Drone delivery systems: A comparative analysis in last-mile distribution

MIT MEGACITY LOGISTICS LAB

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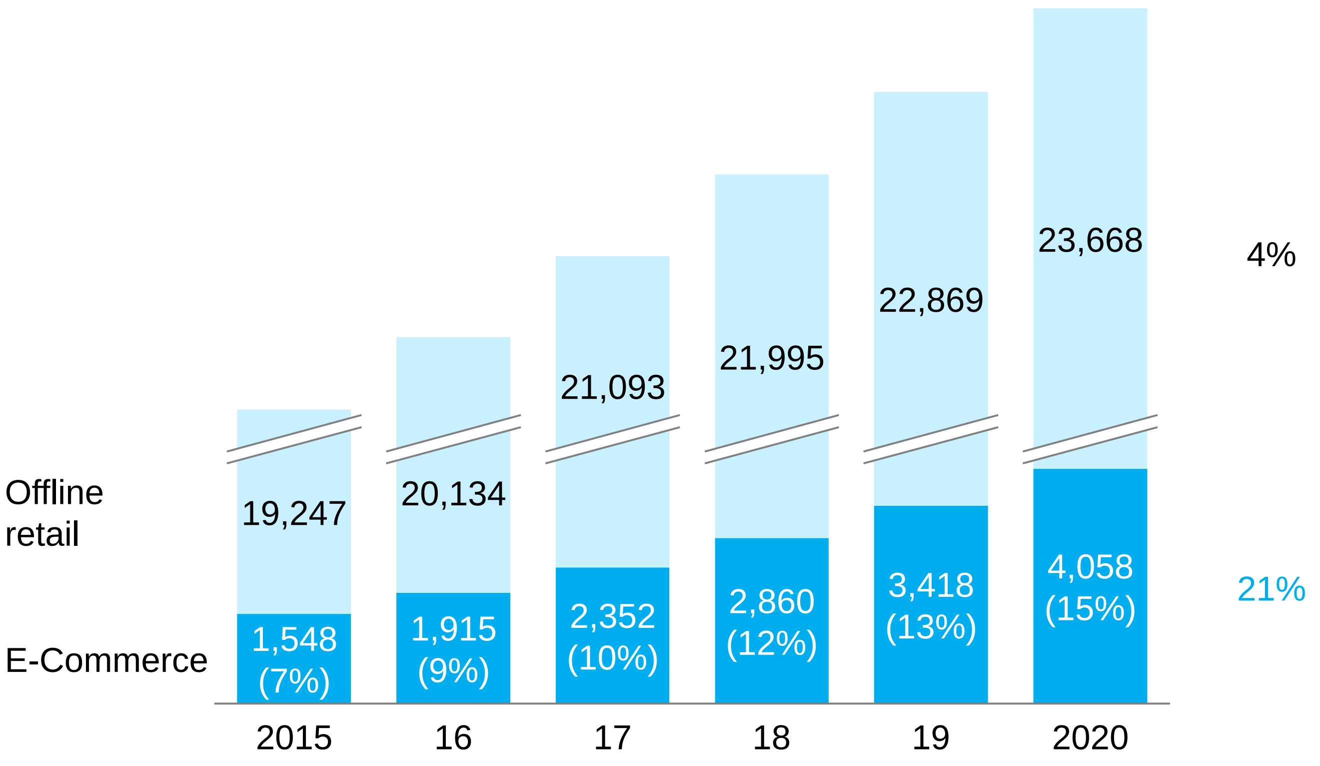
- **Motivation and Background**
- Methodology and Solution
- Analysis and Results

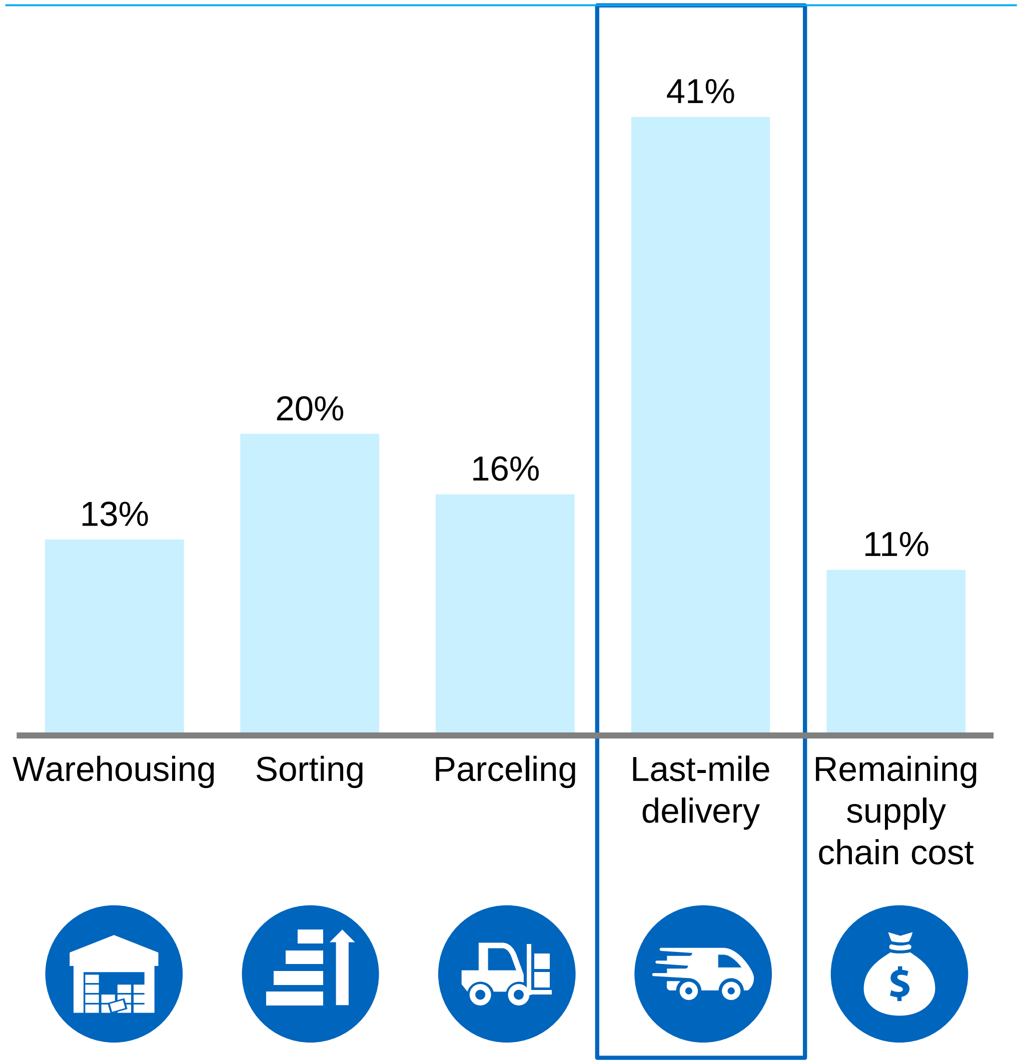
E-commerce continues to outgrow offline retail revenue, fueling global parcel distribution particularly in last-mile delivery

Worldwide retail revenues, 2015-20E
USD billions

CAGR
2015-20



Supply chain cost breakdown
%



Growing e-commerce business fuels global parcel growth
Last-mile delivery shipping volume grows proportionally to e-commerce growth

SOURCE: eMarketer – Worldwide Retail Ecommerce, Capgemini Research Institute, Last-mile delivery executive survey, Oct-Nov 2018, N = 500 executives

Customers service level expectations for last-mile delivery are rising while most of organizations are not ready

	Standard delivery	Next-day delivery	Same-day delivery	Instant delivery
Typical delivery time	2- 5 days	1 day guaranteed	Same day	Within 2-3 hours guaranteed
Expected market growth	↗	↗	↑	↑
% consumers think this delivery speed can increase loyalty	30%	53%	61%	65%
% organizations offering this delivery option	95%	95%	80%	19%

SOURCE: MIT Megacity Logistic Lab research

With the latest technological advancement, drone has emerged as an innovative and viable business solution for commercial last-mile distribution

Current phase

Drone technology driven by military R&D

Drone technology has been **researched and tested for military applications since the 1930's**

Military era
(1930’s - 2000)

Commercial players advance drone technology

With significant cost decreases, drones become **accessible to everyone, creating new commercial drone markets**

Commercial era
(2000 - 2015)

Drone technology takes off

Drones emerge as **innovative and viable business solutions** (e.g. monitoring construction, inspecting turbine blades, surveying fields of crops and **last-mile delivery**)

Near future
(2015- 2030)

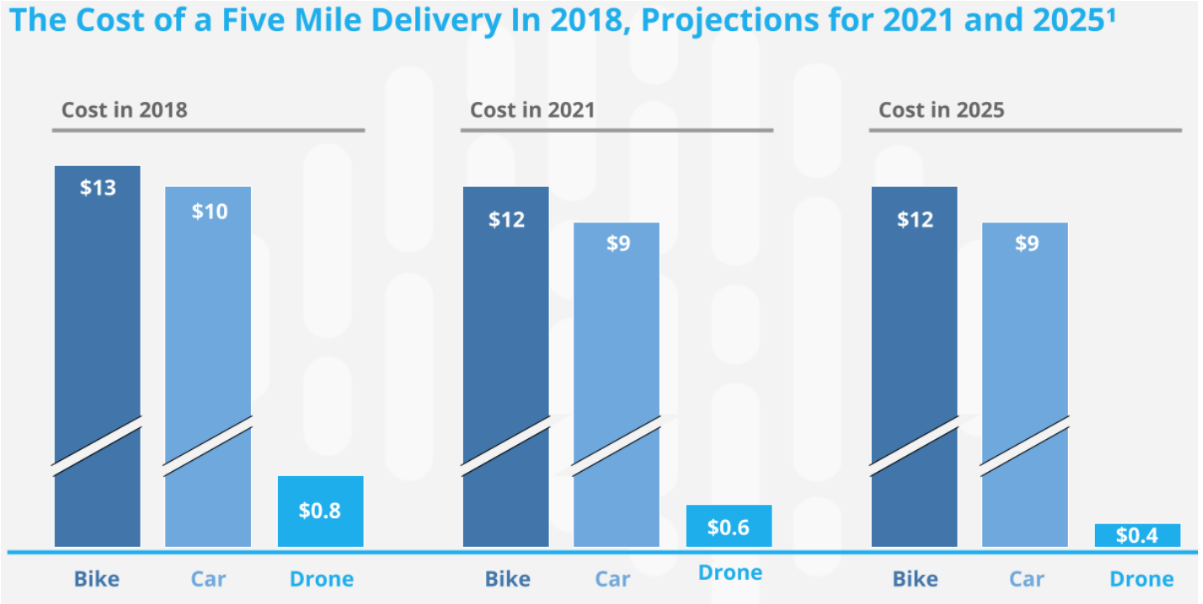
Drone technology fully established

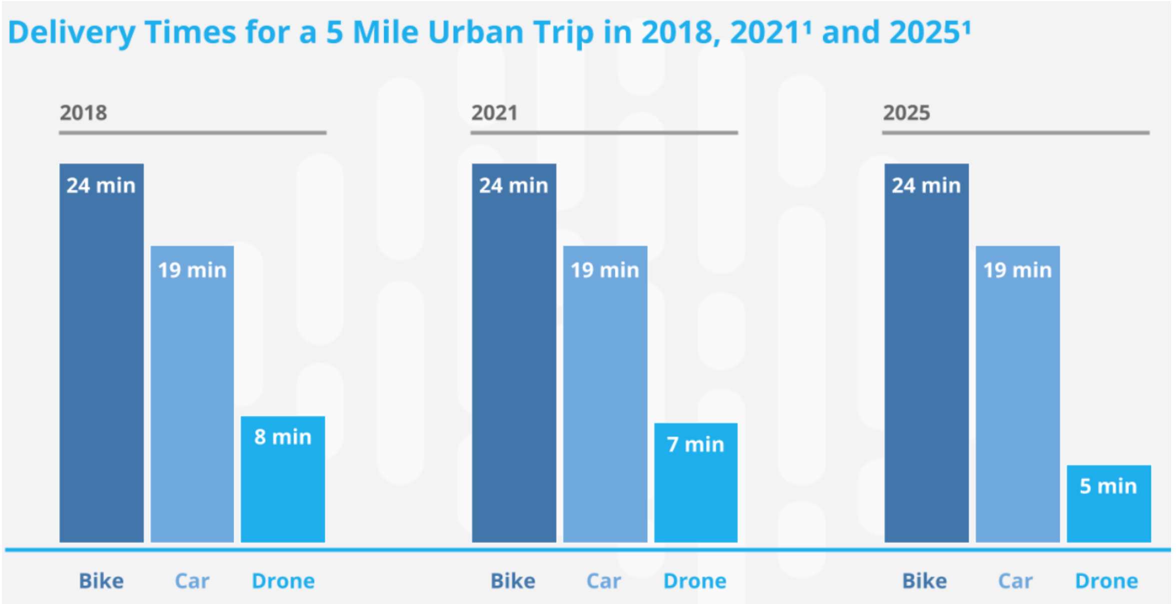
Drones part of daily life and **fully established in people transport, freight traffic,** and other commercial use cases

