last year provide researchers, academics, and professional with a variety of tools to fight the coronavirus, which is responsible for the quality of life in the globe. Concretely, certain systems are proposed to treat covid-19 pandemic. Such systems focus on (1) sustainable solutions, (2) routing algorithms, and (3) supply chain management.

Fig. 1: Distribution of vaccination centers in the smart city of Athens
Source: Authors

2.1 Systems Focusing on Sustainable Solutions

Sustainability is the main effort in this area of adopted solutions. Specifically, according to, [13], the authors study the impact of the coronavirus pandemic on global society's choices with regard to economic and social parameters. They also contextualize such choices from the social innovation point of view, while they try to understand what implications arise out of the coronavirus crisis for the relevant societal smart cities' stakeholders. However, such measures have a high impact on the citizen's quality of life as discussed in, [14]. A downstream system is examined in, [15], where there are examined risks, efficiencies as well and models of product distributions before and during the COVID-19 pandemic. Special focus is given to business-to-business (B2B) and business-to-customer (B2C) channels regarding novel approaches in supporting green and sustainable supply chain methodologies. Research in, [16], analyses covid-19 pandemic based on certain green information channels supporting vaccine delivery, which are evaluated by the smart city's population. Efficient planning of the COVID-19 vaccine problem is proposed in, [17], where the goal of the proposed solution is the minimization of total costs without loss of the provided sustainable healthcare service. A green and sustainable platform, which delivers COVID-19 vaccines from stock by exploiting electric vehicle technology is proposed in, [18]. Such a system uses effectively the available capacity of electric vehicles to perform accurate online distribution of the vaccines in the city. A sustainable system is proposed in, [19], where there is analyzed a facility location distribution solution focuses on a green approach. Such a system incorporates the optimal position of the vaccination vehicles network to face the expiration of stored COVID-19 vaccines.

In this category proposed systems' goal is to maximize citizens' well-being in a smart city. Intuitively, the adopted solution's main effort is to respect the quality of life thus providing green approaches in facing the coronavirus. However, such systems might have more expensive operations than others.

2.2 Systems Focusing on Routing Algorithms

Routing systems, which are based on adopted technical models have also been applied to face coronavirus problems. Specifically, in, [20], the authors focus on methods to treat pandemic supply risk mitigation by incorporating adequate measures and potential recovery paths. Distribution and delivery of COVID-19 vaccines are presented in, [21], where the study focuses on the Ethereum blockchain-based solution for managing data related to covid-19 vaccination context. According to, [22], the authors propose an alternative blockchain platform to treat COVID-19 vaccine distribution by incorporating a prototyping system, which is based on the Ethereum test network. Research in, [23], studies the various transactions performed during the coronavirus pandemic, which are related to vaccine requests, orders, distribution, and tracking by incorporating blockchain technology. A blockchain-based 5G-assisted Unmanned Aerial Vehicle (UAV) vaccine distribution scheme for dealing with covid-19 pandemic is proposed in, [24], where authors used global and local routing algorithms to deliver vaccines to certain areas of the smart city. In, [25], the authors propose a system, that uses blockchain solutions incorporating smart procurement contracts to automate the organization of the routing process for covid-19 vaccination. Research in, [26], treats covid-19 pandemic mainly as a technical problem incorporating certain resource allocation management policies, which exploit the potentiality of a proposed reinforcement learning algorithm. In, [27], the authors of the research effort analyze a routing algorithm, which is able to serve the vaccination needs of a smart city. Specifically, it uses a fleet of UAVs within a certain range and payload constraints to deliver covid-19 vaccine in real time. According to, [28], the authors present a system where it is achieved an effective vaccination process in smart cities based on a proposed routing algorithm. Such a system focuses on routing simulation analysis to deliver COVID-19 vaccines to certain vaccination centers. In, [29], the authors propose an optimal vaccination routing algorithm to face covid-19 pandemic. Such an algorithm is based on a sliding window exploiting available vehicle location data sources under a certain vehicle capacity threshold. According to, [30], the authors analyze a vaccine optimization system for facing smart cities' healthcare requirements. Such a system is able to treat covid-19 vaccination process under a distributed and robust evolutionary routing algorithm.

Solutions adopted in this section focus mainly on technical safety and soundness to treat the coronavirus problem in smart cities. Intuitively, such systems are designed to achieve efficient operation expenses and a wider area of applications within cities' infrastructure.

