APPLICATION OF GRAPH THEORY IN OPTIMIZING TRANSPORTATION AND COMMUNICATION NETWORKS IN DRUG DELIVERY

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ABSTRACT

There are several issues that need to be addressed when involving the distribution of medicine to ensure that the medicine is distributed within the maximum allowable service window. This includes the capacity of the vehicle(s) used for the distribution, the storage conditions needed for the medicine, traffic levels and the security and traceability needs. This mini project aims to investigate this combined transportation and communications network reporting the location, the temperature and delivery using graph theory. The use of multilayer is used for vertices (warehouses, depots, and care sites) as transport vertices, and for road segments as labeled, weighted edges as well as for sensor vertices and communicative vertices (sensors), and data links as reliable-weighted edges. There is a correlation of Interlayer links between each shipment and location to the monitoring endpoint. The proposed scheme is a mixture of shortest paths, capacitated vehicle routing and time windows, k shortest-backup paths and min-cut analysis and prioritisation based by centrality. The edge weights are composed of distances, travel time and costs, disruption risk, emissions and temp exposure. If there is a change in a material's nature in the demand, status of roads, sensor reading, or if there is a change in the availability of roads, then the optimisation workflow gets adapted on the fly. The impact of the framework is shown with a synthetic prototype along with labelled and illustrated results that are juxtaposed against a dispatch recoverable from the graph in relation to Standard dispatch. The project does not aim to replace good distribution practice or product labelling but it does provide a good and traceable decision-making tool which can be used by qualified individuals to plan and monitor drug delivery or re-route it as appropriate.

Keywords: graph theory, drug distribution, vehicle routing, cold chain, communication network, shortest path, multilayer graph, pharmaceutical logistics.

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I. INTRODUCTION

At the end of the line, medicinal products go through a number of hands from the manufacturers to companies' central warehouse and regional depot, before reaching the hospital and last-mile pharmacies. For each and every movement, an additional network is required equipped with a new series of scanners, temperature information loggers, vehicle gateway, low power and cellular interactions, control systems and getting software application. Distance is short, but potentially hazardous due to not having a refrigerated vehicle available, or not being shipped on time to the clinic, or if a temperature excursion was not detected or reported. But, the more important is to have a reasonable or realisable way to follow than the good monitoring. Optimisation needs to be done considering movement and information.

May be naturally represented using graph theory. Each one of the nodes (vertices) can be a facility, a customer or a device and the connections of these (arcs, paths, edges) can be a road or a communication link and the cost, time, risk or reliability of these are represented as weights.

Examples of reusable building blocks are Dijkstra's shortest-path method [2] and the vehicle routing models of Dantzig and Ramser (1966) [3] and k-shortest path method [5]. There are also other constraints imposed on delivering pharmaceuticals: heterogeneous products, priorities, time constraints, perishability, qualified packaging and hand-off recording and route profiling. A recent pharmaceutical routing study [6, 7] also confirms that the multigraph, time dependent and disruption aware representation is important.

In the present work a realistic multilayer system instead of the deployed medical system is proposed. In the case of "drugs delivery", the delivery is a delivery of the final drug product, it is not a "delivery" in the human body, nor is it a "delivery" of the drug product for prescription. Product specific storage requirements (authorised) as well as local regulation always take a step back in the prototype in comparison with the illustrative temperature and the service assumption.

II. GRAPH-THEORETIC FOUNDATIONS AND PROJECT SCOPE

A. Graph Representation

A graph G is a collection of vertices (V) and a collection of edges (E) [1]. The idea of a directed edge (arrow) is a motion/messenger that can be made/created and an edge with a weight (called "prehensile," at least), has a characteristic or characteristics. A path is a series of adjacent vertices, a cycle is a path that begins and ends at the same vertex, the degree of a vertex is the number of vertices that it is adjacent to, is the set of vertices connected? Network with capacities on its edges called a flow network. When cut has a bottleneck, then it's small cut, between the source and the destination. To find vertices in an unusual position, those that have unusual influence, Operational Criticality needs to consider the priority of the drug, capacity, recovery choices and centrality measure.

