Simulating Drone Delivery Networks using SpatialOS

Paul Balaji


POLICE


DHL
M
PACKSET


POLICE

AVIATION

The FAA Says There Will Be 7 Million Drones Flying Over America By 2020

Less than four years away

By Keisey D. Atherton *March 24, 2016*

DJI PHANTOM 4 QUADCOPTER
This is the latest version of a popular drone brand.
Screenshot by author, from YouTube

Right now, there are around 2.5 million drones that regularly fly over American skies, according to the Federal Aviation Administration. In 2020, that number could almost triple, with 7 million drones projected to be active in the skies over our heads, according to a new report) released by the agency today.

THE WALL STREET JOURNAL

FAA expects huge increase in commercial drones in next 5 years

Published: Mar 18, 2018 5:31 p.m. ET

450,000 drones expected by 2020, four times today's number

A DJI Phantom 4 Pro Quadcopter drone takes flight.

By ANDY

U.S. regulators expect the number of commercial drones and people flying them

Microsoft, Altitude Angel and

www.thedrive.com/aerial/14833/microsoft-altitude-angel-and-college-students-are-working-on-internet-of-flying-things

THE DRIVE | ACCELERATOR | THE WAR ZONE | MOTORCYCLES | SHOP | Gear Up | NEWSLETTER SIGNUP | search...

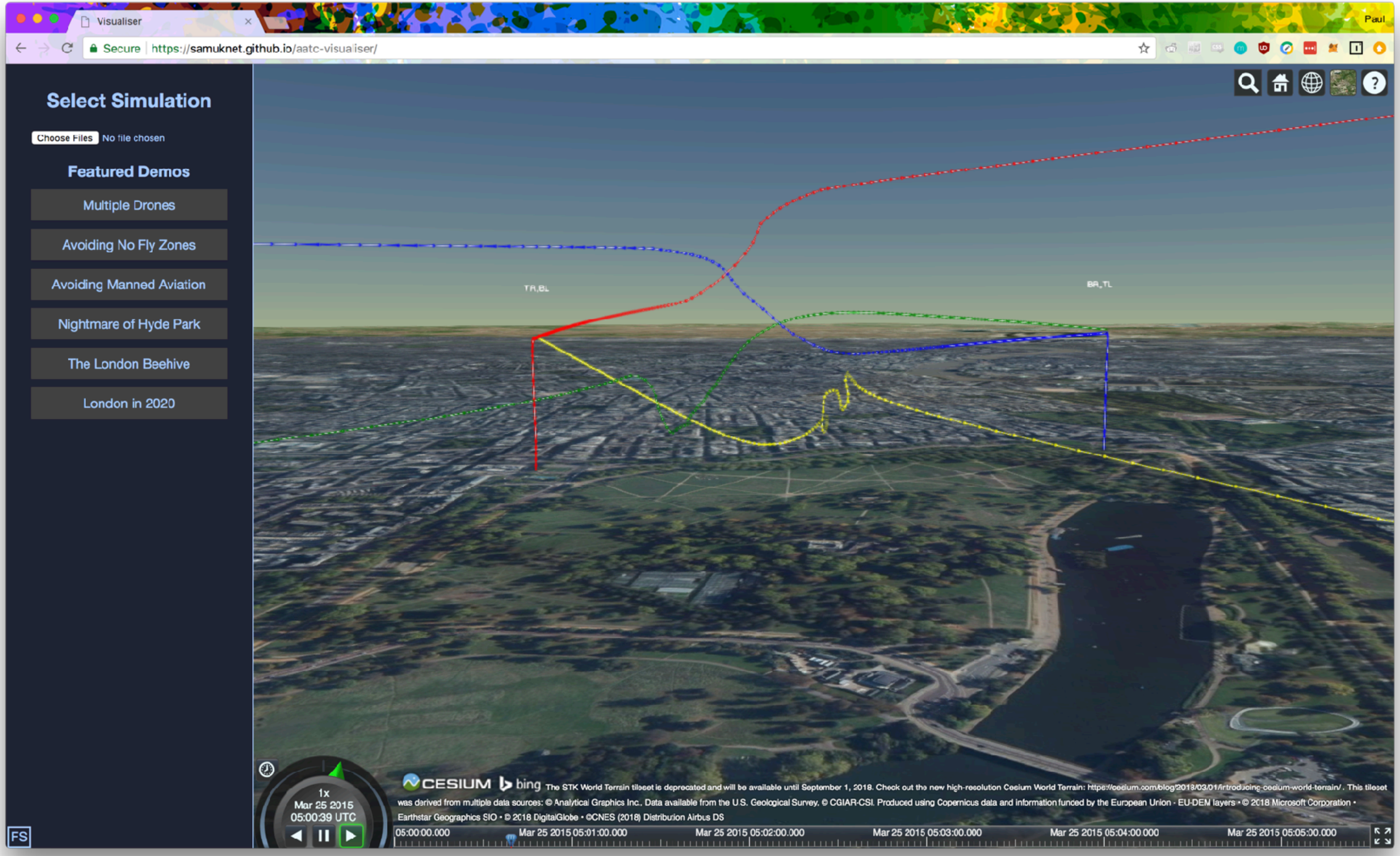
Microsoft, Altitude Angel and College Students Are Working on 'Internet of Flying Things'