2.3 Systems Focusing on Supply Chain Management

Supply chain management systems are also provided as solutions to the coronavirus pandemic. According to, [31], the authors propose a supply value chain design of an adopted system, which is able to support the demands of the contemporary circular economy in green ecosystems. Such a system handles effectively the implications that emerge from the daily performance of the Industry 4.0 infrastructure technology as a fundamental component of sustainable manufacturing in smart cities. Concretely, in, [32], the authors adopt a healthcare supply chain system, that focuses on emergent reactions in the case of covid-19 pandemic. Such a system is based on a robust least square regression aiming to find the parameters and the forecasting estimates, which are extensively used in case of a healthcare incident emergency in smart sustainable living areas in smart city terrain. Modeling the barriers of a transparent supply chain for a COVID-19 research scenario is proposed in, [33]. Authors identify and model certain barriers in the process of implementing a transparent supply chain for covid-19 pandemic. They suggest that customer privacy involves more barriers to the system. To overcome such inefficiency, they propose a data pipeline to make the process transparent to the end users. According to, [34], the authors discuss the impact of supply chain disruption management on SMEs' performance with regard to covid-19 pandemic in India from the perspective of developing countries' survivability. The consequences of supply chain practices on flexibility during covid-19 pandemic with risk analysis and management options are studied in, [35]. Of particular research interest is the supply chain management in several economic sectors in India, such as the goods pricing, revenue, and transportation, that was implemented by stakeholders to face lockdown COVID-19 pandemic inefficiencies as presented in, [36]. Measures to prevent the spread of covid-19 such as lockdowns and closures of the borders are taken to protect the population from the pandemic. In, [37], the authors have designed a system, which is able to provide a vaccine supply chain to citizens according to their needs. They have taken into consideration the fragrant nature of COVID-19 vaccines and have performed risk management analysis to provide vaccines in cool temperatures thus avoiding loss of healthcare equipment. In, [38], the authors take into consideration the sensitivity of COVID-19 vaccines and propose a local simulation to improve the supply chain logistics performance for vaccine distribution within the smart city. They used anyLogistix simulation platform software to study a real-world problem in Norway. A mathematical programming solution is provided in, [39], which is able to treat COVID-19 vaccine distribution in developing countries as a supply chain and stock operations problem. The study encodes certain types of vaccines according to their current temperature and distributes them in an efficient way, thus eliminating the loss of vaccines due to high temperatures. According to, [40], the authors in their research effort analyze efficient logistics and supply chain management operations during the period of the coronavirus pandemic. They are also discussing how the research community can learn lessons from the COVID-19 era and be ready to face the next pandemic in the future. In, [41], the authors propose an efficient supply chain management system able to handle covid-19 pandemic. Such a system focuses on a robust delivery network of vehicles distributing time-available vaccines to certain vaccination centers.

Systems adopted in this area focus on supply chain management, which treats the coronavirus problem as a socio-technical problem. Provided approaches are designed to both cover citizens' well-being needs as well as technical operational efficiency.

In this paper, there is an intention to design a supply chain global and local routing system, which will exploit the strengths of the available research efforts while simultaneously avoiding their weaknesses. The proposed system exploits related work systems' potentiality to maximize strengths and eliminate weaknesses of the addressed research efforts. Specifically, we propose a green supply chain system architecture, which faces the population that needs to be vaccinated. Concretely, the adopted system focuses on the sociotechnical concept of supply chain management to effectively treat covid-19 pandemic. Such research effort is designed to fulfill citizens' daily activities in the city. Intuitively, special effort is given to ensure that the proposed system operates in time-critical emergency reactions, which affect the quality of technical soundness based on the adopted infrastructure. Certain use cases are introduced, namely UC-I and UC-II, to evaluate the proposed vaccination delivery process. Specifically, sustainable supply chain technology is assessed by incorporating certain evaluation parameters for both use cases, such as spatial and temporal distance, fuel consumption, and cost of routes in Euros. In addition, adopted parameters are input to the proposed system's global and local routing algorithms to assist the vaccination delivery process. Such algorithms are able to provide results with regard to time complexity robust behavior. Both use cases have strengths and weaknesses, which are further analyzed based on the adopted experimental system parameters. Subsequently, findings are provided to support third parties, such as the smart city of Athens Ministry of Health, and decision support headquarters' control center. Concretely, the control center is responsible for assessing the observed results and deciding which supply chain use case and proposed algorithm to adapt to face the coronavirus pandemic.

3 Supply Chain System Architecture

The sustainable supply chain system architecture is composed of a warehouse located at the Athens airport, where the COVID-19 vaccines that enter Greece are stocked in places with cool temperatures since vaccines need to be preserved in low temperatures to avoid loss. The smart city of Athens has a certain amount of vaccination centers where the vaccines should be distributed on time to use for citizens' vaccination. Trucks collect COVID-19 vaccines from the warehouse stock and deliver them to vaccination centers in the city. Such trucks are equipped with refrigerators to preserve the low temperatures of vaccines during the distribution process. Vaccination centers have adequate storage areas to stock delivered vaccines. The distribution of vaccination centers in the smart city of Athens is presented in Figure 1.

Stocks keep a track record of entered and used COVID-19 vaccines to be aware of the amount of vaccines that should be ordered from the green supply chain architecture for use by certain city populations. In addition, vaccination centers take into consideration the time required for a number of vaccines to get to the proper temperature for use in citizens. There are two use cases to assess the potentiality of the adopted supply chain architecture, namely UC-I and UC-II. Specifically, adopted use cases enhance research focuses on supply chain management to face COVID-19 as a social health threat that needs urgent technical treatment. Such a proposed approach is designed to provide citizens an adequate well-being status quo as well as technical operational efficiency during their daily social interaction schedule in a smart city.