Graph concept	Transportation meaning	Communication meaning	Decision use
Vertex	Warehouse, depot, hospital, pharmacy or patient zone	Sensor, gateway, control tower or receiving app	Locate demand, stock and responsibility
Edge	Permitted road, air leg or transfer	Wireless, cellular, internet or system interface	Represent feasible movement or messaging
Weight	Distance, time, cost, risk, emission or exposure	Latency, loss, cost, energy or cyber risk	Rank routes and trade-offs
Capacity	Vehicle, road, dock or stock throughput	Link bandwidth, gateway queue or battery budget	Prevent infeasible assignment
Path / cut	Route and physical bottleneck	Alert path and communication bottleneck	Plan primary and recovery options
Centrality	Operationally influential hub	High-impact gateway or service	Prioritise protection and redundancy

B. Multilayer Scope

For some other different coupled transportation graph G_t exists. If no tracking link exists, there can be no transport edge, and the communication path could be reliable but slow. A consignment, a vehicle or a facility and the device providing information about the status of the consignment, vehicle or a facility is called a "coupling link". This model can also incorporate questions in which a set of questions is asked simultaneously – which route meets the capacity and time requirements? What will the rest of us do if all roads are shut down? Thinking questions – Is there a responsible person who will hear the alarm in another way?

C. Aim and Objectives

The aim is the development of a graph-theoretic decision-making process to ensure safe, efficient and observable drug distribution. Objectives are to: build a transportation/communication graph; set the weight of edges based on risk; set Routing and Reliability constraints; identify Critical Hubs and Critical cuts; build up the "back-up" routes; define re-optimisation workflow for rolling; and analyse a synthetic prototype with the measures of service, cold-chain and resilience and communication.

III. REVIEW OF RELATED WORK

The overall classical vehicle routing problem is to minimise the cost of the routing needed to service the customers from a single or more than one depot [3,4]. New variations are time windows, heterogeneous vehicles, priorities and uncertainty.

Cook, Held and Helsgaun [9] For pharmaceutical inventory-routing, Baghdadi et al. build a multi-graph with perishable products and disruptions that will be used in a time-dependent fashion [7].

Table 2: Related-work synthesis and framework response

Evidence area	Established contribution	Remaining gap	Project response
Shortest paths [2], [5]	Minimum-cost and ranked alternative paths	A shortest road may violate drug constraints	Use constrained, risk-weighted candidate paths
Vehicle routing [3], [4], [9]	Fleet assignment and route construction	Communication health is usually separate	Couple dispatch with observable event paths
Pharma routing [6], [7]	Time windows, perishability and multi-graph travel	Operational recovery needs explicit redundancy	Add k paths, cuts and rolling re-optimisation
Cold-chain algorithms [8]	Multi-objective distance, cost and freshness optimisation	Product integrity cannot be inferred from route alone	Use monitored exposure and safety gates
Sensor networks [10]–[12]	Temperature sensing, traceability and visibility	Data path failure may delay intervention	Optimise communication reliability and escalation

IV. SYSTEM REQUIREMENTS

The functional needs are: Order capturing, demand capturing, product and storage-rule classification, stock visibility, vehicle qualifying, building the route graph, updating of the route graph with regard to time, mapping of shipments onto the sensors, route and communication optimizing, exception alerting, human approval, proof of delivery and export of audits. Non-functional requirements are safety, traceability, low latency alert alerts, availability, privacy, cyber security, interoperability, explainable route suggestions and data recovery if one of the items of data is missing. The original event record and the cause for each change, either manual or algorithmic, of the route in the system, should be retained.

V. PROPOSED MULTILAYER GRAPH FRAMEWORK

A. Architecture

Figure 1 illustrates two layers that are coupled. The arcs that are possible to move along and the facilities are in G-. The sensors, gateways, control tower and receiving applications are at G_C. The relationships between a consignment, a facility and an event source are known as interlayer mapping. Common parameters shared among the states are identity, demand, priority, authorised temp range, current location, expected arrival and sensor status and delivery confirmation. This state is known to the optimiser, and is not supposed to vary during the execution of the product requirement under regulation.

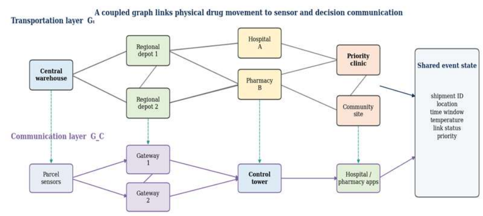

Figure 1: Proposed multilayer transportation and communication graph for drug delivery.