Microsoft joins London's Imperial College students and drone services company Altitude Angel to develop an air-traffic management system.

BY MARCO MARGARITOFF OCTOBER 3, 2017

AERIAL | AERIAL | DRONES

http://www.thedrive.com/aerial/14833/microsoft-altitude-angel-and-college-students-are-working-on-internet-of-flying-things



https://samuknet.github.io/aatc-visualiser/

Drone-tracking system paves

Secure https://www.bbc.co.uk/news/technology-43302583

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Technology

Drone-tracking system paves way for UK deliveries from air

By Leo Kelion
Technology desk editor

6 March 2018 Share

The new system should make it safer for drones and passenger jets to share the sky

Efforts to create an automated UK drone-tracking system pave the way for commercial operators to fly unmanned aircraft regularly over longer distances than is currently possible.

At present, owners are required to keep drones within **their own line of sight**

Top Stories

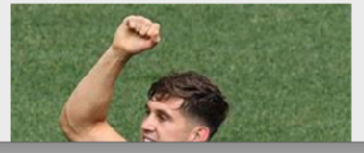
England make World Cup history
England achieve their most emphatic World Cup result as Harry Kane's hat-trick helps them thrash Panama and reach the last 16.
4 hours ago

Highlights: England 6-1 Panama
4 hours ago

Erdogan ahead in early results in Turkey
7 minutes ago

Features

Will new obesity measures make your life easier?



https://www.bbc.co.uk/news/technology-43302583

Things can go wrong...

Things can go wrong...

https://edition.cnn.com/videos/cnnmoney/2018/04/03/russian-postal-mail-delivery-drone-crash-cnnmoney-orig.cnnmoney

Things can go wrong...

$20,000

https://www.engadget.com/2018/04/04/russian-mail-drone-crash/

https://edition.cnn.com/videos/cnnmoney/2018/04/03/russian-postal-mail-delivery-drone-crash-cnnmoney-orig.cnnmoney

Simulate!

SpatialOS

Cutting-edge simulation technology

Cloud-based distributed computation platform

Entity-Component-Worker Model

Server boundaries are abstracted away

Experience from Industrial Placement

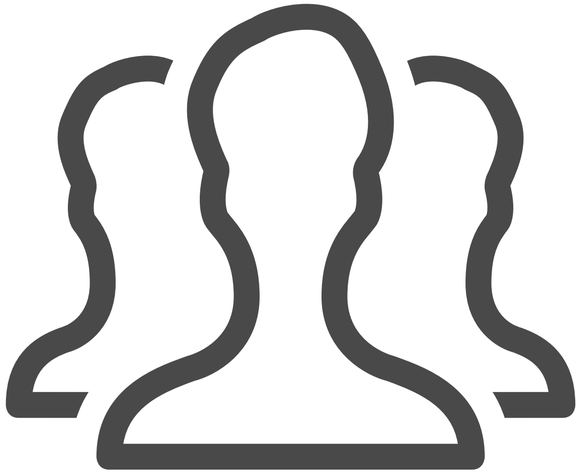
Simulating a Drone Delivery Network

What is a good design for a drone delivery network?