Far future
(2030+)

SOURCE: Press search: A brief history of drones – Imperial war museum (https://www.iwm.org.uk/history/a-brief-history-of-drones)

Drone will write the future of last-mile delivery: faster and cheaper





SOURCE: NewtonX research (https://www.newtonx.com/insights/2018/03/26/drone-delivery/)

Over the past 5 years, major logistic and e-commerce companies have been testing drones as last-mile delivery system

Country	Company	Drones provider	Description	Timeline
	DHL	DHL	Parcelcopter delivered < 1 kilogram medicine	2013 Dec
	Alibaba.com	YTO 圆通速递 YTO EXPRESS	Alibaba partners with Shanghai YTO Express to deliver tea to 450 customers around select cities in China	2015 Feb
	SF	XAIRCRAFT	SF Express provides delivery services with Xaircraft drones in China	2015 Mar
	FPS	droneflight	FPS distribution completed first commercial delivery using UAV in Sheffield	2015 Mar
	Rakuten	ACSL	Rakuten delivers golf balls, sweets and drinks at the golf course in Chiba	2016 Apr
	Flirtey anything anytime anywhere	Flirtey anything anytime anywhere	Domino delivers world's first ever pizza by drone in New Zealand	2016 Nov
	JD.COM 京东	JD.COM 京东	JD has launched four drone bases in remote parts of Beijing, Jiangsu, Shaanxi and Sichuan, making it easier for local villagers to tap into China's largest sales festival	2016 Nov
	amazon	amazon	Amazon made its first drone delivery in UK	2016 Dec
	aha	FLYTREX	Iceland largest ecommerce website AHA launched drones in partnership with Flytrex	2017 Aug
	Rakuten	Rakuten	Rakuten provices drone delivery service in Minamisoma city	2017 Oct

Google

FAA gives approval to Google's Wing for Drone Deliveries in U.S

2019 Apr

SOURCE: Press search (DHL, Amazon, Alibaba, Bloomberg, JD, Domino, Flytrex, Rakuten), Deutsche Bank analysis

- Motivation and Background
- **Methodology and Solution**
- Analysis and Results

There are various operating models for a drone-based last-mile delivery system, from pure drone delivery to unsynchronized truck-drone delivery system

DRONE DELIVERY SYSTEMS:

A comparative analysis in last-mile distribution

Customer location
Depot
Truck route
Truck
Drone route
Drone area of reach
Drone

MODEL 1

Pure drone delivery system

MODEL 2

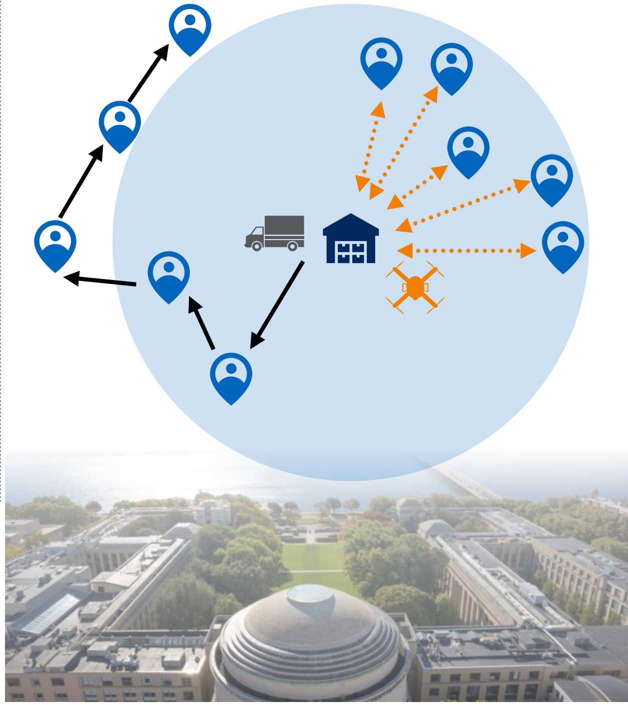
Drone-inner/Truck-outer

MODEL 3

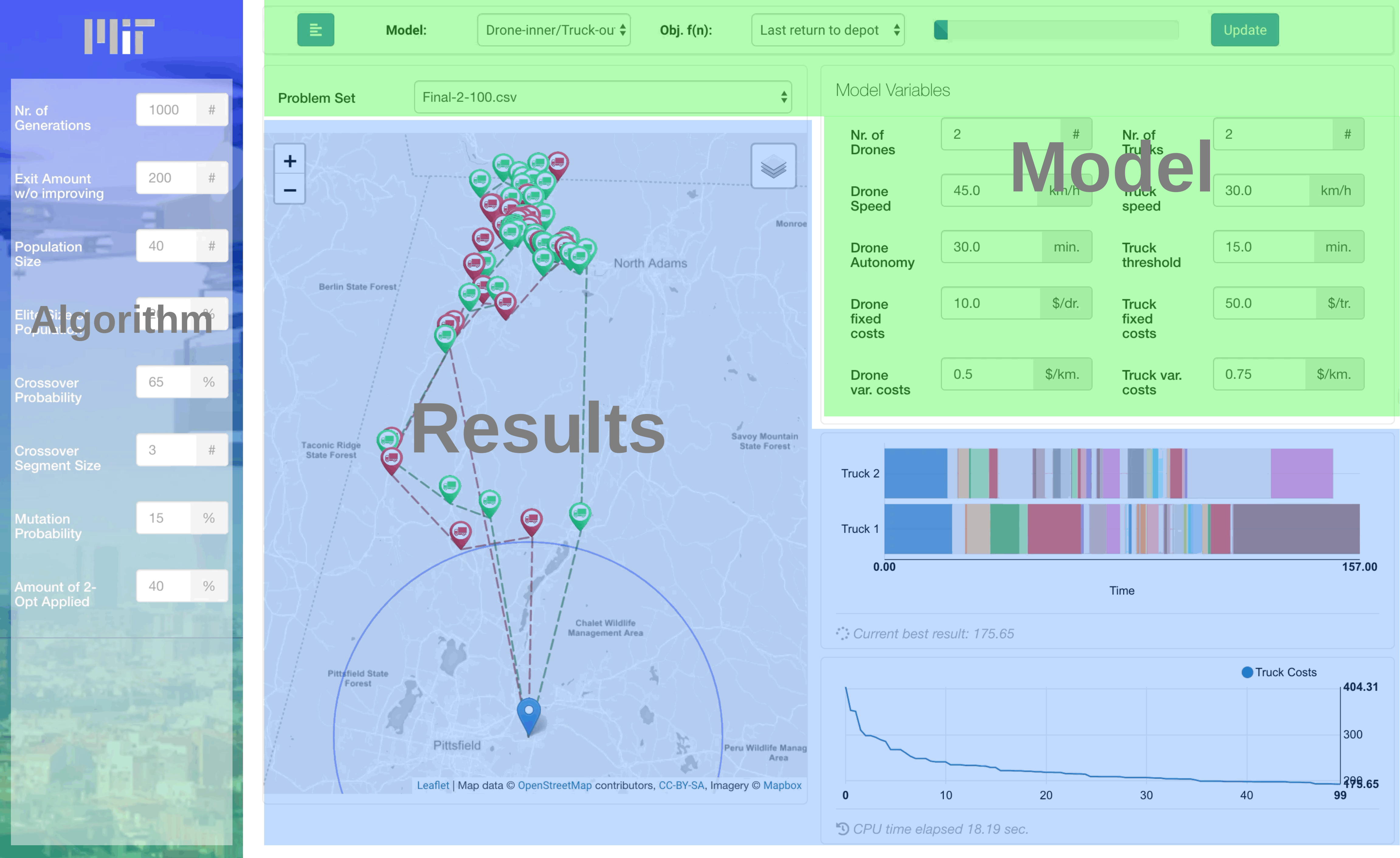
Truck-inner/Drone-outer

MODEL 4

Shared Truck-Drone



Our research evaluates the optimal design and operational performance of different drone delivery models


Algorithm
Model
Results
Model:
Drone-inner/Truck-ou
Obj. f(n):
Last return to depot
Update
Problem Set
Final-2-100.csv
Model Variables
Nr. of Drones
2
Nr. of Trucks
2
Drone Speed
45.0
km/h
Truck speed
30.0
km/h
Drone Autonomy
30.0
min.
Truck threshold
15.0
min.
Drone fixed costs
10.0
$/dr.
Truck fixed costs
50.0
$/tr.
Drone var. costs
0.5
$/km.
Truck var. costs
0.75
$/km.
Nr. of Generations
1000
Exit Amount w/o improving
200
Population Size
40
Crossover Probability
65
%
Crossover Segment Size
3
Mutation Probability
15
%
Amount of 2-Opt Applied
40
%
North Adams
Monroe
Berlin State Forest
Taconic Ridge State Forest
Savoy Mountain State Forest
Chalet Wildlife Management Area
Pittsfield State Forest
Pittsfield
Peru Wildlife Manag Area
Leaflet | Map data © OpenStreetMap contributors, CC-BY-SA, Imagery © Mapbox
Truck 2
Truck 1
0.00
157.00
Time
Current best result: 175.65
Truck Costs
404.31
300
175.65
0
10
20
30
40
99
CPU time elapsed 18.19 sec.