B. Data and Edge States

Transport-edge attributes are: distance, predicted time, toll or fuel cost, road class, vehicle eligibility, disruption probability and emissions estimate and exposure route-profiled. Measuring the parameters at the perimeter of the communications network, latency, delivery probability, bandwidth, battery effect and provider variety and security status are all measures. Edge may be in an ACTIVE state, a DEGRADED state or it may be UNAVAILABLE. The TimeStamp indicates when the measured data and forecast(s) and/or manually entered report(s) are latest. The ConfidenceLevel refers to the difference between measured data and forecasts and/or manually entered reports.

C. Governance and Human Control

If an excursion takes place, the logistics planner gives the "go-ahead" for dispatch, the product is handed to the pharmacist/quality representative who dispatches it and the receiving site confirms the hand off, with communication services managed by IT and security. Storage and distribution are considered controlled activities and responsibilities are designated appropriate to this type of activity, as advocated by WHO [13] and for time and temperature sensitive products, route profiling/temperature monitoring are used [14]. The framework doesn't automate anything release or quality disposition which it intends to document recommendations, approvals, alerts and acknowledgements.

VI. MATHEMATICAL MODEL

A. Graphs and Composite Edge Weights

Suppose that $G_t = (V_t, E_t)$ is the transport graph, $G\_C = (V\_C, E\_C)$ is the communication graph and M is a set of interlayer mapping. Each transport edge (i, j) has the distance d_{ij}, and duration t_{ij}, cost c_{ij}, risk r_{ij} and emission e_{ij}. Normalisation eliminates issues from a scale dominance of one unit.

$$G = \{G_t, G\_C, M\}, \quad M \subseteq V_t \times V\_C \tag{1}$$

$$w_{ij} = \alpha(d_{ij}/d_{max}) + \beta(t_{ij}/t_{max}) + \gamma(c_{ij}/c_{max}) + \delta r_{ij} + \eta(e_{ij}/e_{max}) \tag{2}$$

Information about values of α, β, γ, δ and η is provided in the scenario. It is possible to increase the increase in β or in the cost weight for an emergency delivery or in the planned replenishment, also in the latter one. K-shortest paths have been utilized to rank the alternatives in the case of disrupting and if the edge weights are not negative the Dijkstra's algorithm can be applied to case of disrupting.

B. Capacitated Routing with Time Windows

If vehicle k is travelling on edge (i, j) then x_{ijk} is 1. L_i is the lateness of customer i, Ξ_k is the cost of the temperature exposure of the route k and Ω_k is the loss of monitoring / event communication. The objective below is for guidance only and in actual deployment – penalty scales should be based according to quality and clinical priority and services policy.

$$\min J = \Sigma_k \Sigma_{(i,j)\in E_t} w_{ij} x_{ijk} + \lambda^L \Sigma_i L_i + \lambda^T \Sigma_k \Xi_k + \lambda^c \Sigma_k \Omega_k \tag{3}$$

$$\Sigma_i\, q_i y_{ik} \le Q_k \quad \forall k \tag{4}$$

$$\Sigma_j\, x_{ijk} = \Sigma_j\, x_{jik} = y_{ik}, \quad a_i \le s_i \le b_i \tag{5}$$

Now, we define q_i as the demand of vehicle, Q_k as capacity, y_{ik} as assignment and $[a_i, b_i]$ as receiving window and s_i as service start. Other constraints which apply to the depot departure/return, continuity of the route, vehicle product fitting and subtour elimination also apply. Multigraphs are graphs, in which several roads connect a pair of places [7].

C. Communication Reliability and Resilience

If the probability of successful communication on edge e is p_e then a path's success probability is the product of the probabilities of its edges. The task of maximising the product is the same as minimising a sum of non-negative negative-log weights. This can be used to get the shortest path machinery with a reliability interpretation.

$$R(P) = \prod_{e\in P} p_e, \quad P^* = \arg\min_p \Sigma_{e\in P} [-\ln(p_e)] \tag{6}$$

Another way the framework works is by computing for each available back path, the back paths are composed of edges that don't share a node (also known as vertex) or vertices that don't share an edge (also known as "edge-disjoint" paths). Min-cut: identifies the links/gateways which when removed, cut off a site. Nothing is said about trust, security, ownership or diversity of providers – something central is not necessarily more trustworthy, no "why," as to why the most central nodes are to be more trusted.