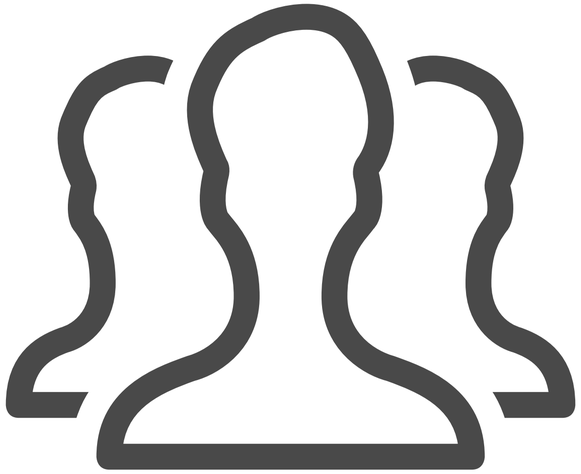
Can we experiment with the pricing model?

How do we schedule deliveries to make more money?

Forget about Drones



Customer Orders



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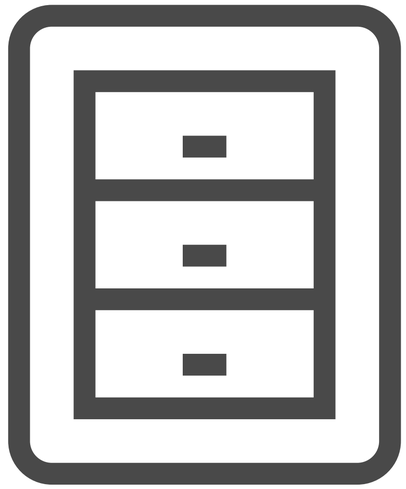
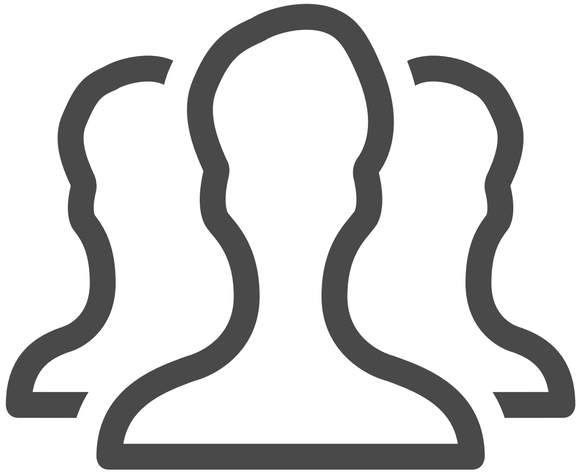
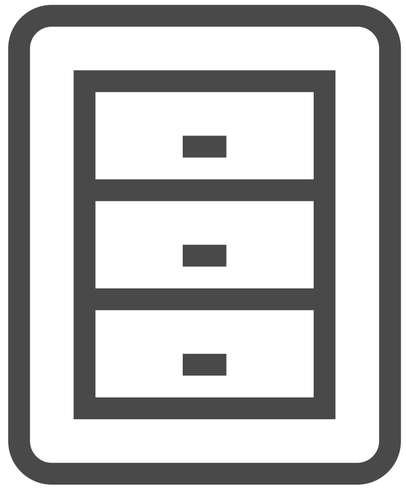


Fulfilment Centres



Customer Orders



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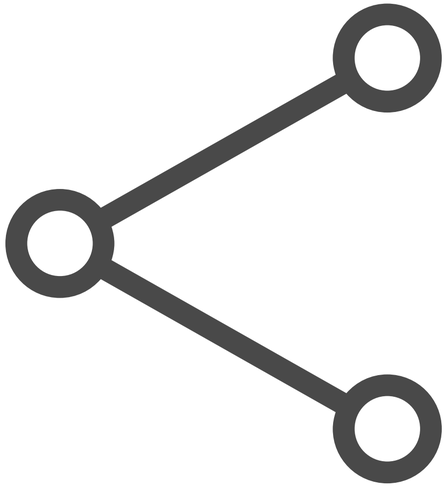
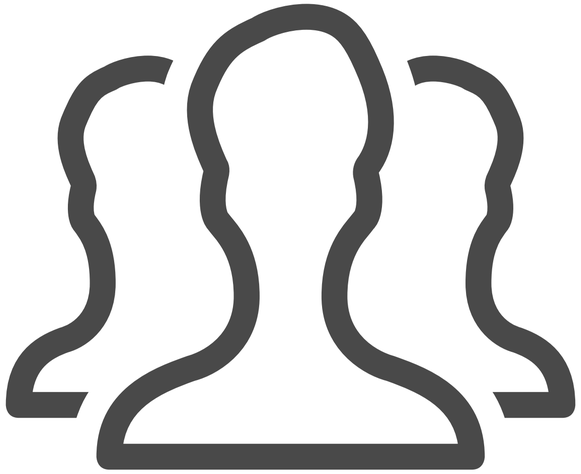