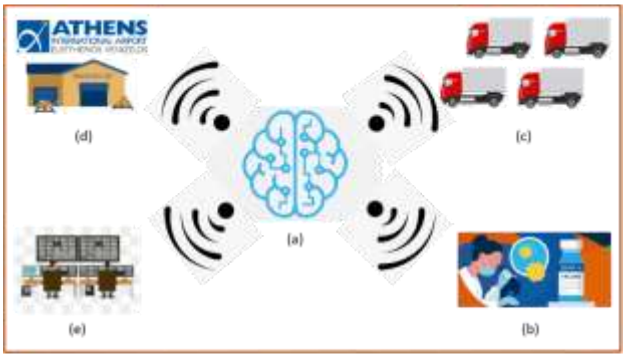

Fig. 2: Sustainable green supply chain architecture overview: (a) routing algorithms at conceptual level, (b) vaccination center, (c) trucks, (d) smart city of Athens airport, and (e) smart city headquarters control center

Source: Authors

Intuitively, smart city sectors are divided based on municipality regions serving a certain amount of population, which are a special category of political boundaries. The adopted system is based on a dedicated homogeneous fleet of trucks to deliver on time the vaccines to the vaccination centers. There are no available electric trucks or a heterogeneous fleet of trucks to support such a service in the smart city of Athens to provide a green footprint in the designed infrastructure. However, sustainability requirements are met regarding the adopted shortest path model used to eliminate carbon dioxide emissions during efficient routing in the city road network, as presented in Figure 7. Specifically, Figure 7, it is assesses the effectiveness of UC-II compared to UC-I with respect to the CO_2 emissions produced in kilograms. It is proved that UC-II is more efficient than UC-I since UC-II produces less carbon dioxide emissions than UC-I (See Section 6). Concretely, shortest routes technology is adopted, which serves the nearest vaccination centers like these that are near the airport. In addition, such routes follow a multi-hop approach to serve distant points after delivering vaccines to the shortest ones. Actually, the proposed algorithms are implementing the traveling salesman problem by decomposing each delivery based on the exploited shortest route between the prior and the next vaccination center.

Table 1. UC-I system parameters

Parameter	Value
a: Airport	1
h: Whole smart city	1
m: Number of trucks	100
c: Vaccination centers	1000
v: Number of vaccines	[100000, 200000]
d: Spatial distance (kilometers)	[10, 60]
t: Temporal distance (hours)	[0.5, 4.5]
f: Fuel consumption (litters)	[4.2, 9.8]
e: Total cost (Euros)	[8.9208, 20.8152]
n: Total CO_2 emission (kilograms)	[3.5532, 8.2908]
p: Total CPU Time (minutes)	[8.6217, 14.8162]

Table 2. UC-II system parameters

Parameter	Value
a: Airport	1
s: Number of smart city sectors	50
m_s: Number of trucks per sector	2
c_s: Vaccination centers per sector	20
v_s: Number of vaccines per sector	[2000, 4000]
d_s: Spatial distance per sector (kilometers)	[10, 20]
t_s: Temporal distance per sector (hours)	[0.5, 1.5]
f_s: Fuel consumption per sector (litters)	[4.2, 6.3]
e_s: Total cost per sector (Euros)	[8.9208, 13.3812]
n_s: Total CO_2 emission per sector (kilograms)	[3.5532, 5.3298]
q: Total CPU Time (minutes)	[23.2034, 31.1607]

Table 3. UC-I global routing algorithm

UC-I global routing algorithm
Input: a, h, m, c, v, g
Output: $globalRoute, d, t, f, e, n, p$
Begin
If $(g == True)$ **Then** // If a trigger occurs global routing is performed
For $(i \in m)$ **Do** // i, takes values of all trucks m in the
// whole smart city h
$[globalRoute, d, t, f, e, n, p] \leftarrow ShortestPathUC\_I(i, a, h, m, c, v)$
End For
Return $[globalRoute, d, t, f, e, n, p]$
End If
End

Specifically, in the case of UC-I, the distribution of vaccines from the airport warehouse to end-point vaccination centers is performed by a dedicated global routing algorithm for the whole coverage area of the city. Instead, in the case of UC-II the vaccine delivery is based on a local routing algorithm where routes are changed through time upon certain requirements defined by the served vaccination centers located in certain sector areas in the smart city. The proposed sustainable and green supply chain system architecture overview is presented in Figure 2.

Table 4. Shortest path UC-I algorithm

Shortest path UC-I algorithm
Input: i, a, h, m, c, v
Output: $globalRoute, d, t, f, e, n, p$
Begin
$globalRoute \leftarrow a$ // Initialize global route with the airport
// a location
For $(c \in h)$ **Do** // For all vaccination centers c belong to the whole
// smart city h
$deliver(c, v)$ // Deliver with truck i a certain number of vaccines
// v to certain vaccination
// center c in the whole smart city h
$globalRoute \leftarrow c$ // Append global route with certain vaccination
// center c location
$update \leftarrow (d, t, f, e, n, p)$ // Update system parameter values
// d, t, f, e, n, p for certain truck m
// delivery in the whole smart city h
End For
Return $[globalRoute, d, t, f, e, n, p]$
End