Table 3: Decision variables, constraints and operational meaning

Element	Symbol / test	Operational meaning	Failure response
Route choice	$x_{ijk} \in \{0,1\}$	Vehicle k uses transport edge (i, j)	Select next feasible path or hold dispatch
Customer assignment	$y_{ik} \in \{0,1\}$	Customer i served once by a compatible vehicle	Reassign vehicle or split authorised demand
Capacity	$\Sigma q_i y_{ik} \le Q_k$	Load remains within qualified capacity	Use second vehicle or depot
Time window	$a_i \le s_i \le b_i$	Receiving site can accept and control the hand-off	Re-sequence or escalate appointment
Temperature	$\Xi_k = 0$ preferred	Predicted and measured exposure is acceptable	Alert; authorised quality review
Communication	$R(P) \ge R_{min}$	Alert and event path meets reliability target	Activate disjoint backup or store-and-forward

VII. OPTIMISATION ALGORITHM AND OPERATIONAL WORKFLOW

A. Hybrid Solution Strategy

The prototype is a sub-optimal heuristic solution and the whole problem is of combinatorial type. Eliminate fixed vehicle locations, vehicle availability constraints and product/container information in edge. Second, identify a number of possible transportation/communications routes. while for the larger instances, heuristics can be used to support the roll replanning process [4] and [6].

B. Rolling Re-optimisation

The last figure depicts the operational cycle of the graphs as shown below: The operational cycle: Orders, traffic and vehicles' location, and temperature and link health are refreshed on the graphs. It is equipped with persistence and thresholds rules determining whether or not a change is material or not to avoid performing a re-computation of the system for each noisy measure. The update to the route could be due to a road closure. The network can cause the communication backup even if there has not been an outage – it could simply be a short outage from the cells. An alert and quality process is triggered if the temp goes over which allows the route optimisation not to give the product a go good.

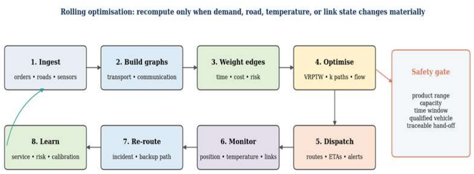

Figure 2: Rolling graph-optimisation and monitored drug-delivery workflow.

C. Stage-Level Workflow

Table 4: Inputs, graph operations and controlled outputs

Stage	Main input	Graph operation	Controlled output
1. Plan	Orders, stock, product rules, fleet and site windows	Build feasible subgraph and initial weights	Candidate dispatch plan
2. Route	Predicted traffic, cost, risk and capacity	k paths, VRPTW and local improvement	Primary and recovery routes
3. Connect	Sensor, gateway and provider link states	Reliable path, disjoint path and min-cut analysis	Monitoring and escalation plan
4. Approve	Plan, exceptions and evidence	Constraint and explainability report	Authorised dispatch
5. Monitor	GPS, temperature, ETA and communication events	Incremental weight and state update	Alerts and revised ETA
6. Recover	Road, vehicle, temperature or link incident	Recompute affected subgraph only	Approved re-route, hold or hand-off
7. Close	Delivery, condition, receipt and deviation records	Path reconstruction and KPI calculation	Traceable delivery record

D. Explainability

For each recommendation, you will find the selected path, rejected hard constraints, principle costs incurred, estimated time of arrival, vehicle load, minimal required monitoring path and recovery path (if any) and changes in the edges since the last plan generation. To provide a route description one must be "optimal." The planner needs to show the trade-offs and constraints that led to the planner and include a statement of justifications from the planning process that should include a planning override.

VIII. COLD-CHAIN COMMUNICATION, TRACEABILITY, AND RISK

A. Product Integrity and Monitoring

According to WHO [13] storage and transport & distribution is under good storage and distribution practice (GSDP). Safe transportation of pharmaceutical products, qualified systems, route profiling and monitoring, are provided for pharmaceutical products that are temperature and time sensitive [14]. The graph is now the condition profile to be authorized for a shipment, the sensors are evidence sources and the graph is used as an attribute. You will find that the range and handling conditions for the prototype are as follows: 2-8℃ only - each medicine will have its own specified range and handling conditions.

In the presented sensor works [10] sensor gathering and communication in the vehicle with the base station is in a wireless way, and only temperature data is taken. In [11] a pharmaceutical Cold Chain case-study deployment is discussed that introduces advantages and challenges of adoption of Wireless Sensor. Continuous traceability and counterfeit-prevention evidence can be obtained with the use of IoT systems [12]. There are various aspects of calibration, battery, position, synchronisation, data and data governance to consider that enable aspects of these features to be visible. In the case of a missing reading, a reading could be not 'safe reading'.