Job Allocation



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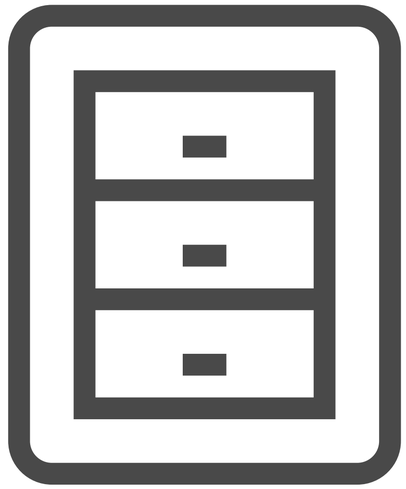

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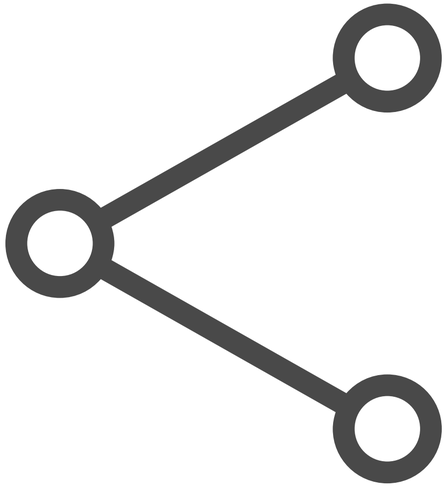


Job Allocation

Package Delivery

Conventional

Multiple orders can be delivered in one trip

Few large “centres”

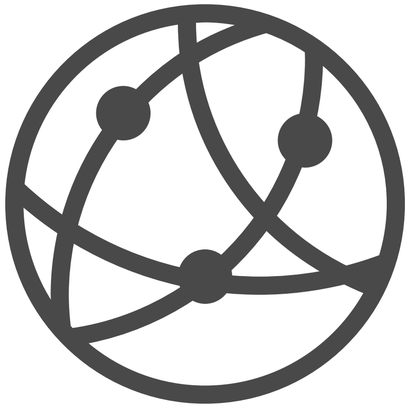
ETA in *days*

Flat fee per delivery

Conventional	Drone-based
Multiple orders can be delivered in one trip	Only one order is served per round trip
Few large “centres”	Many small “hubs”
ETA in *days*	ETA in *minutes*
Flat fee per delivery	Variable fee per delivery

Key Entities and Components

ORDER GENERATOR



CONTROLLER

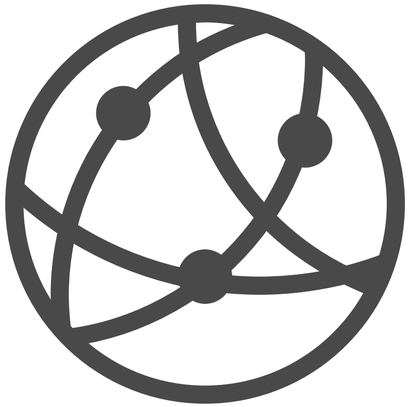
DRONE

Key Entities and Components

ORDER GENERATOR

Simulate Orders

Order Routing



CONTROLLER

Drone Lifecycle

Pathfinding

Scheduling

DRONE

Movement

Collision Avoidance

Energy Tracking

Where are we simulating these drones?