Table 5. UC-II local routing algorithm

UC-II local routing algorithm
Input: a, s, m_s, c_s, v_s
Output: $localRoute, d_s, t_s, f_s, e_s, n_s, q$
Begin
While $(True)$ **Then** // Execute local routing continuously
For $(i \in m)$ **Do** // i, takes values of certain trucks m in specific
// sector belongs to s
For $(j \in s)$ **Do** // j take specific value from certain sectors s
$[localRoute, d_s, t_s, f_s, e_s, n_s, q] \leftarrow ShortestPathUC\_II(i, j, a, m_j, c_j, v_j)$
End For
End For
Return $[localRoute, d_s, t_s, f_s, e_s, n_s, q]$
End While
End

4 System Parameters

The supply chain of COVID-19 vaccine stock management is based on adopted system parameters to be able to assess the system's efficiency. Parameters are differentiated according to the proposed use cases incorporated in the research effort study, except for the parameter a, which denotes the Athens airport where vaccines are imported from abroad countries and has value 1 airport. Specifically, in the case of UC-I, we have the parameter h, which denotes the whole city where vaccines are delivered by trucks and has a value of 1 smart city. The number of trucks assigned to deliver vaccines from the airport to the whole city of Athens is defined to be $m = 100$, trucks. The number of vaccination centers is defined with the parameter c, and has a value 1000. The number of vaccines is denoted with v, which are transported by assigned trucks in the city and is defined to be with the interval [100000, 200000] covid-19 vaccines.

Spatial distance covered from the airport to all vaccination centers is defined with parameter d, and is defined within the interval [10, 60] kilometers, where the nearest vaccination center in the city has a distance of 10 kilometers from the airport, while the most distant vaccination center in Athens has distance 60 kilometers from the airport. Parameter t, is assigned to the temporal distance a truck requires to transport vaccines to vaccination centers in the city, such parameter takes values with the interval [0.5, 4.5] hours. Fuel consumption parameter f, denotes the litters of oil consumed for COVID-19 vaccine delivery in the whole city of Athens and is defined within the interval [4.2, 9.8] litters. The total cost of fuel in the Euros parameter e, for vaccine distribution, is defined within the interval [8.9208, 20,8152] Euros, where diesel oil is considered to cost 2.124 Euros per 1 litter of fuel. Total CO_2 emission n, during truck movement is defined in the interval of [3.5532, 8.2908] kilograms, where diesel oil is considered to produce CO_2 emissions of 0.846 kilograms per 1 litter of fuel.

Table 6. Shortest path UC-II algorithm

Shortest path UC-II algorithm

```
Input: i, j, a, m_j, c_j, v_j
Output: localRoute, d_s, t_s, f_s, e_s, n_s, q
Begin
 localRoute ← a // Initialize local route with the airport a location
 localRoute ← j // Append local route with certain sector j location
 For (c_j ∈ j) Do // For all vaccination centers c_j belong to certain
                  // sector j
  deliver(c_j, v_j) // Deliver by truck i certain number of vaccines
                    // v_j to the certain vaccination center c_j belong to
                    // specific sector j
  localRoute ← c_j // Append local route with certain vaccination
                   // center c_j location of specific sector j
  update ← d_j, t_j, f_j, e_j, n_j, q // Update d_j, t_j, f_j, e_j, n_j, q system
                                      // parameter values for certain
                                      // truck m delivery in specific sector j
 End For
 update ← d_s, t_s, f_s, e_s, n_s, q // Update system parameter values
                                     // d_s, t_s, f_s, e_s, n_s, q for specific
                                     // performed deliveries of certain sectors s
 Return [localRoute, d_s, t_s, f_s, e_s, n_s, q]
End
```

The Central Processing Unit (CPU) total execution time of the global routing algorithm is denoted with p, while it is defined in the interval [8.6217, 14.8162] minutes. System parameters for UC-I are presented in Table 1.

System parameter values for UC-II are defined as follows. The smart city of Athens is divided into certain sectors s, where this parameter takes the value of 50 separate sectors in the city. In addition, assigned trucks transport and deliver COVID-19 vaccines locally to assigned sectors according to current vaccination centers' needs. The number of trucks assigned to each sector is defined to be $m_s = 2$ trucks to serve a certain sector. Vaccination centers per sector are defined to be $c_s = 200$ centers. Vaccines transported by trucks per sector are denoted by v_s, and are defined within the interval of [20000, 40000].