Nr. of Generations

800 **1000** 1200

Exit Condition

100 **200** 300

Population Size

40 **60** 80

Elite Size of Population

20% 40%

Crossover Probability

50% **65%** 80%

Crossover Segment

1 2 **3**

Mutation Probability

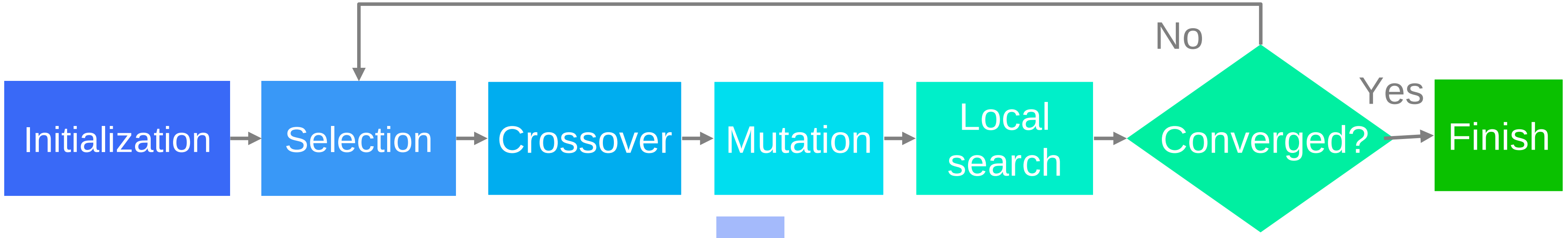
10% **15%** 20%

Amount of 2-Opt

40% **50%** 60%

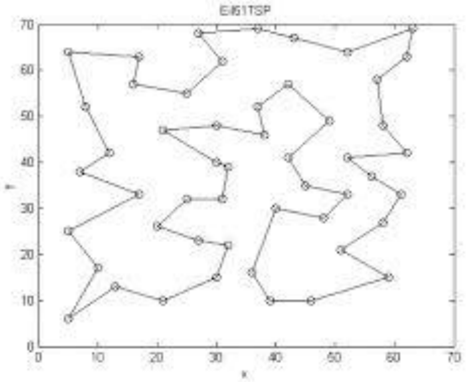
Algorithm Details

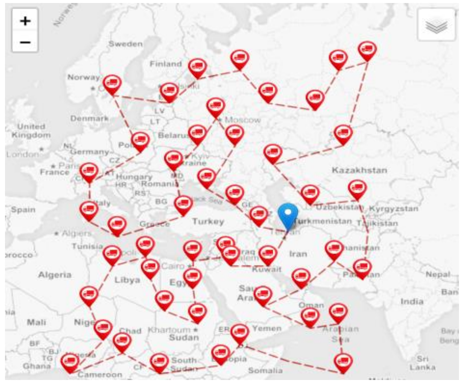
- Developed a variant of the Genetic Algorithm called **Memetic** inspired by evolution



- Fine tuning of algorithm by running multiple sensitivity analyses in order to find the optimal set of parameters to achieve optimal results

- Validated performance against standard academic benchmarks
- Our best solution of **eil51** (*Christofides 1969*) within **3.7%** of best tour time





Model variables

- Three objective functions are considered to minimize different goals:

Last return to depot

Total fleet cost

Total waiting time

- Operational parameters can be adjusted to simulate different conditions:

- Nr. of Drones
- Drone Speed
- Drone Autonomy
- Drone fixed costs
- Drone variable costs

- Nr. of Trucks
- Truck speed
- Truck threshold
- Truck fixed costs
- Truck variable costs

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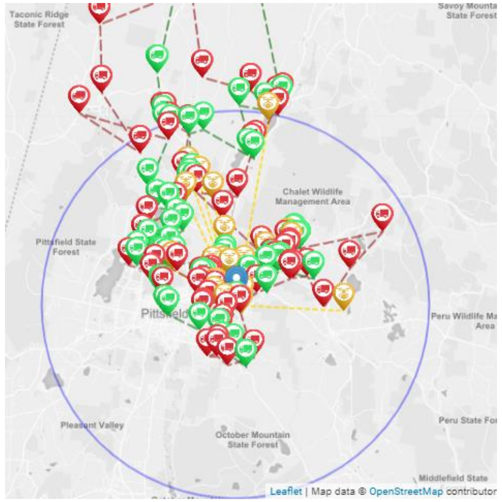
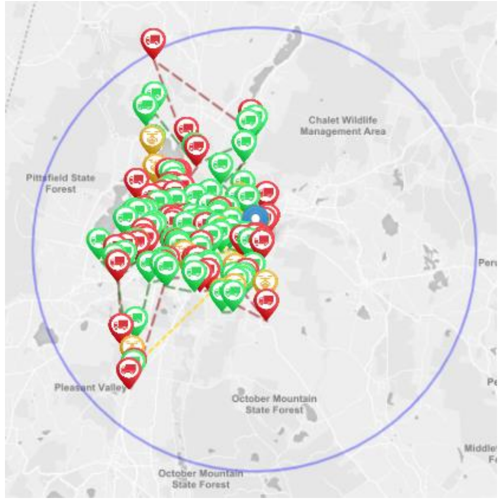
Analysis: Impact of adding a single drone to pure-truck delivery system

Problem instance

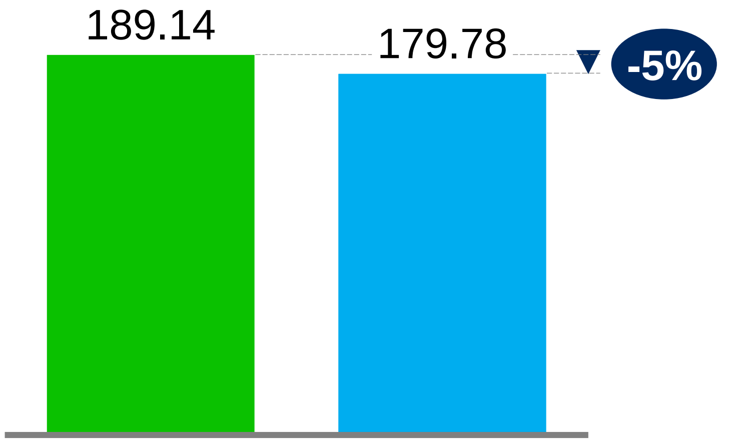
Problem instance 3 (150 customers – some are outside drone range)

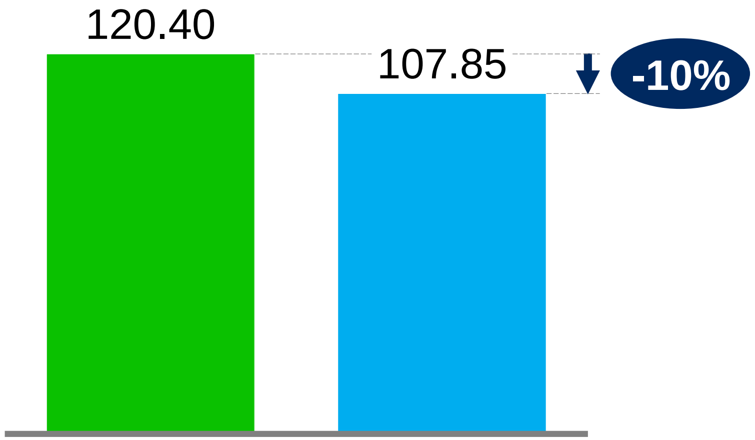


Problem instance 4 (150 customers within drone range)

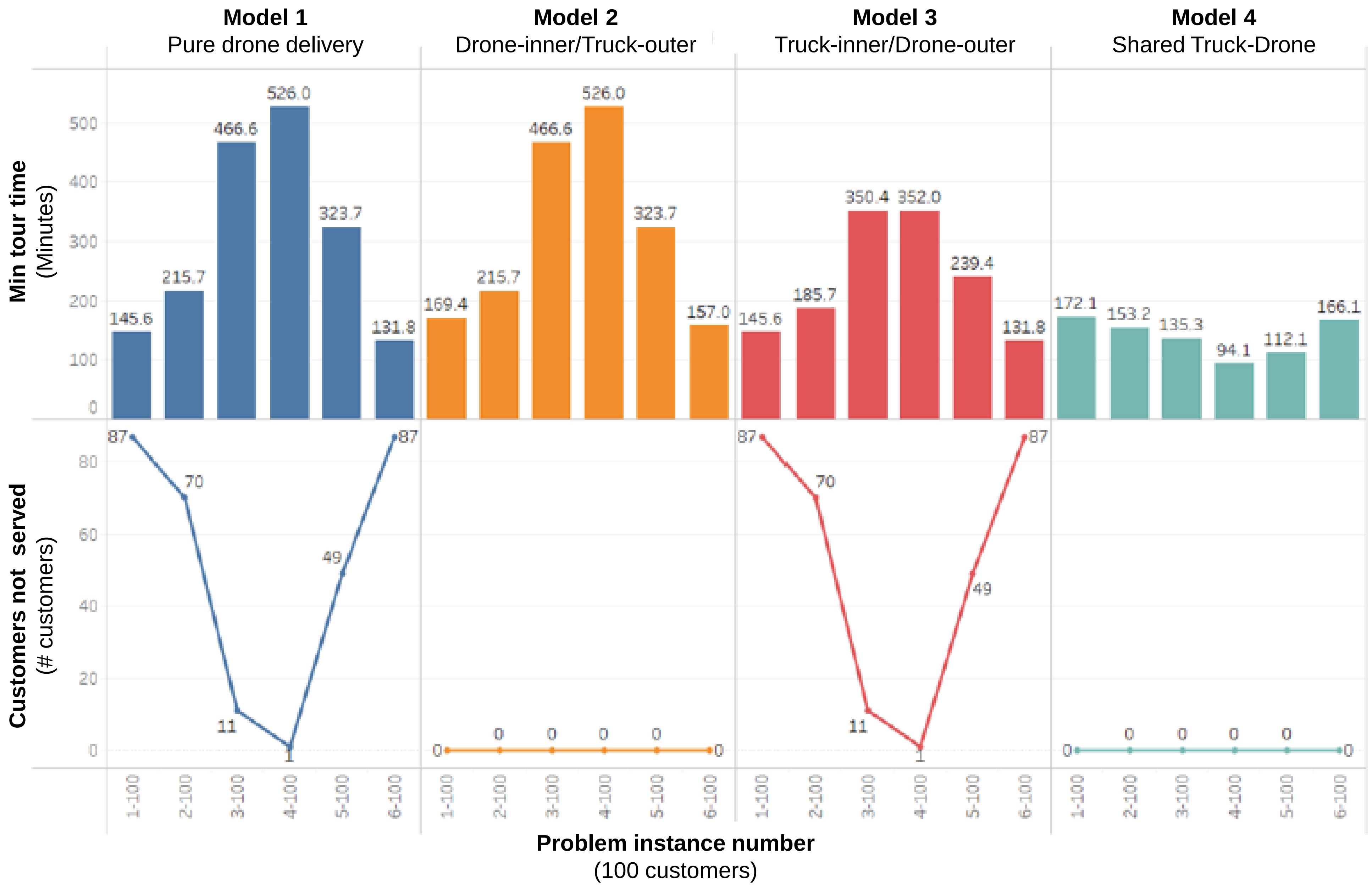


Minimum tour time, Minutes





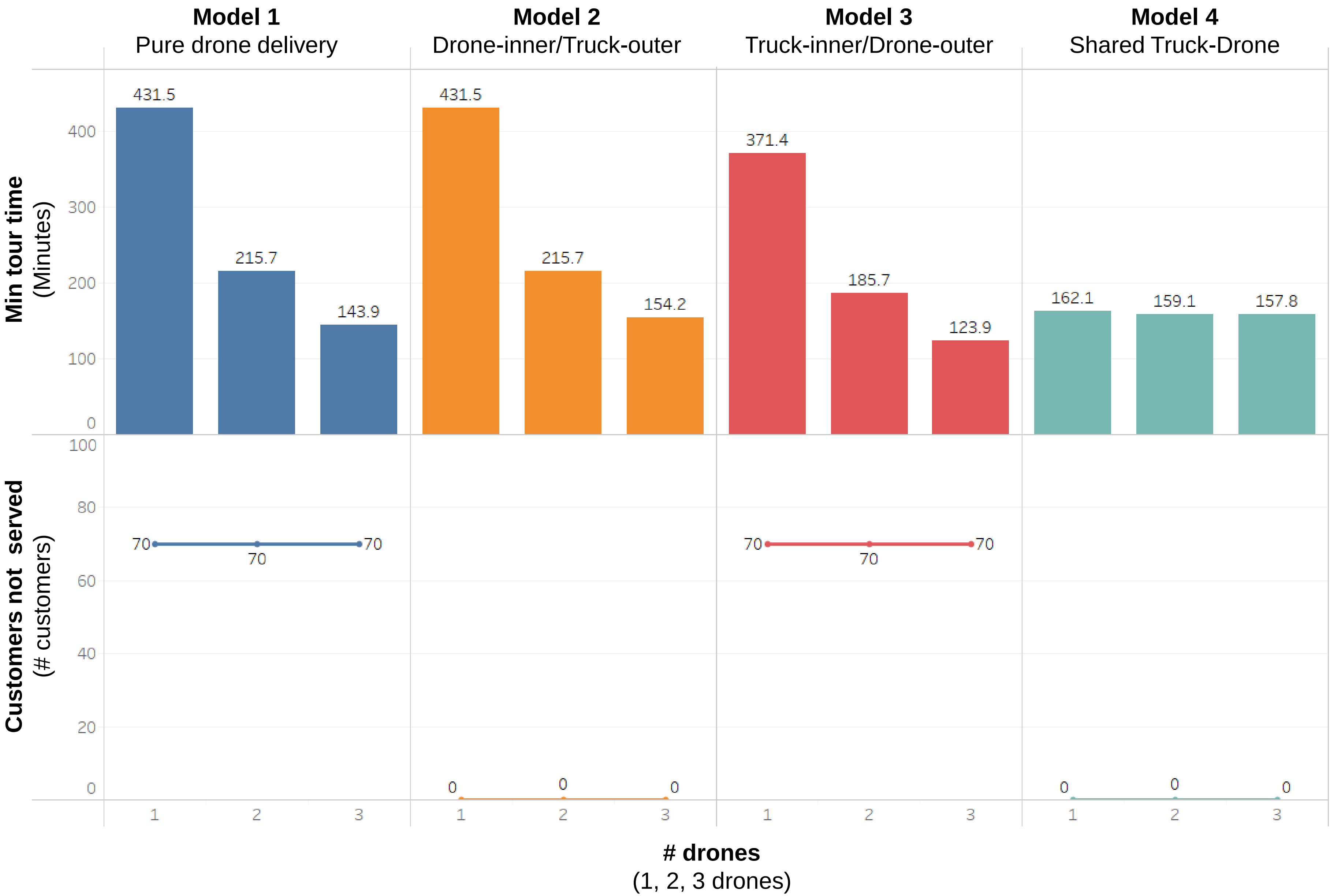
Analysis: Drone delivery model performance