The Harry Potter Shop at Platform 9 3/4
The Lexington
Victoria Miro
Sadler's Wells Theatre
City, University of London
Jamie Oliver's Fifteen
SHOREDITCH
Columbia Road Flower Market
Shoreditch London ltd - Shoreditch event venues
XOYO
The Book Club
Rich Mix
Village Underground
Boxpark Shoreditch
The British Library
The Foundling Museum
FINSBURY CLERKENWELL
ST. LUKE'S
Charles Dickens Museum
SOAS University of London
Great Ormond Street Hospital
Russell Square
GOLDEN LANE ESTATE
Queen of Hoxton
Brick Lane Market
Improbable
Fabric
Barbican Centre
Old Spitalfields Market
The British Museum
Bounce Farringdon
BARBICAN
Broadgate Circle
Rosewood London
Museum of London
St. Bartholomew's Hospital
Dominion Theatre
Google
Guildhall
BlackRock
Duck & Waffle
Whitechapel Gallery
King
London School of Economics and Political...
Cambridge Theatre
St. Paul's Cathedral
30 St Mary Axe (The Gherkin)
Palace Theatre
One New Change
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Strand
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Darwin Brasserie
Grange Tower Bridge
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Empire Casino
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River Thames
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Oxo Tower Wharf
Shakespeare's Globe
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Tower of London
Mondrian London
Purcell Room
London
HMS Belfast
Underbelly Festival
Underbelly Festival • Today
Borough Market
Pizza Festival • Now
Tower Bridge
St Katharine Docks Marina
Banqueting House
The Shard
Coca-Cola London Eye
Potters Fields Park