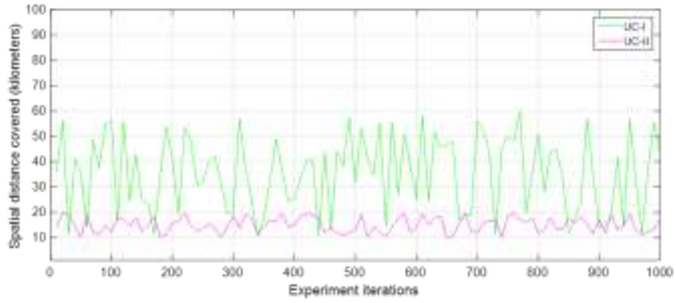

Fig. 3: Spatial distance covered in kilometers
Source: Authors

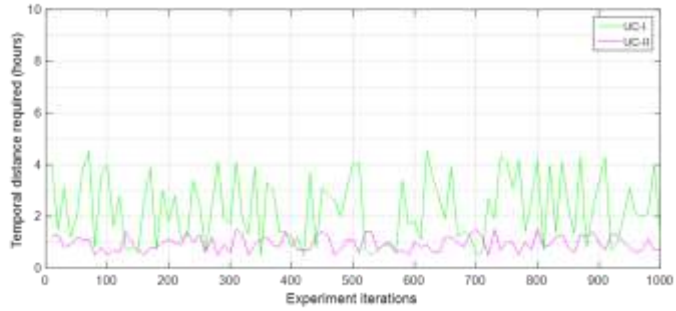

Fig. 4: Temporal distance required in hours
Source: Authors

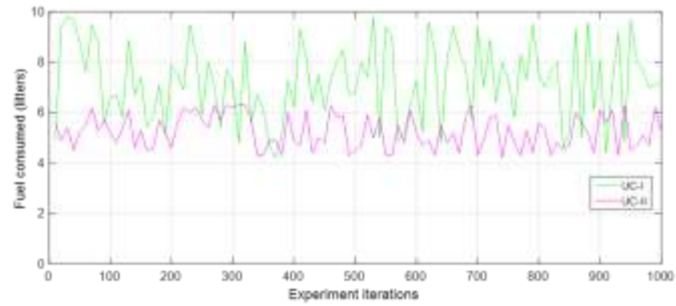

Fig. 5: Fuel consumption in litters
Source: Authors

Spatial distance d_s, required to transport a stock of COVID-19 vaccines from the airport to certain vaccination centers per sector is defined with the interval [10, 20] kilometers, where the nearest vaccination center within a sector has distance of 10 kilometers and the most distant vaccination center within a sector has distance of 20 kilometers. Temporal distance t_s, required to transport a certain amount of vaccines per sector is defined within the interval [0.5, 1.5] hours. Fuel consumption f_s, of oil fuel consumed by trucks to all vaccination centers per smart city sectors is defined within the interval [4.2, 6.3] litters. Total cost of COVID-19 vaccine delivery per sector e_s, is defined to be in the interval of [8.9208, 13.3812] Euros, where diesel oil is considered to cost 2.124 Euros per 1 liter of fuel. Total CO_2 emission n_s, during truck movement is defined in the interval of [3.5532, 5.3298] kilograms, where diesel oil is considered to produce CO_2 emissions of 0.846 kilograms per 1 liter of fuel. The Central Processing Unit (CPU) total execution time of the local routing algorithm is denoted with q, while it is defined in the interval [23.2034, 31.1607] minutes. System parameters for UC-II are presented in Table 2.

5 Use Cases' System Algorithms

Each use case executes a different algorithm to compute its routing map based on different delivery needs. Specifically, UC-I is based on a global routing algorithm, which means that execution is performed in rare periodical time slots according to the supply chain transportation of vaccine requirements. Such a global algorithm is based on Dijkstra's shortest path routing algorithm (i.e., customized Shortest Path UC-I) to transport a vehicle with a stock of COVID-19 vaccines from an origin to a given destination in the whole smart city, [42]. *Note that delivery is relevant to the whole smart city area.* That is a certain fine tuning on the algorithm parameters is performed once and then the global route might change in case of emergency, such as loss of COVID-19 vaccines due to high temperatures occurring due to heavy traffic latencies in the smart city's road network. UC-I incorporates assignment instructions to match a truck with a certain route within the whole city of Athens. The time computation complexity of the UC-I algorithm is defined to be $O(m)$, since a route assignment is performed to each smart city truck during global algorithm execution. UC-I global routing algorithm is presented in Table 3, while the Shortest path UC-I algorithms are presented in Table 4.

In the case of UC-II instructions performed by the supported local routing algorithm are relevant to the needs of certain city sectors. Such sectors' requirements are variable and changing locally to provide effective services to each sector, thus avoiding the loss of vaccines due to high temperatures in real-time. The local routing algorithm is executed online each time slot a new COVID-19 vaccine stock requires transport and delivery by available trucks. Such a local algorithm is also based on Dijkstra's shortest path routing algorithm (i.e., customized Shortest Path UC-II), which however is used to deliver stock of COVID-19 vaccines from an origin to a given destination per certain sector of the smart city, [42]. *Note that delivery is relevant to certain sector areas of the city.* This means that routing a truck follows is not global for a certain period of time in the whole city but it changes according to the current sector's needs. So, it is possible to have local detours of the computed local route to deliver COVID-19 vaccines to specific vaccination centers based on real-time changes in road network traffic latencies such as road labor tasks, malfunctioned vehicles on the road, or a water leakage in a certain central road segment. The local routing algorithm is able to provide a robust route to overcome such problems in the road traffic network. The time computational complexity of the UC-II algorithm is defined to be $O(m^s)$, since a route assignment is performed to each smart city truck per selected sector, which faces online routing inefficiencies during local algorithm execution. UC-II local routing algorithm is presented in Table 5, while the Shortest path UC-II is presented in Table 6.