Model 4 (shared truck-drone model) performs superior to other three models:

- Providing **100% coverage to all customers**
- **Reducing minimum tour time** as high as 80%

Analysis: Impact of operating parameters (# drones)



Increasing number of drones has **positive impacts** across all drone delivery models:

- Increasing **drones from 1 to 2 reduces minimum tour time** by ~50% for Model 1, 2 and 3
- Further **increasing number of drones to 3 reduces time by ~30% for Model 1, 2 and 3**
- **Model 4 also yielded positive impact by ~4%**

Conclusions

		Insights
Research insights	**Benefit of drone**	**Adding a drone** to a traditional last-mile delivery system that uses trucks only can **reduce minimum tour time by up to 10%**
	Optimum drone delivery model	**Model 4: shared truck-drone model** — where truck and drone operate the same area of service — **performs superior** to other three models, providing **100% coverage to all customers** and **reducing minimum tour time as high as 80%**
	Operational parameter	**Higher number of drones yields better results** than an increase in the speed or the flight limit (battery life) of the existing drone fleet
Potential future areas of research		Add **vehicle capacity** and **time delivery window** to simulate more realistically Conduct **full cost benefit analysis** by collecting actual fixed and variable costs

Q&A

BACKUP

Motivation / Background

With the latest technological advancement, **drone has emerged as an innovative and viable business solution for commercial last-mile distribution**.

Compared to traditional last-mile distribution with truck, **drone has competitive advantages** such as **lower cost structure** (~80% cost reduction), **reduced delivery time**, **farther reach** in poor infrastructure areas and **less CO2 emission**.

It is estimated that around **86% of packages delivered by e-commerce weigh less than 5 lbs.**, presenting a big opportunity for drone delivery system. Over the past 5 years, **major logistic and e-commerce companies have been testing drones as last-mile delivery system**

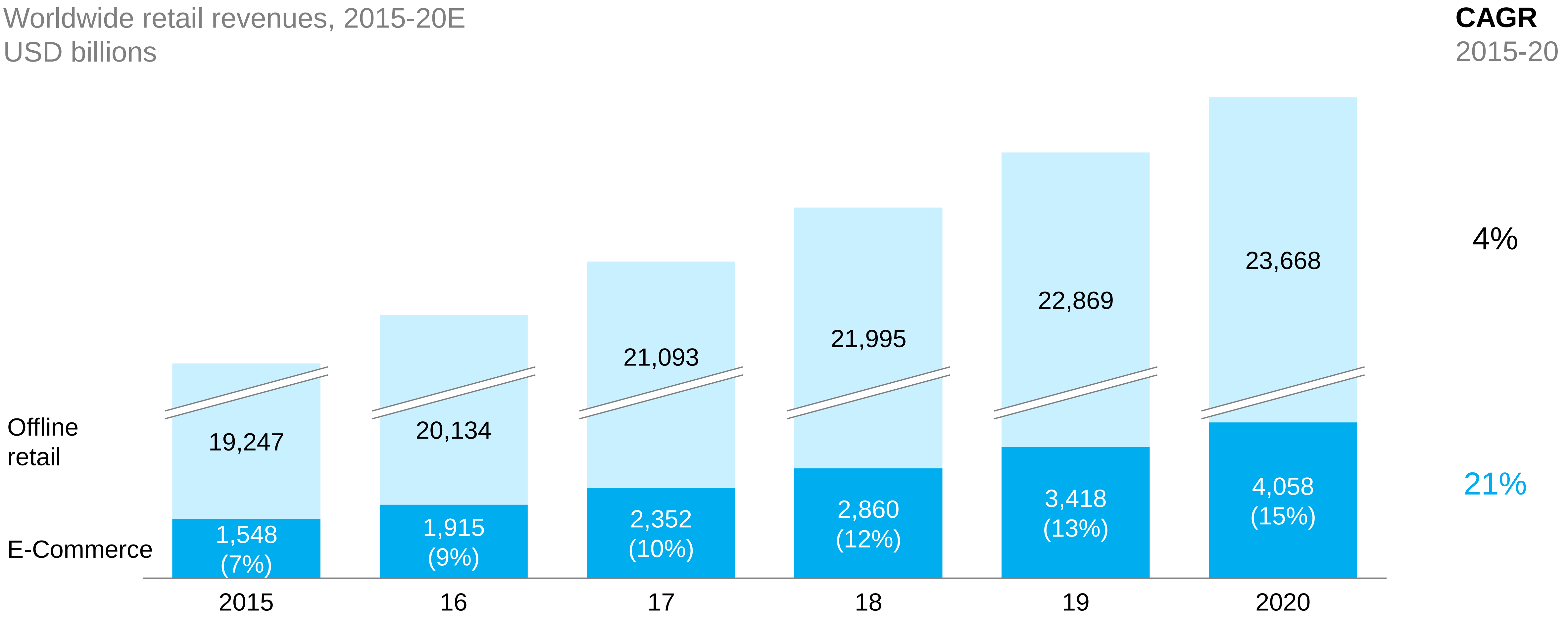
Problem statement

An efficient drone delivery system has to address the classic routing problem (VRP): "**What is the optimal set of routes for a fleet of drones to serve a given set of customers**"

In addition, a drone routing problem needs to consider several specific constraints, such as **operational limit of the drones** (e.g. distance covered, endurance, payload) and unique **technical characteristics of drone delivery** (e.g. one package per time, no pick-up, no night-time operation).

This project will solve for **optimal routes of truck and drones** given drone operational limitation

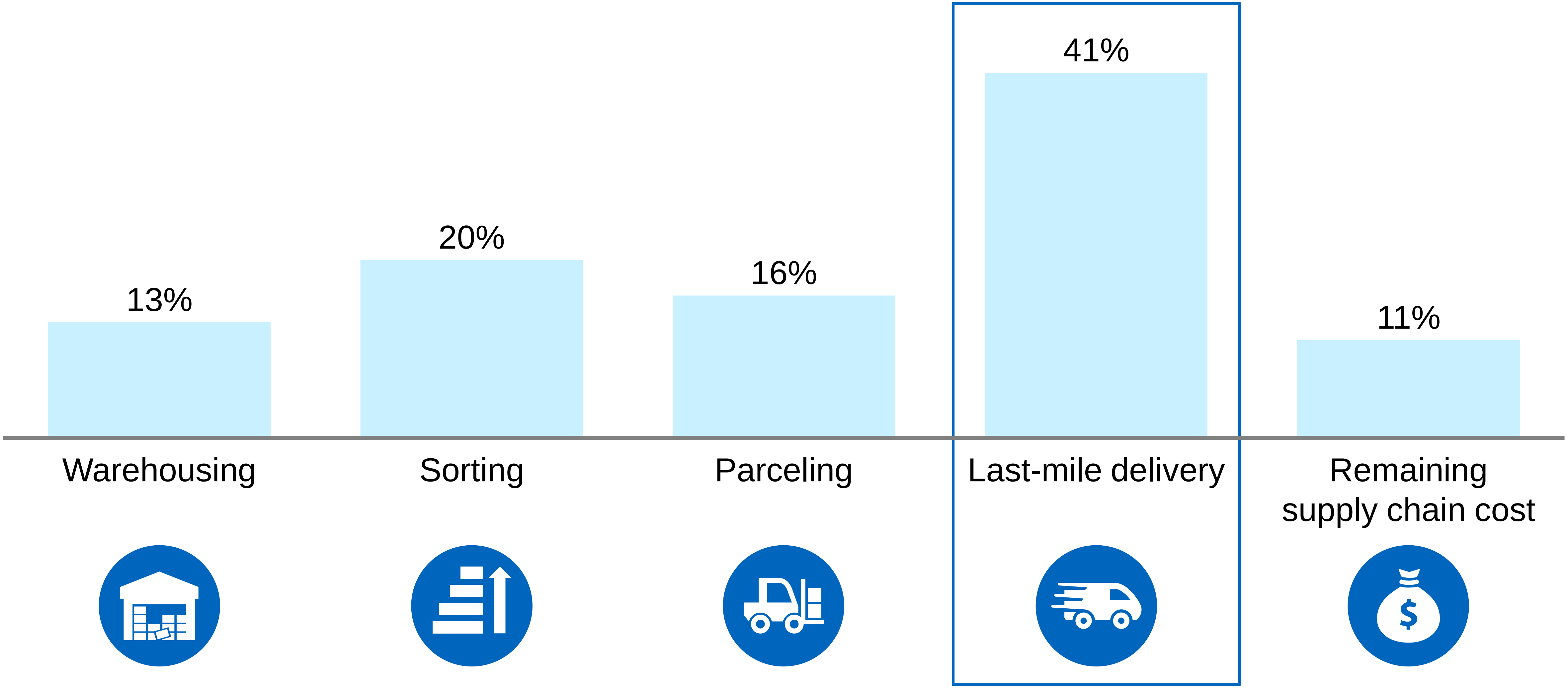
E-commerce continues to outgrow offline retail revenues and will reach ~15% of global retail share until 2020



Growing e-commerce business fuels global parcel growth
Last-mile delivery shipping volume grows proportionally to e-commerce growth