Westminster Bridge
Big Ben
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Palace of Westminster
White Cube
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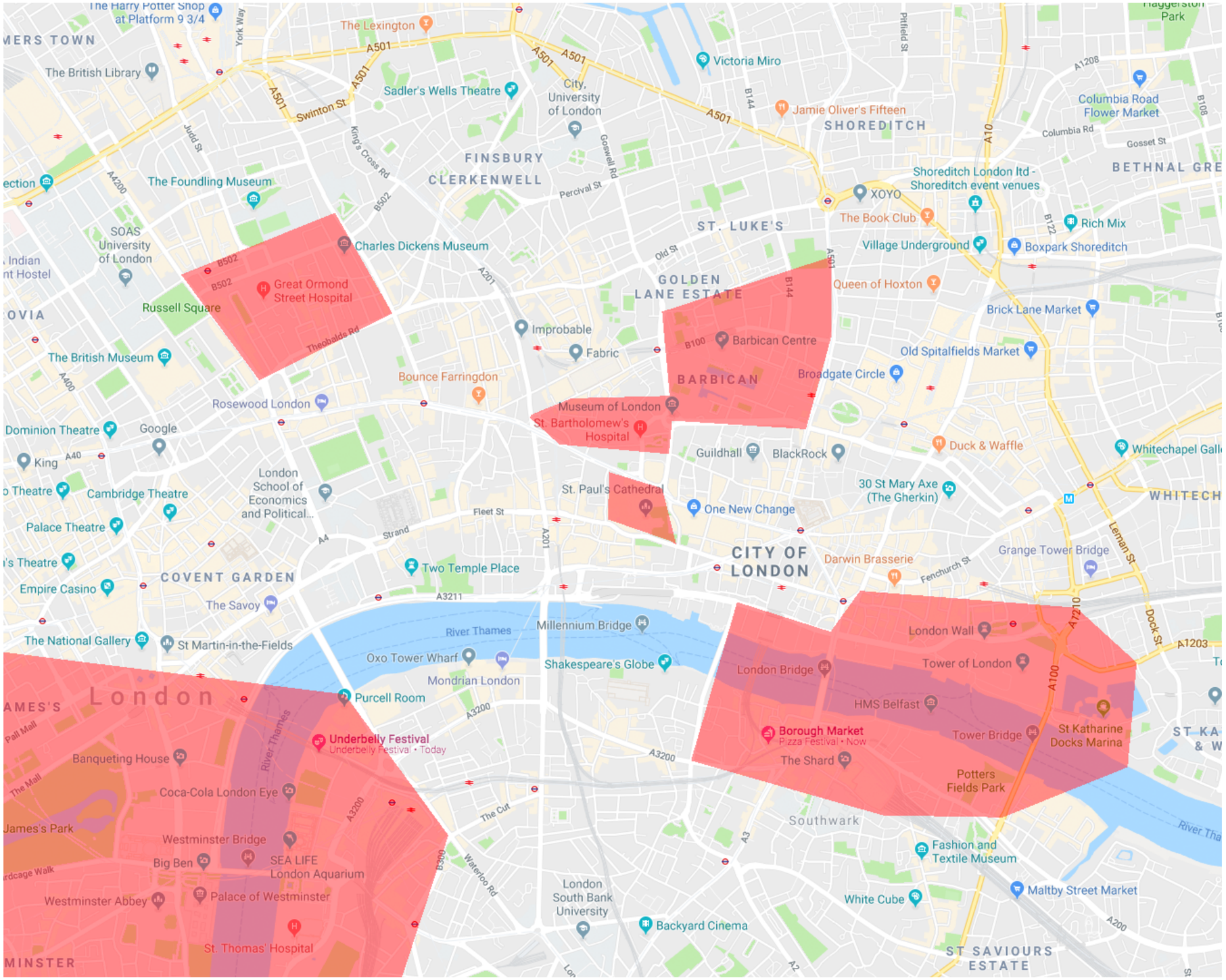
Backyard Cinema
St. Thomas' Hospital
ST SAVIOURS ESTATE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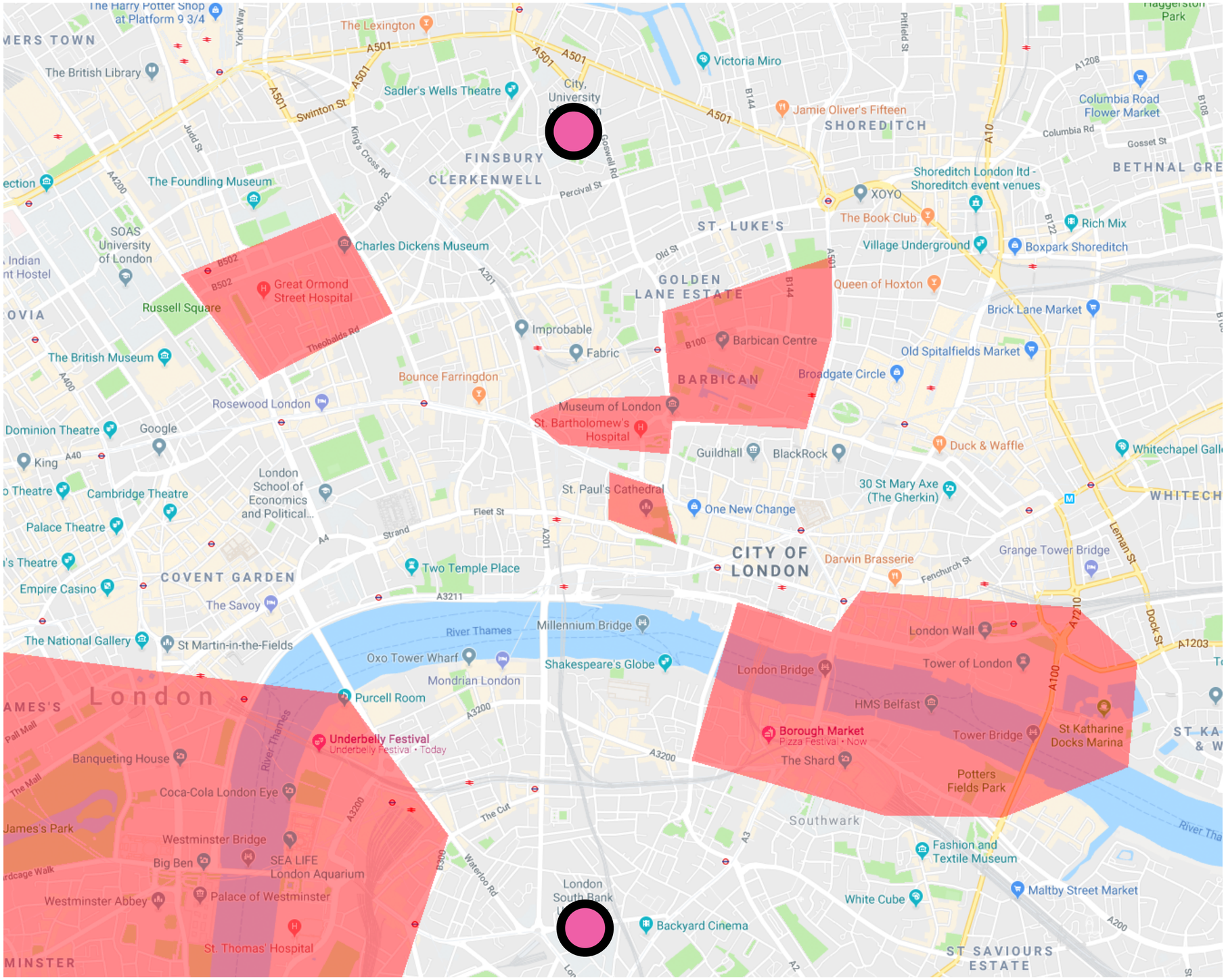
ST SAVIOURS ESTATE
A501
A4200
B502
A201
B144
A10
A1208
B108
B122
A400
A40
A4
A3211
A3200
A3
A100
A1210
A1203
Dock St
Leman St
Fenchurch St
Pitfield St
Old St
Swinton St
King's Cross Rd
Goswell Rd
Percival St
Judd St
Theobalds Rd
Pall Mall
The Mall
The Cut
Waterloo Rd
B3300
A200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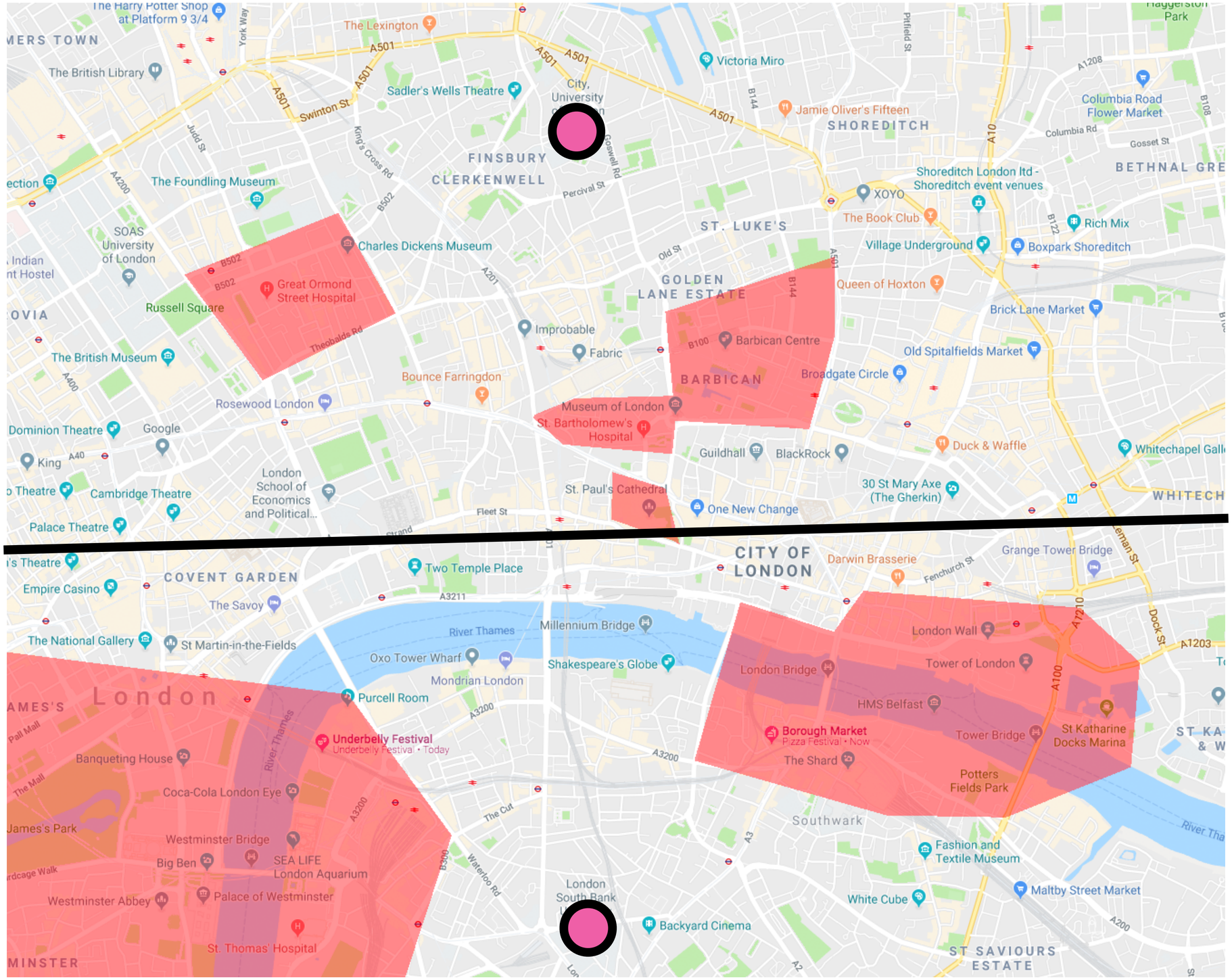
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Let's see it in action!