B. Event Communication and Traceability

A minimum event is a shipment identifier, a product and (if authorised) a batch, event time, read point, business location, condition reading, source device and route version and responsible organisation. GS1 EPCIS 2.0 is the specification that defines a set of rules for expression in a shared language for visibility events such as what, when, where and why [15]. Events can be exported by the framework, where they can be used by the other framework (and retain access controls, local retention policy). The communication graph supports the transmission of various types of information (e.g., telemetry, alerts, acks and proof of delivery (PoD)) that may have varying levels of latency and/or reliability.

C. Risk Controls

Table 5: Transportation and communication risks with graph controls

Risk	Graph signal	Preventive control	Response evidence
Road closure / congestion	Edge unavailable or time weight rises	Time-dependent weights and k feasible routes	New route, reason, approver and ETA
Vehicle or refrigeration fault	Vehicle vertex/compatibility edge disabled	Qualified fleet alternatives and capacity reserve	Transfer, hold or controlled return record
Temperature excursion	Shipment-state threshold and exposure penalty	Continuous monitoring and response workflow	Raw readings and authorised quality decision
Gateway / provider outage	Communication edge loss or min-cut alarm	Disjoint provider path and store-and-forward	Alert delivery and acknowledgement log
Data tampering / spoofing	Identity, time or path inconsistency	Authenticated devices, signed events and anomaly checks	Incident case and preserved original events
Critical hub failure	High centrality with weak alternatives	Redundant depot, gateway or cross-dock plan	Recovery test and restoration time
Late or missing hand-off	Time-window or receipt vertex not reached	Receiving confirmation and escalation path	Deviation, custody and disposition record

D. Security, Privacy, and Safety Boundaries

The security of the communication layer covers least privilege access, encryption in transit, device identity, time synchronisation and audit logs, as well as tested incident response and backups. Patient identifiers are minimised, routing can be using pseudo anonymous delivery zone authorized contact token. Data is only kept if essential; Only data to location and temperature are kept. Information can be used for safety reasons but public dashboards cannot be used to show sensitive information of the facility, vehicle or patient if it is authorized information and it needs to be shared with the responders.

E. Operational Acceptance

A plan will only be accepted for dispatch after all the hard constraints are met, a human planner accepts the plan, a vehicle is assigned and a monitoring device continual temperature-measurement tools and transport conditions documented for vaccines [16]. The same brand of discipline ought to be found in the product and the jurisdiction.

IX. PROTOTYPE METHODOLOGY

A. Synthetic Test Network

There is one transport vertex for the prototype's central warehouse, three transport vertices for the regional depots and eight transport vertices, which serve as the hospitals/Pharmacy destinations, resulting in 12 transport vertices and 26 directed road edges. The number of package three gateways, one control Service and two receiving channels with simulated and/or measured delay and send probability. Each shipping reporting device is associated with all the routing stops through interlayer mappings.

B. Experimental Conditions

Table 6: Prototype scenarios and controlled comparisons

Scenario	Transportation condition	Communication condition	Purpose
Baseline	Nearest-neighbour routes with static travel times	Single default gateway/provider	Reference service, cost and visibility
Graph-optimised	Composite weights, VRPTW and local improvement	Reliability path with backup	Measure coordinated performance
Traffic disruption	10% of edges delayed or closed after dispatch	Normal links	Test rolling route recovery
Communication outage	Normal roads and demand	Primary gateway or provider removed	Test disjoint path and store-and-forward

C. Procedure

The baseline method and proposed method are both simulated for 30 operating days, and the seeds of demand are the same for both methods, as well as for disturbance. The process will validate input, create both graphs, create initial plans, and add scheduled incidents, simulate rolling recovery, log all events and reconstruct the attempted trajectory. Plans for a sample of activity are moderated by an independent moderator who will ensure that they satisfy capacity, time window, product, route/communication requirements. Random seed, solver settings and data versions are preserved in order to allow for the repetition of the comparison.