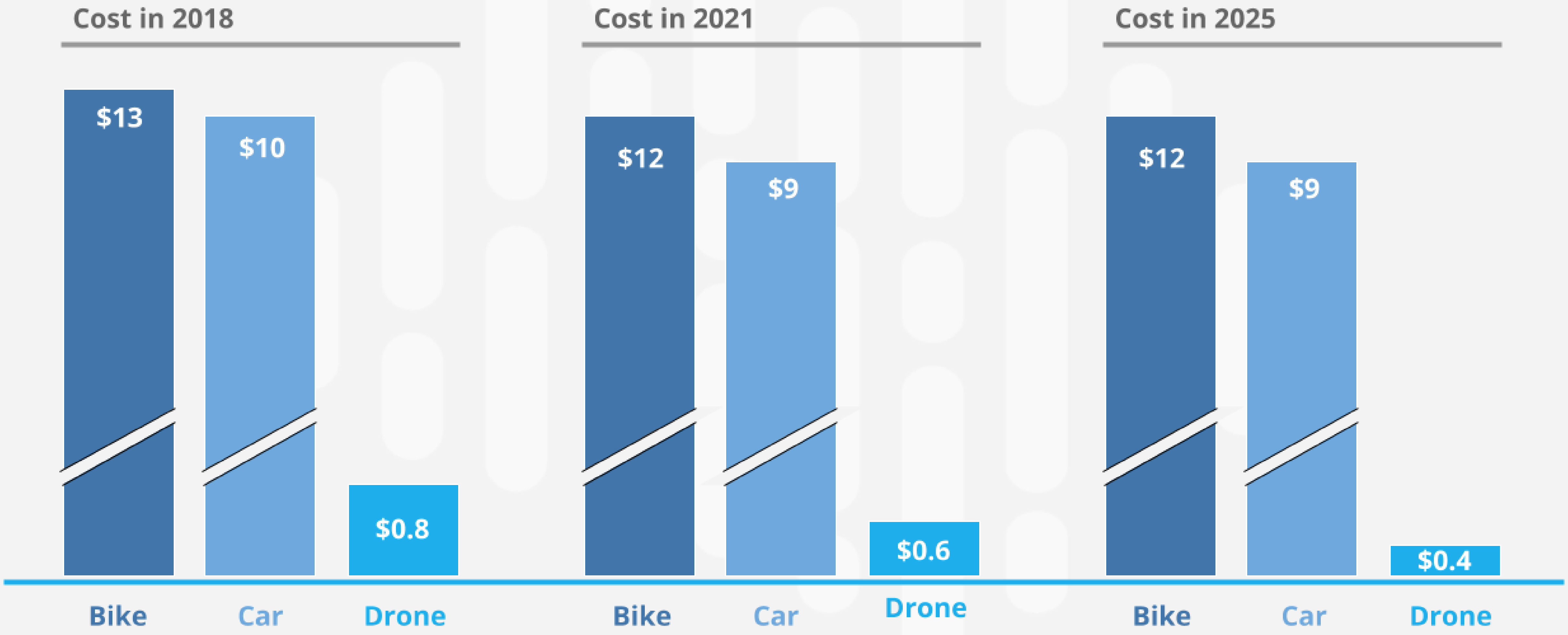
SOURCE: eMarketer – Worldwide Retail Ecommerce (https://www.emarketer.com/Article/Worldwide-Retail-Ecommerce-Sales)

Last-mile delivery is the costliest step in supply chain, accounting more than 40% of the total cost



SOURCE: Capgemini Research Institute, Last-mile delivery executive survey, Oct-Nov 2018, N = 500 executives

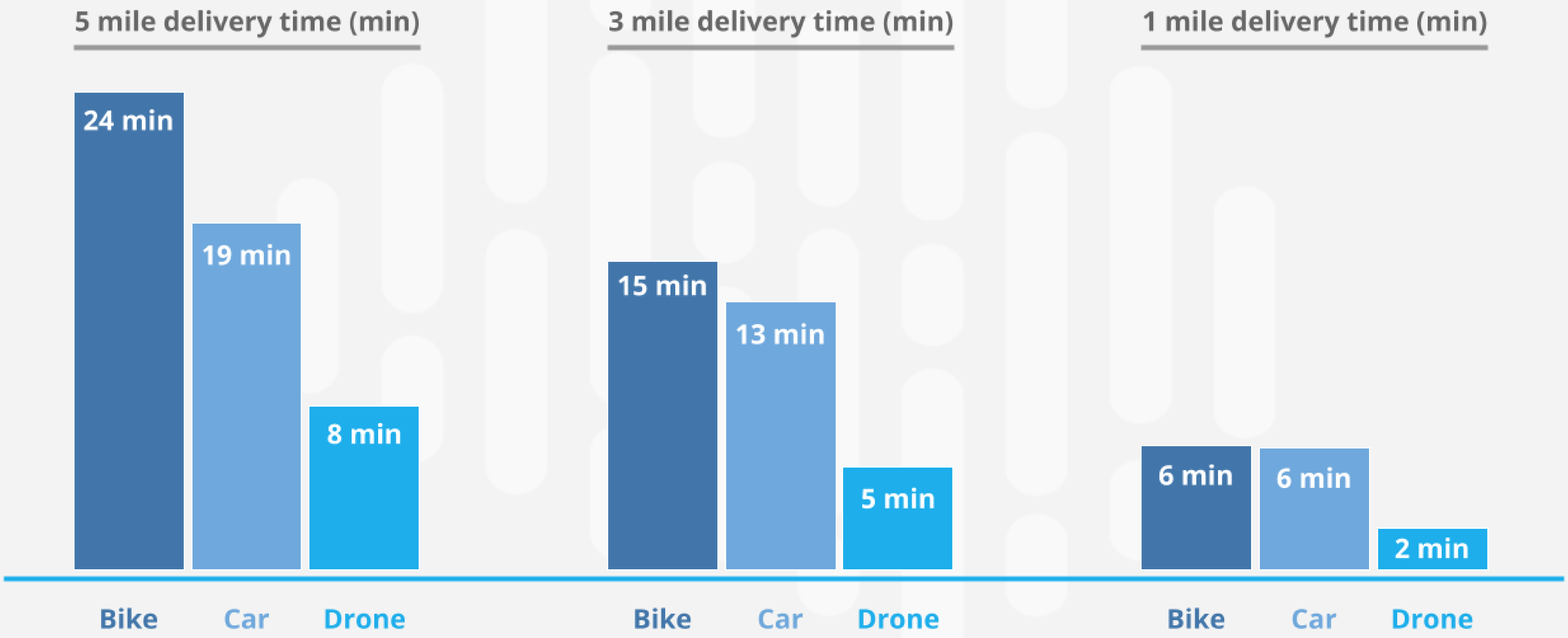
The Cost of a Five Mile Delivery In 2018, Projections for 2021 and 2025[1]



1. Calculation of cost includes salaries, parts, and fuel for all transportation modes, and autonomous drones

NEWTONX ACCESS KNOWLEDGE

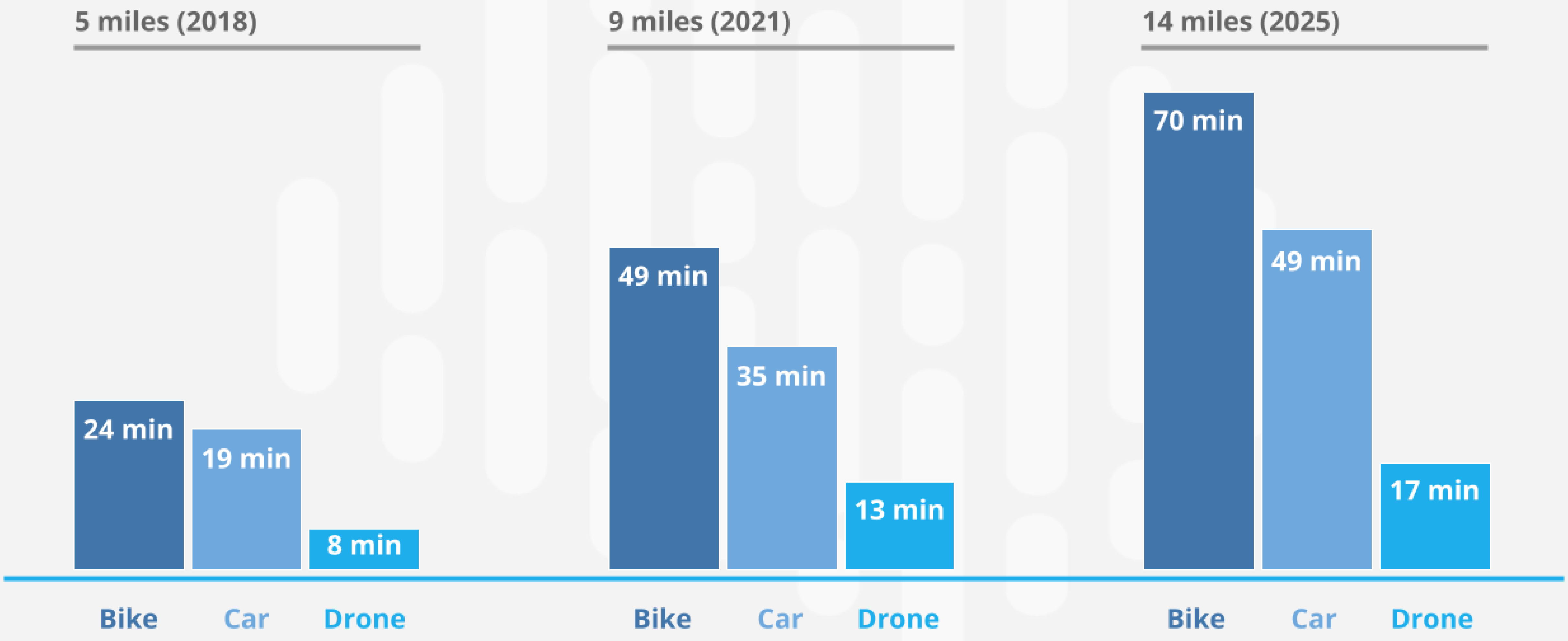
Average delivery time in urban environment[1] - Bike vs. Car vs. Drone



1. *Delivery times provided by NewtonX experts based on 2018 industrial drones specifications*

NEWTONX ACCESS KNOWLEDGE

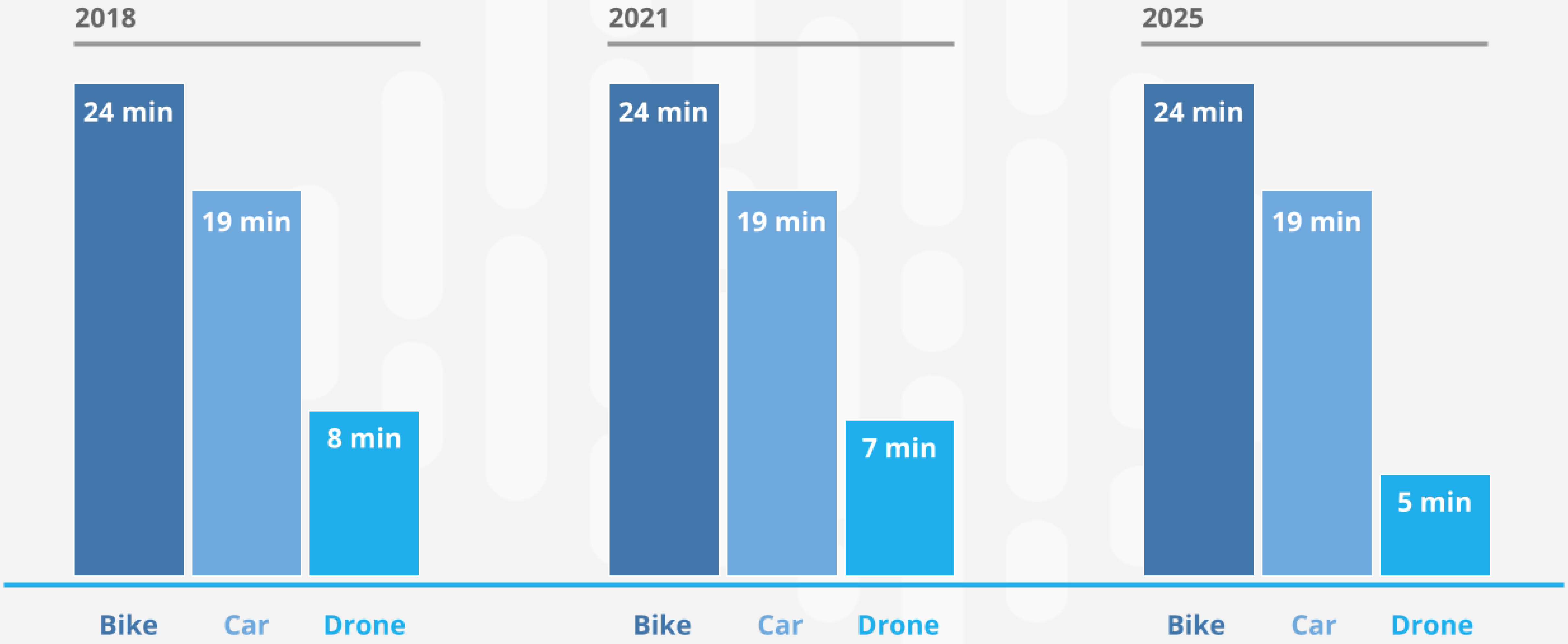
Delivery Time Projections in Urban Environment (2018-2025)