It should be noted that a modified shortest path algorithm is used as the main model of routing in both adopted use cases in the current research effort. Such a modification has been performed to extend the shortest path potentiality from origin to multiple destinations based on the concept of the traveling salesman problem. Concretely, given the whole global area of the city, in the case of UC-I, or a certain amount of local municipality sectors, in the case of UC-II, certain trucks are following a spatiotemporal trajectory. A given trajectory serves subsequently each vaccination center starting from the nearest one up to the furthest of them based on certain inferred route vectors computed per cycle of the model's execution.

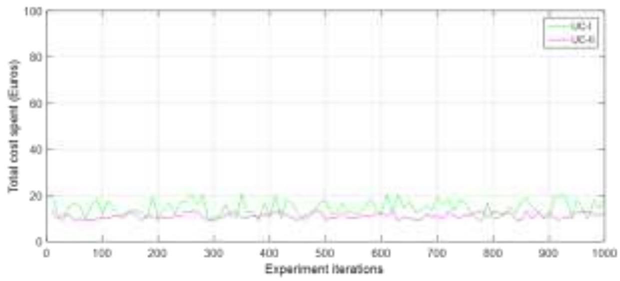

Fig. 6: Total cost spent in Euros
Source: Authors

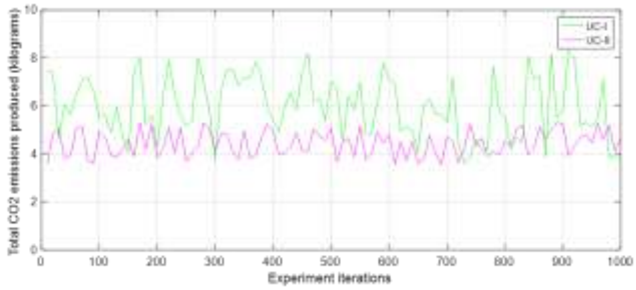

Fig. 7: CO_2 emissions produced in kilograms
Source: Authors

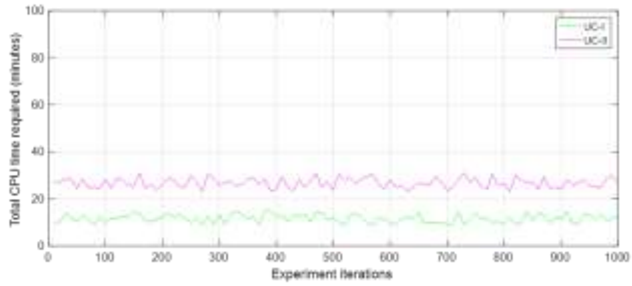

Fig. 8: Total CPU execution time required in minutes
Source: Authors

6 Experimental Evaluation and Results

We experimented with the adopted global and local routing algorithms defined for the proposed use cases, UC-I and UC-II. An experimental smart city is the capital city of Greece, which is Athens. The data used for the experiments are synthetic. Specifically, there are used real unclassified data provided online by the smart city of Athens, [43]. Such data are the number of vaccination centers, the number of vaccines, and the number of trucks. Based on these real data we implemented a simulation environment to test the proposed global and local routing algorithms. Synthetic data are formed by using real data as ground truth information for our simulations. Specifically, unclassified data provided in [43], were preprocessed to feed adopted UC-I and UC_II models. Such data contain the vaccination centers' location in the smart city as well as the need for vaccines in the whole area of the city of Athens. Distribution of vaccination centers in the city were visualized as shown in Figure 1. Consequently, the sum of the vaccines required to be delivered to the whole city where divided by the number of vaccination centers as presented in Table 1 and Table 2 for UC-I and UC-II, respectively. Subsequently, vaccination centers were divided by the number of municipalities that existed in the whole city area thus forming the examined sectors. Based on this information a certain fleet of trucks is assigned to the whole smart city for UC-I while a set of smaller fleets were assigned to certain municipality sectors.

Concretely, we added on provided real data certain Gaussian distribution white noise to observe simulated realistic values for the incorporated parameter variables of the proposed system. Simulation algorithms are implemented in Python release version 3.9.10, while experiments were performed on an HP ProBook 455R G6 computer with 8.00 GB memory. We performed 1000 experimental iterations invoking adopted global and local routing algorithms of UC-I and UC-II use cases, where the observed results were visualized.

Subsequently, in Figure 3, there are presented the results of spatial distance covered, in kilometers, by UC-I and UC-II. Figure 4, presents the temporal distance required to deliver vaccines, in hours, in both use cases. Figure 5 presents the fuel consumption, in litters, of the local and global algorithms. Figure 6, presents the total amount of cost, in Euros, spent in delivering vaccines to vaccination centers by both algorithms. Figure 7 presents the CO_2 emissions produced, in kilograms, to the smart city green and sustainable environment for UC-I and UC-II. Figure 8, presents the total CPU execution time required, in minutes, to observe the results of the adopted global and local algorithms.