Table 7: Evaluation metrics and acceptance rules

Dimension	Measure	Acceptance rule
Service	On-time deliveries and priority-window violations	No critical delivery outside its window without authorised escalation
Efficiency	Distance, travel time, vehicle hours and route cost	Improvement without lower safety-gate compliance
Product integrity	Excursions, exposure duration and missing readings	Zero unreported excursion; every gap classified
Communication	Availability, alert latency and acknowledgement	≥99% target availability in the synthetic scenario

D. Implementation Plan

Table 8: Week mini-project plan

Stage	Weeks	Main activity	Completion evidence
1. Scope	1	Products, sites, roles, constraints and risk boundary	Approved specification and data dictionary
2. Data	2	Road, order, fleet, sensor and event preparation	Validated synthetic dataset
3. Model	3	Graph schema, weights, constraints and baselines	Tested model and unit cases
4. Solver	4–5	Path, routing, resilience and re-optimisation logic	Reproducible prototype

X. ILLUSTRATIVE RESULTS AND ANALYSIS

A. Simulated Comparison

The data provided in figure 3 and table 9 are synthetic and is not field and clinic data. The reduced scenarios are: Graph optimised scenario: 535 km of travel distance, and 4 late deliveries, as compared to 620 km of travel distance, and 11 late deliveries for the "as is" scenario. Risky paths/early recovery due to events lower the temperature, to 2. The second communication path enhances availability of the communication 99.3% as compared to 96.2%. Median incident time is reduced by half using re-route time (from 28 minutes to 11 minutes). The values come at the command and instruction of the proposed analysis and should not be taken as benefits.

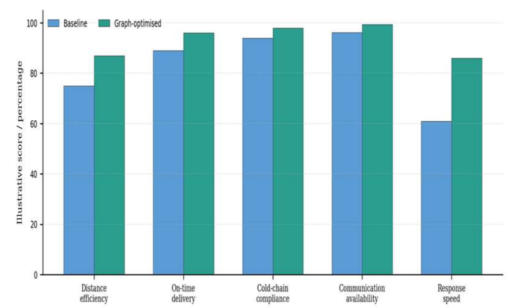

Figure 3: Illustrative simulated comparison; values are not operational findings.

Table 9: Illustrative simulated performance for 30 operating days

Metric	Baseline	Graph-optimised	Illustrative change
Total travel distance	620 km	535 km	−13.7%
Late deliveries	11	4	−63.6%
Temperature excursions	6	2	−66.7%
Communication availability	96.2%	99.3%	+3.1 percentage points
Median incident re-route time	28 min	11 min	−60.7%

Metric	Baseline	Graph-optimised	Illustrative change
Mandatory traceability fields complete	92%	100%	+8 percentage points

B. Sensitivity and Interpretation

If the distance saved is small / narrow windows then the savings are decreased, and the same applies for a fleet with little distance. Priority service has a higher lateness / risk weight that might cause a further increase in distances. The availability of communication relies heavily on using the same provider, power source or gateway for alternative communication paths and when there is a shared infrastructure, the graph does not provide true independence. Thus reporting as a profile (one measure, rather than one score) is appropriate.

XI. DISCUSSION, LIMITATIONS, AND FUTURE SCOPE

A shared goal with regards to drug movement, and a shared set of critical data that is needed to manage drug movement. Graph theory visualizes the route of the transaction, the choke points & hubs and what can be recovered. This method is particularly effective for a slightly longer trip, in which the risk of exposure is minimized, when there is an adequate receiving vehicle, is an open receiving window, and the monitoring is more likely to be accurate. It also highlights safety requirements that are 'hard' requirements and firm efficiency requirements.

There are limitations on the prototype to the quantity of synthetic data available, assumptions of independence and static product rules. Accuracies of travel times and exposures to temperatures can be wrong, as can be the chances of communications. There are workload and access inequities because of the route choices and there can be missing or biased sensor readings. The model is not used to identify medical need or an alternative to the medicine or to decide whether it will be useful to have a child exposed to a medicine. Validation for future operational data, digital twins, stochastic demand, electric and drone modes (where legal), privacy preserving analytics, controlled field testing with pharmacists, drivers and receiving sites.

XII. CONCLUSION

The mini project was done on Graph Theory which was Optimisation of Drug Delivery Transportation & Communication Network. In the proposed Multi-layer graph the concepts of warehouses, depots and care sites as well as the sensors, gateways and receiving systems are linked. Efficient and resilient planning is enabled through the use of weighted paths, capacitated routing, time windows, k-path redundancy, min-cut analysis and rolling updates. Within these limits, the performance of the framework is optimised respect to distances, time, cost, emissions and communication without fixing additional parameters (mandatory requirements of the product). It is helpful as it can provide an overview of the path travelled from the warehouse release to controlled receipt - path taken and path monitored, plus the trade-offs, exceptions and decisions.

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