1. Delivery times calculated based on 2018 industrial drones specifications - Forecasts for 2018 and 2025

NEWTONX ACCESS KNOWLEDGE

Delivery Times for a 5 Mile Urban Trip in 2018, 2021[1] and 2025[1]



1. Delivery times calculated based on 2018 industrial drones specifications - Forecasts for 2018 and 2025

NEWTONX
ACCESS KNOWLEDGE

Last-mile complexity – the UPS example

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120

delivery stops per route

annual cost savings of

$50,000,000

**6,689,502,913,449,135,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
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000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000**

possible route sequences

55,000

daily delivery routes

1 mile

average distance reduction

Sources: UPS, Wall Street Journal (2015)

The effects of urbanization create city-specific logistics challenges, depending on the local context

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Urbanization progresses rapidly at a global scale

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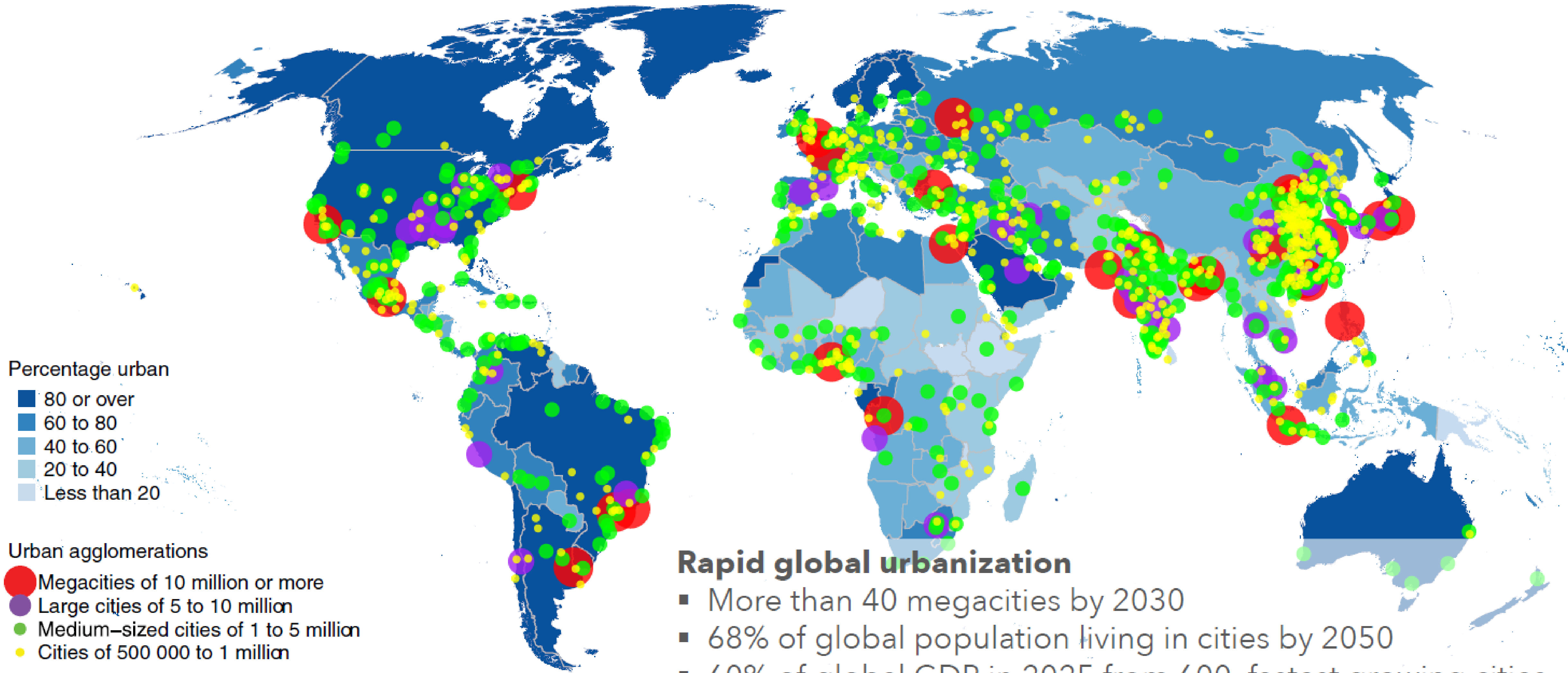

Rapid global urbanization

- More than 40 megacities by 2030
- 68% of global population living in cities by 2050
- 60% of global GDP in 2025 from 600 fastest growing cities

Source: United Nations (2014)

Applications of drones in logistics

Retailers

Postal Services

Healthcare
Emergency Services

Food and Beverages

Drones may become a game changer in last-mile delivery operations

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Need for more efficient last-mile delivery

- Continued boom in e-commerce
- Increased traffic congestion
- Changing customer preferences (same-day delivery, time windows, etc.)

+ Advantages of drone-based delivery

- ✓ Higher / more constant travel speeds
- ✓ Three dimensional travel-space
- ✓ Not tied to a physical road infrastructure
  - access to rural areas, islands, valleys, areas affected by disasters, etc.
  - not impacted by traffic / congestion

– Limitations of drones

- ✓ Travel range constraint
  - due to limited battery capacity
  - due to regulation ("line of sight")
- ✓ Capacity constraint (number, size and weight)

Mathematical formulation

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2- Unsynchronized truck-drone model **with shared area:**

$$\mathit{Minimize} \quad w$$

Subject to:

1: $$w \geq \sum_{i \in C_0} \sum_{\substack{j \in C_E \\ i \neq j}} d_{ij} x_{ij},$$

2: $$w \geq \sum_{i \in C_R} (\hat{d}_{0i} + \hat{d}_{i,c+1}) y_{iv}, \qquad \forall v \in V,$$

3: $$\sum_{\substack{i \in C_0 \\ i \neq j}} x_{ij} + \sum_{\substack{v \in V \\ j \in C_R}} y_{jv} = 1, \qquad \forall j \in C,$$

4: $$\sum_{j \in C_E} x_{0j} = 1,$$

5: $$\sum_{i \in C_0} x_{i,c+1} = 1,$$

6: $$\sum_{\substack{i \in C_0 \\ j \neq i}} x_{ij} = \sum_{\substack{g \in C_E \\ g \neq j}} x_{jg}, \qquad \forall j \in C,$$

7: $$u_i - u_j + 1 \leq (c+2)(1 - x_{ij}), \qquad i \in C, \forall j \in \{C_E : j \neq i\},$$

8: $$1 \leq u_i \leq c+2, \qquad \forall i \in C_R, \forall j \in C_E, i \neq j,$$

9: $$x_{ij} \in \{0,1\}, \qquad \forall i \in C, \forall j \in C,,$$

10: $$y_{iv} \in \{0,1\}, \qquad \forall i \in C, \forall v \in V.$$

Minimize completion time

Completion time of truck

Completion time of drones

All customers have to be served

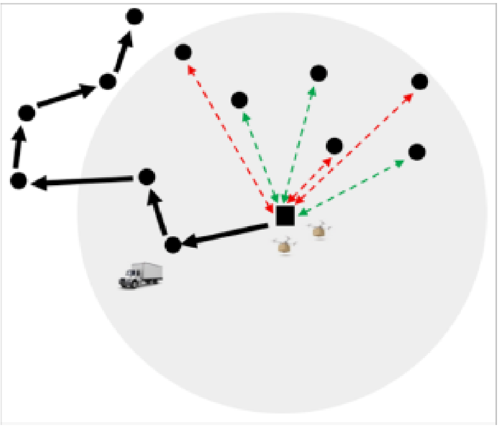
Truck starts from depot

Truck returns to depot

Conservation of flow (truck)

Sub-tour elimination (truck)

Variable type and range



c	Number of customers
C	Set of customers
w	Completion time
x_{ij}	1, if truck travels from node i to node j; 0, o.w.
y_{iv}	1, if customer i is served by drone v; 0, o.w.
u_i	Integer: Position of customer i in truck route

Drones of JD (Chinese e-commerce giant)

M-TC2
Power: Battery
Load weight: 10KG
Reach: 10 km per charge
Maximum speed: 100km/h
Usage: Automatic discharge; high-speed

M-TB1
Power: Battery
Load weight: 5KG
Reach: 10 km per charge
Maximum speed: 72km/h
Usage: 'Short-hop' delivery

M-SC1
Power: Battery
Load weight: 8KG
Reach: 8 km per charge
Maximum speed: 80km/h
Usage: 'Short-hop' delivery

V-FA1
Power: Battery
Load weight: 5KG
Reach: 30 - 50 km per charge
Maximum speed: 90km/h
Usage: High-speed; long-distance delivery

CT-120
Power: Gasoline
Load weight: 15KG
Reach: 30 km per charge
Maximum speed: 54km/h
Usage: Heavy-load; long-endurance

Literature review summary – Parcel and drones trend

Literature title	Source	Insights
Drones mean business	**Deloitte University Press**	▪ Global commercial drone market, the fastest growing segment for UAV, will exceed USD 20bn by 2021 - Goldman Sachs ▪ New FAA regulations have clarified rules for commercial drones, with FAA believing the rules could help lead to as many as 600,000 commercial drones in operation by mid 2017 ▪ DJI accounts for 70% of non-military drone market and its revenue skyrocket from USD 4mn in 2011 to USD1bn in 2015 ▪ Piloting a drone is hard and inefficient. Hence to extract value, navigation software can improve versatility ▪ Walmart expects to have computer vision enabled drones monitoring warehouse inventory by mid 2017, reduce manual inventory process of 30 day into single day
Managing the evolving skies	**Deloitte**	▪ Air Navigation Service Providers (ANSPs) have been the primary source of oversight for safe and secure airplan travel for decades, but how will the flight paths of thousands - possibly millions - of daily unmanned drone flights be managed? Unmanned aircraft system traffic management (UTM) will be needed to manage various stakeholders (Drone operators, Communication system provider, Data service provider, Air navigation service provider) ▪ Currently introduction of UAV aircraft to airspace has been limited to visual line of sight (VLOS) operations. Only handful of countries (Australia, Canada, China, Denmark, NZ, Poland, South Africa, Switzerland and some US states) have taken measures to incorporate UAVs beyond visual line of sight (BVLOS) operation - which includes package and food delivery
An onslaught of new rivals in parcel and express	**BCG**	▪ Parcel and express startup funding has increased 20-fold from USD 0.2bn in 2014 to USD 3.9bn in 2016 ▪ Investment breakdown by value chain: value chain orchestration (34%), end-to-end logistics (32%), last-mile delivery (29%), digital support (5%) ▪ 75% of investment in last 5 years went to China ▪ Amazon is trying to control its own logistic and transportation: operating its won airline fleet, experiments with delivery drones, starting up a logistic as a service offering called Shipping with Amazon
Parcel delivery - The future of last mile	**McKinsey**	▪ Cost of parcel delivery (excluding pickup, line-haul and sorting) is EUR 70 billion, with China, Germany and US accounting >40% of the market ▪ Growth rate in 2015 ranging between 7-10% in mature markets such as Germany and USA, and almost 300% in developing markets such as India ▪ Last mile parce delivery cost is often reaching or exceeding 50% ▪ Trend 1: A growing group of consumers desires faster home delivery, yet most remain highly price sensitive: 70% customers prefer cheapest option of home delivery ▪ Trend 2: Autonomous vehicles including drones will deliver close to 100% of X2C and 80% of all items ▪ Public opinion conering AV including drones has already started to shift - with 60% of consumers indicating they are in favor of or at least indifferent to drone delivery ▪ Drones is cost-competitive in rural areas, at only ~10% above the cost of today's delivery model ▪ Drones could offer a solution for smaller parcels delivery in rural areas - that is extremely costly to offer delivery within a specified time window or on the same day with any kind of driving vehicle due to large distances that need to be covered to be in the right place at the right time ▪ Drone limitation: (1) Limited load of 5 kg. Potential to increase to 15 kg, but 5% of items still weigh more than that (2) Require landing area of 2m2 ▪ Drones will deliver all time window and same day items in rural areas due to far fulfillment center from recipients (e.g. 75% of all recipients in US live in cities less than 50,000 inhabitants)