7 Discussion

The results of both use cases are promising to provide a set of sustainable policies to be adopted by the smart city of Athens. Specifically, comparing UC-I with UC-II regarding the dimension of the spatial distance covered by the fleet of trucks we can observe that values observed in UC-II are more robust compared with experimental values observed in UC-I accordingly. Concretely, it should be noted that in Figure 3, UC-II is optimal compared with UC-I according to the spatial distance covered with regard to the increasing discrete values of experimental iterations. This is observed due to the fact that UC-II achieves to covers less spatial distance than UC-I. This is explained by the fact that delivering medical COVID-19 vaccines by dedicated trucks to certain sectors in the city is more robust compared with the massive transportation of the COVID-19 vaccines to the whole smart city without segmentation of the city into adequate sectors. In addition, the emergence of routing problems due to labor work or an accident on the road affects the traffic load in the whole city rather than just a small sector. In the last case, such problems are solved locally by incorporating UC-II instead of UC-I without affecting the massive fleet of trucks during their time-sensitive operation.

It should be noted that both use cases have a dynamic nature in computing the inferred routing vectors to be used by the incorporated vaccination trucks in the city. Specifically, in the case of UC-I inferred routes might be relatively more stable in time since trucks have a dedicated schedule. However, even in such a case, a change in delivery to a certain vaccination center is highly possible, which is able to reactivate the UC-I model to provide new dynamic routes for the engaging trucks of the whole city according to their current positions in the smart city. Concretely, UC-I is less efficient since it is executed based on a centralized concept, which may not be efficient enough when having to compute an integrated route trajectory for all the trucks. Intuitively, in the case of UC-II, it has adopted a distributed architecture, which is more flexible in emerging routing inefficiencies during truck visits to deliver vaccines in certain centers. In such a case distributed nature of municipality-defined sectors provides a more robust trajectory routing vector required to serve the upcoming needs of the sectors' vaccination units. Subsequently, the adopted research effort has taken into consideration that the mobility of assigned trucks is supported by smart city policies to provide priorities to the fleet of trucks. Since such policies are applied horizontally to the smart city infrastructure proposed models were executed based on equally input transportation conditions.

Concretely, the temporal distance required by the fleet of trucks either in UC-I or in UC-II is relational and affected by the spatial distance covered. Specifically, it should be noted that in Figure 4, UC-II is optimal compared with UC-I according to the temporal distance required with regard to the increasing discrete values of experimental iterations. This is explained due to the fact that UC-II achieves to requires less temporal distance than UC-I. In addition, road network problems such as traffic bottlenecks in certain areas of the city increase the values of temporal distance, which should be as minimal as possible to avoid loss of COVID-19 vaccines due to road network latencies. So, localizing the distribution problem incorporating city sectors has the positive impact of less time required to deliver the vaccines observed in UC-II which results in the robustness of UC-II compared with UC-I regarding the temporal experimental parameter. Another relation exists in the comparison between the fuel consumption observed by both use cases. Subsequently, it should be noted that in Figure 5, UC-II is optimal compared with UC-I according to the fuel consumption required with regard to the increasing discrete values of experimental iterations. This is explained due to the fact that UC-II achieves to requires less fuel consumption than UC-I. It holds that high values of the spatial and temporal distance parameters of UC-I lead to an inefficient use case compared to low values of temporal and distance parameters observed in the case of UC-II. So, it holds that fuel consumption is more efficient in the case of UC-II than that of UC-I based on the observed results.

Subsequently, the total cost spent in Euros for UC-I is much more than the amount of money spent in the case of UC-II. Concretely, it should be noted that in Figure 6, UC-II is optimal compared with UC-I according to the total amount of cost spent with regard to the increasing discrete values of experimental iterations. This is observed due to the fact that UC-II achieves to spent less total amount of cost than UC-I. This is explained, by more fuel consumption levels observed by high values of spatial and temporal distances in the case of UC-I. In addition, this fact leads to a more robust efficiency of UC-II compared to UC-I, with regards to the adopted sustainable and green supply chain system for COVID-19 vaccine delivery. Concretely, more fuel consumed in the case of UC-I results in more CO_2 emissions produced in this case. Intuitively, it should be noted that in Figure 7, UC-II is optimal compared with UC-I according to the CO_2 emissions produced with regard to the increasing discrete values of experimental iterations. This is explained due to the fact that UC-II achieves to produces less CO_2 emissions than UC-I. Since in case UC-II fuel consumption is less than UC-I, observed results by the experiments indicate that UC-II is more robust compared to UC-I with regards to the proposed system's effectiveness. However, in case the total CPU execution time is required by both use cases, it holds that UC-I is better than that of UC-II. Concretely, it should be noted that in Figure 8, UC-I is optimal compared with UC-II according to the CPU execution time required with regard to the increasing discrete values of experimental iterations. This is observed due to the fact that UC-I achieves to requires less CPU execution time than UC-II. This is explained by comparing the time computational complexities of the two use cases' adopted algorithms. Specifically, in the case of UC-I proposed global algorithm has less time computational complexity than that required by the UC-II local routing algorithm. We expected this result since the local routing of UC-II has to take into consideration more computational inputs to produce a route for the available trucks assigned per sector. Instead, the global routing of UC-I is more lightweight compared to the local routing of UC-II.