The theory behind it: Why Genetic algorithm works

Genetic Algorithms can find solutions to highly non-linear or discrete problems by emulating evolutionary mechanisms and making minimal assumptions about the solution

What Genetics does well …	… can be used for optimization
▪ Starts with **population** of individuals	▪ Efficient **parallel** processing
▪ Evolves this population over **many generations** through:	▪ **Sufficient seek time** for the best solution by:
– **Selection:** survival of “elite individuals” to the next generation	– Remembering the **best solution** so far
– **Crossover:** creation of new children from the “fittest parents”	– Using the **best elements** of good solutions
– **Mutation:** random genetic changes	– **Avoiding local optima** and continuing to seek even better solutions

When designing an optimum drone delivery model, we have to solve for classical Vehicle Routing Problem (VRP)

Problem statement

An efficient drone delivery system has to address the classic routing problem (VRP):
"**What is the optimal set of routes for a fleet of drones to serve a given set of customers**"

Literature review

Despite a wealth of knowledge and literature exist for classical vehicle routing problem (VRP), **specific VRP literature for drone delivery systems tends to be limited, especially for combined drones and trucks delivery system**

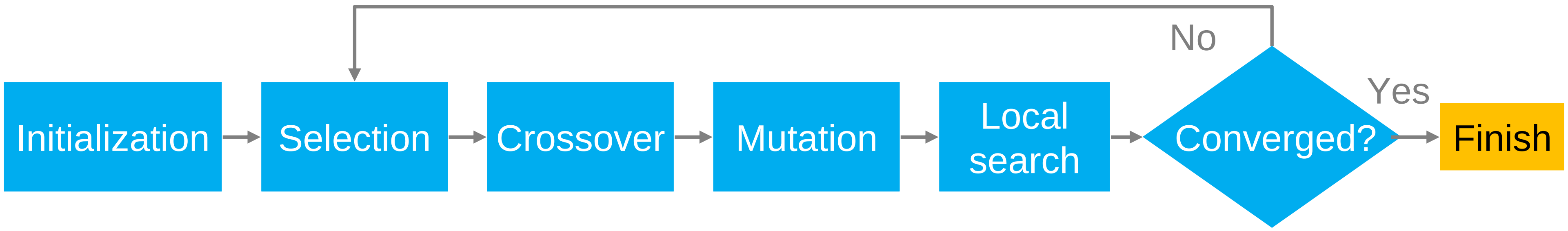
- **Murray C., Chu A. 2015**. *The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery*
- **Kim S., Moon I. 2018**. *Traveling salesman problem with a drone station*
- **Ham A. 2018**. *Integrated scheduling of m-truck, m-drone and m-depot constrained by time-window*

Our methodology

This project will solve for **optimal routes of truck and drones** given drone operational limitation for four different drone delivery systems, from **pure drone delivery system to unsynchronized drones-trucks system in separated and shared area system**.

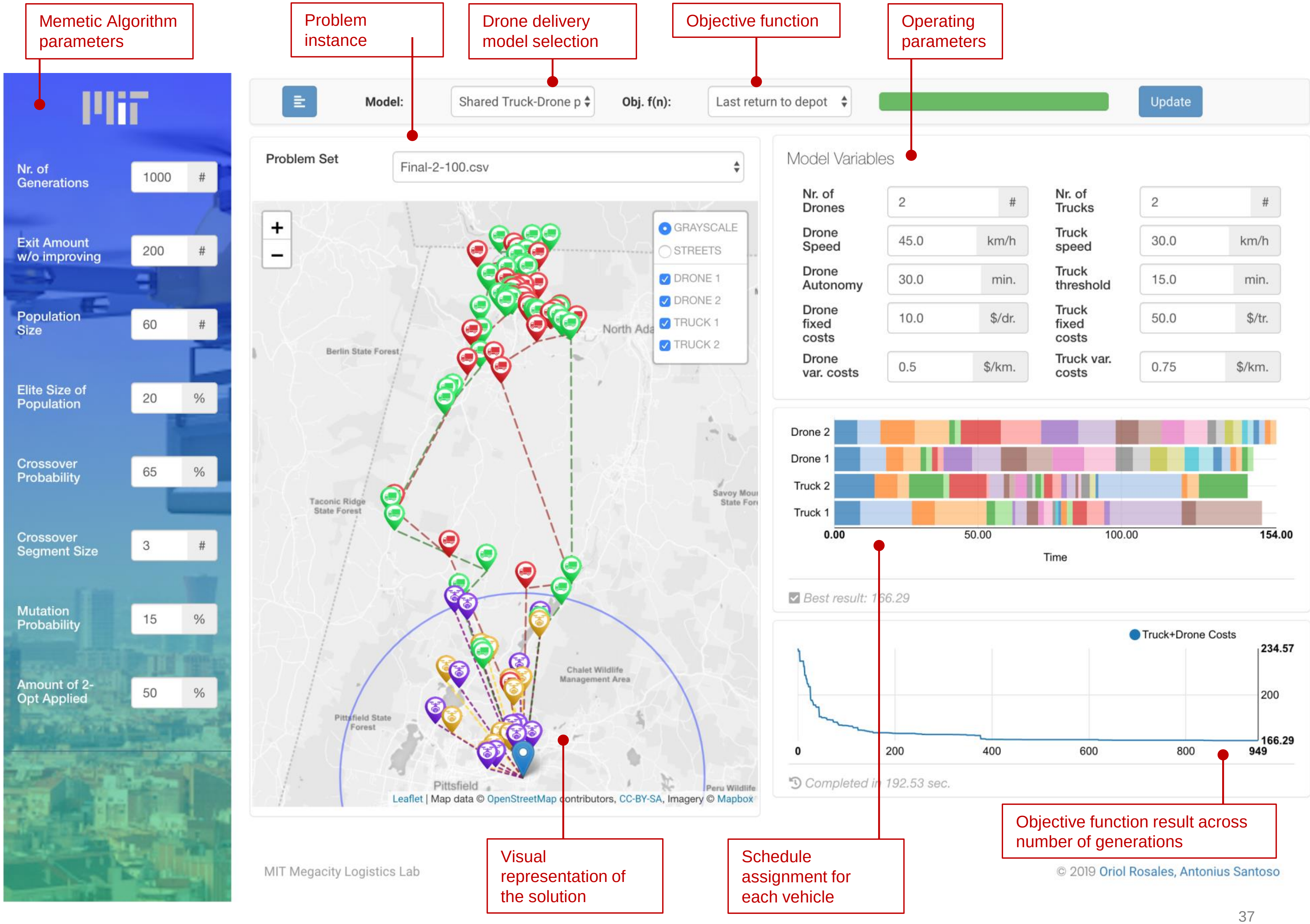
A **Memetic Algorithm** is developed and used to optimize delivery routes of drones and trucks in such systems

Memetic Algorithm flowchart



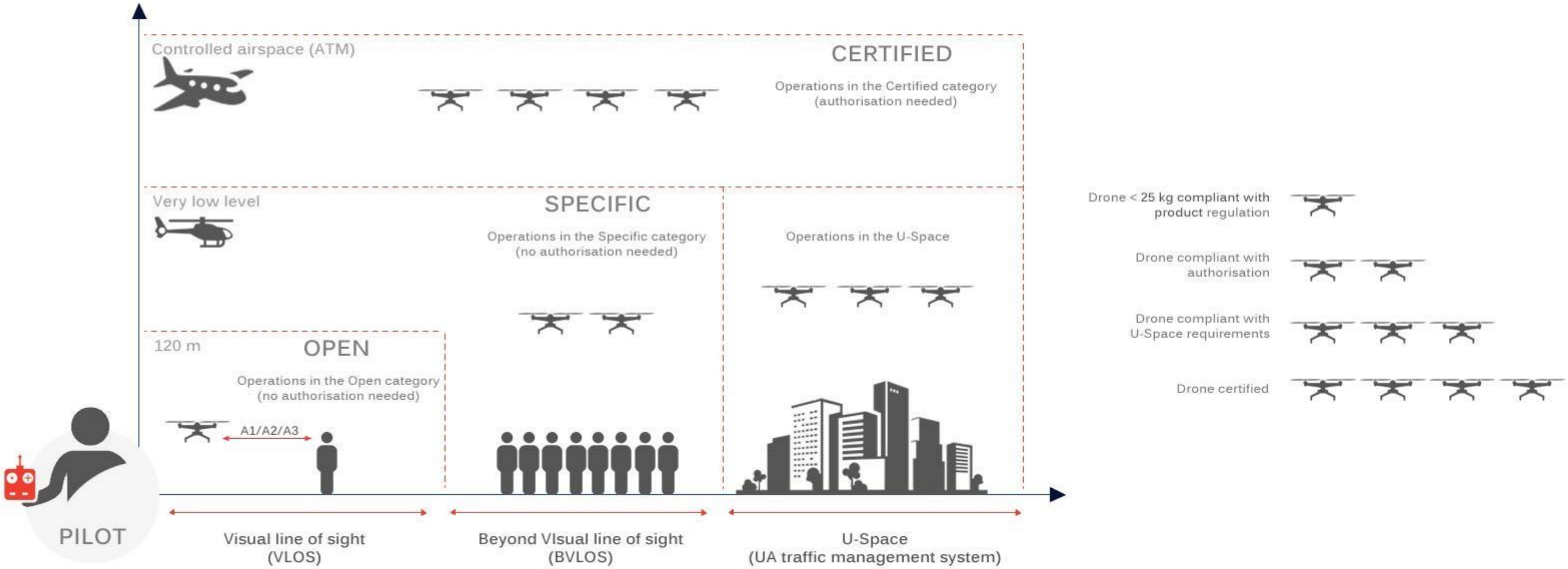
SOURCE: Literature review

Developed solution: Drone delivery system evaluation



Drone regulation

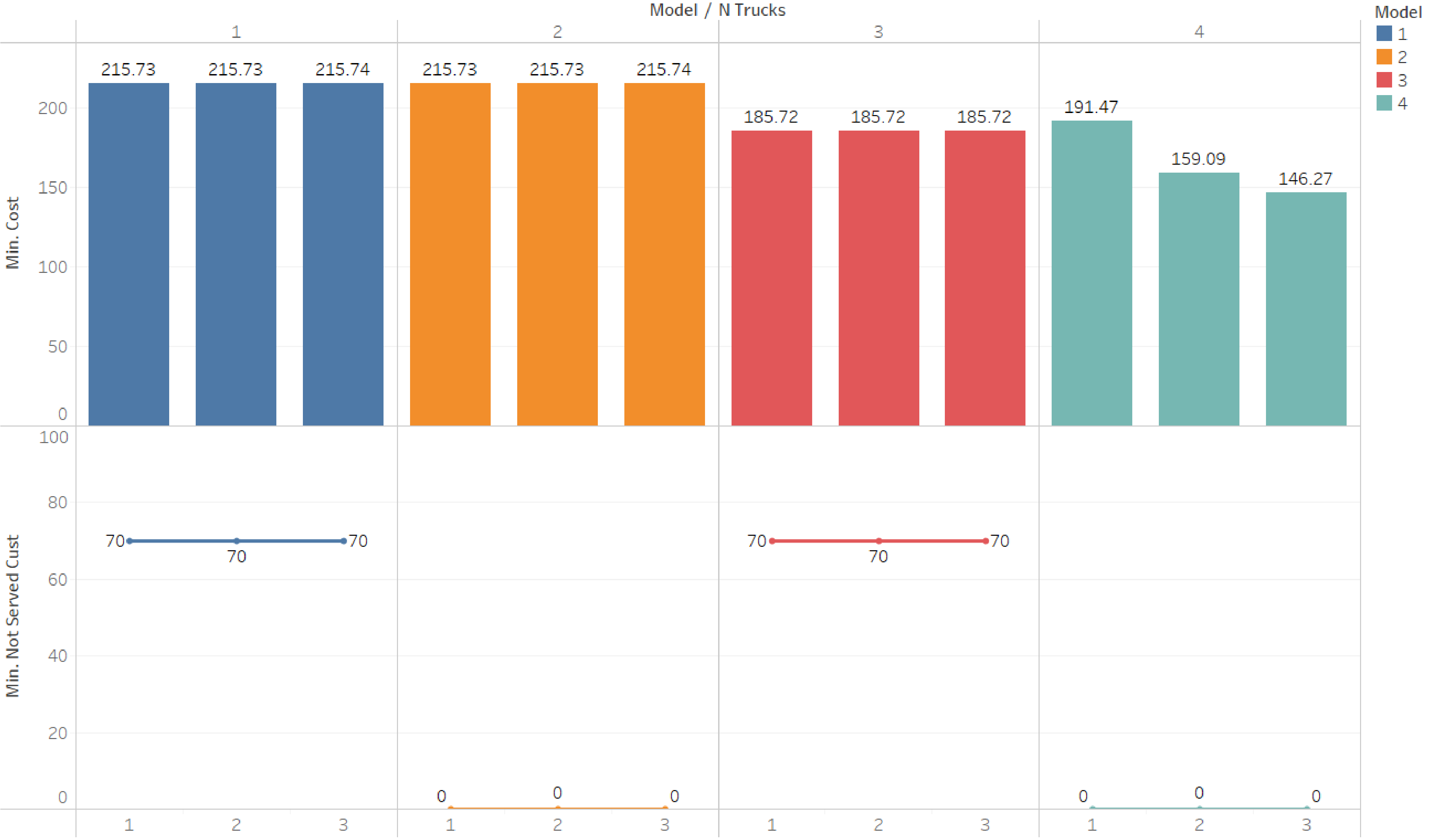
Drone regulation: EU



Drone regulation: USA

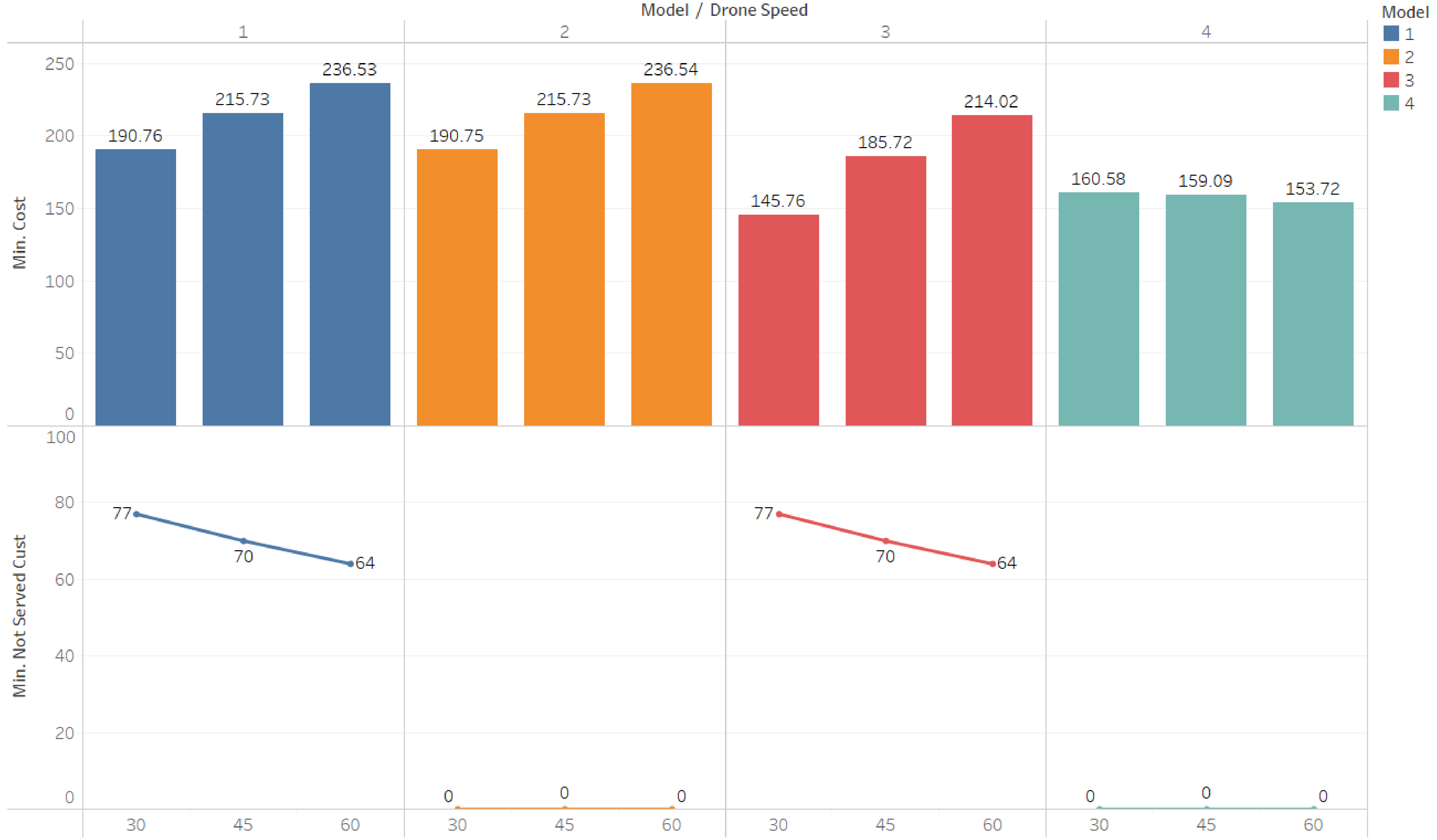
Nevertheless, there are still plenty of regulatory barriers limiting the development of drone delivery. The current regulatory framework in the US is set by the Federal Aviation Administration (FAA). Part 107 of the regulation states that drones or unmanned aircraft systems (UAS): Cannot fly over most federal facilities, at night, or over people; must fly below 400 feet and at less than 100 mph; and must weigh under 55 pounds. Additionally, and perhaps the most limiting rule when it comes to the widespread use of drones, is that they must be kept in the operators' line of sight, and not fly within 5 miles of an airport. However, this has been waived often by the FAA in federally sponsored projects in exchange for data that may help shape future regulation.

Test case 3: # Trucks



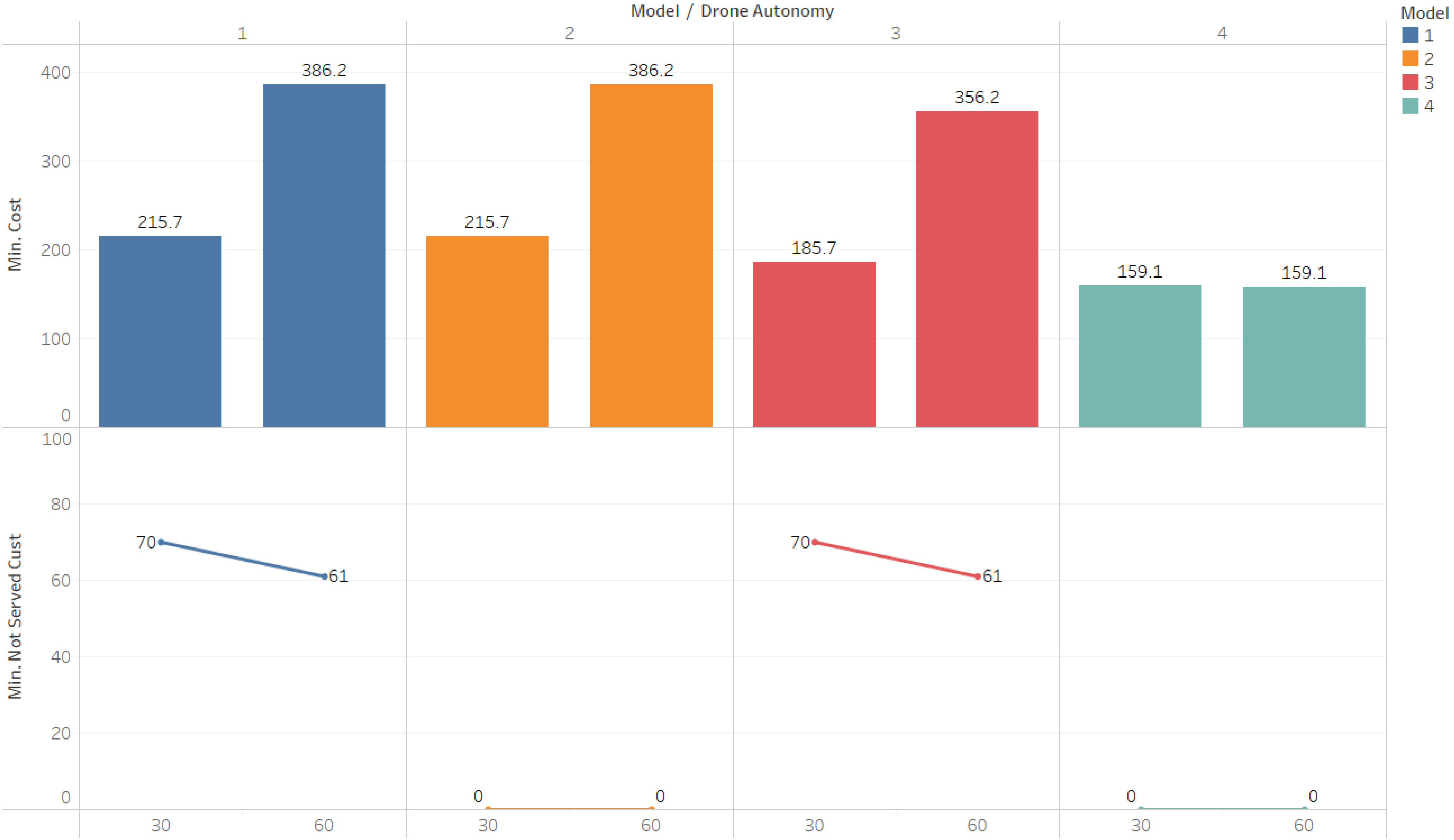
The trends of minimum of Cost and minimum of Not Served Cust for N Trucks broken down by Model. Color shows details about Model. The data is filtered on Drone Autonomy, Drone Speed, Filename and N Drones (group) 1. The Drone Autonomy filter keeps 30. The Drone Speed filter keeps 45. The Filename filter keeps /../problems/final/2-100.csv. The N Drones (group) 1 filter keeps 2.

Test case 3: # Drone Speed



The trends of minimum of Cost and minimum of Not Served Cust for Drone Speed broken down by Model. Color shows details about Model. The data is filtered on N Trucks, Drone Autonomy, Filename and N Drones (group) 1. The N Trucks filter keeps 2. The Drone Autonomy filter keeps 30. The Filename filter keeps /../problems/final/2-100.csv. The N Drones (group) 1 filter keeps 2.

Test case 3: # Drone flight limit



The trends of minimum of Cost and minimum of Not Served Cust for Drone Autonomy broken down by Model. Color shows details about Model. The data is filtered on N Trucks, Filename, N Drones (group) 1 and Drone Speed. The N Trucks filter keeps 2. The Filename filter keeps /../problems/final/2-100.csv. The N Drones (group) 1 filter keeps 2. The Drone Speed filter keeps 45. The view is filtered on Drone Autonomy, which keeps 30 and 60.