Concretely, it seems that there are two choices for the smart city's Greek Ministry of Health headquarters control center. In addition, it should be noted that the proposed system exploits the benefits of having real-time information to schedule each of the adopted use cases to focus on supply chain management. Such a system design raises the need to consider the COVID-19 pandemic as both a social and technical problem. Experiments on UC-I and UC-II are mainly focused on covering citizens' well-being needs. Cost-benefit analysis is performed as a factor, which balances the trade-off between social impacts in daily life on one side as well as technical soundness and operability on the other side. To explain such a concept, it is crucial to examine both use cases with regard to certain cost indicators like values relevant to CPU time complexity, spatial distance, temporal distance, fuels, CO2 emissions, and cost spend. Intuitively, the first choice indicates that the control center will use UC-I to observe low values of CPU time complexity required but have high values of spatial distance covered, temporal distance required, fuel consumed, total cost spent in Euros, and total CO2 emissions produced. The opposite holds in case the second choice where will hold if the control center adopts UC-II. In this case CPU time complexity required is high but the rest of the parameter quantities are low. It is at the discretion of the Greek Ministry of Health to decide which of the two policies, P-I and P-II, is better for adoption for supporting a sustainable and green supply chain to deliver COVID-19 vaccines to vaccination centers in the smart city of Athens by the significant support of adopted trucks. Overall smart city's control center will decide, which use case to adopt based on certain priorities that emerged upon the proposed parameters.

8 Conclusions and Future Work

A supported supply chain technology is proposed in this paper, which incorporates two separate use cases to treat vaccines during their transport to the city. The first use case, UC-I, assumes that the smart city supply chain management area is flat, which means that a truck can collect a load of vaccines and transport them in any area within the city. In the case of the second use case, UC-II, it is assumed that the city is divided into certain sectors, and trucks are assigned to serve certain sectors. Supply chain technology is assessed by incorporating certain evaluation parameters for both use cases, such as spatial and temporal distance, fuel consumption, cost of routes in Euros, and efficiency of sustainable global and local routing algorithms to assist the vaccination delivery process with regard to algorithms' time complexity. Observed results state that UC-II is better than UC-I compared with spatial, temporal, fuel, and cost parameters. However, UC-I achieves better results regarding the time complexity parameter.

An alternative conventional delivery priority, which will be based on same-day delivery of online vaccine orders by certain vaccination centers could be supported in a future quarantine of an emerging pandemic. Such a delivery priority should exploit the AMAZON routing trajectory, which is based on Unmanned Aerial Vehicles (UAV) technology. Concretely, future routing might face rapidly changing congestion in the potential routes, while simultaneously incorporating real-time information to provide a decisive vaccination delivery service.

It is suggested that it is at the discretion of the smart city headquarters' control center to choose, which of the two use cases will be incorporated according to its priorities upon the proposed parameters. Future work should focus on how to evaluate lessons learned from covid-19 pandemic to be ready to face a possibly emerging new pandemic in the near future. In addition, in the future more social and economic contexts should be exploited to provide a robust cost-benefit analysis based on the adopted use cases. Information like this might be provided by running the adopted models for a certain amount of time in real conditions to gain more inside into the proposed healthcare city infrastructure. Such economic analysis would focus on smart city challenges to provide the Greek Ministry of Health headquarters the information required to decide if adopting UC-I and UC-II capabilities into their control center is meaningful regarding relative cost requirements. Humanity after the coronavirus pandemic is wiser and acts more rationally to protect its offspring and the next generation of humankind. Green and sustainable supply chain and vaccine stock system technology should be further evaluated with continuous domain-specific research to be ready for the next time their services should be needed for the sake of humanity's healthcare and safety.

We conclude the paper by summarizing the proposed research impact of the current study. Specifically, it has been performed analytical exploitation of state-of-the-art contemporary research in the domain. In addition, it has been described in deep detail the proposed supply chain system, while has been exploited the adopted architecture based on two separate use cases for system experimentation. Subsequently, it has been presented the system parameters used to input supported infrastructure. Concretely, it has been adopted two vaccination routing algorithms, namely global and local, to support vaccination distribution in the smart city of Athens, while it has been evaluated experimentally the proposed supply chain system architecture with regards to the adopted use cases' routing algorithms. Subsequently, it has been performed in-depth discussion on the observed results of the research effort, and finally, it has been proposed future research work required by the domain experts to be ready to face an emerging pandemic in the near future.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Theodoros Anagnostopoulos and Michail Ploumis were the main authors and were responsible for the conceptualization, the writing of the original project, the investigation, the statistics, the formal analysis, the resources, the software, the methodology, and the visualization.
- Alkinoos Psarras and Faidon Komisopoulos were responsible for the conceptualization, the methodology, the resources, and the writing review & editing.
- Ioannis Salmon and Klimis Ntalianis were responsible for the review of the statistics, the methodology, the validation, the supervision, and the writing review & editing.
- S.R. Jino Ramson was responsible for the methodology, the supervision, the project administration, the writing review & editing, and the funding acquisition.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

This research was funded by the Master of Business Administration (MBA) of the Department of Business Administration at the University of West Attica, Greece.

Conflict of Interest

The authors have no conflicts of interest to declare.