Where’s the $$$?

Delivery Fee Considerations

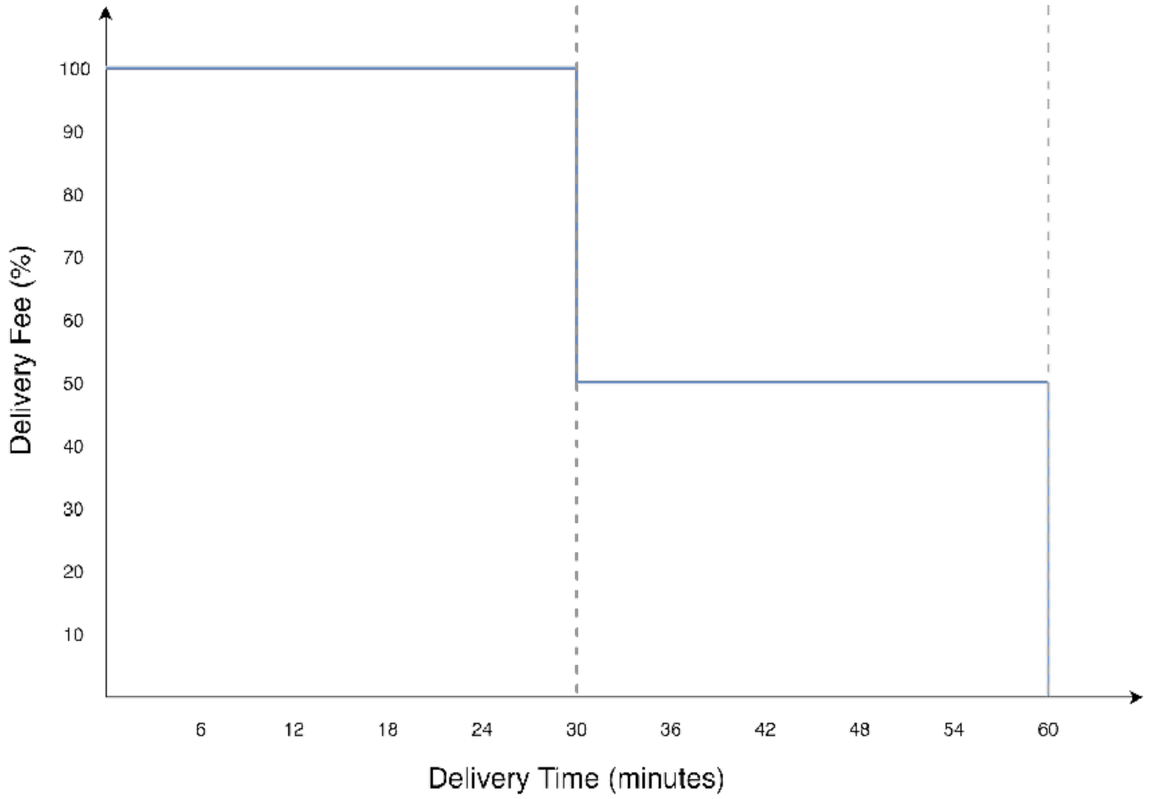
How big and heavy is the package?

What was the priority of the order?

How long did it take to be delivered?

Which function of time gives us the fee?

The Halvening



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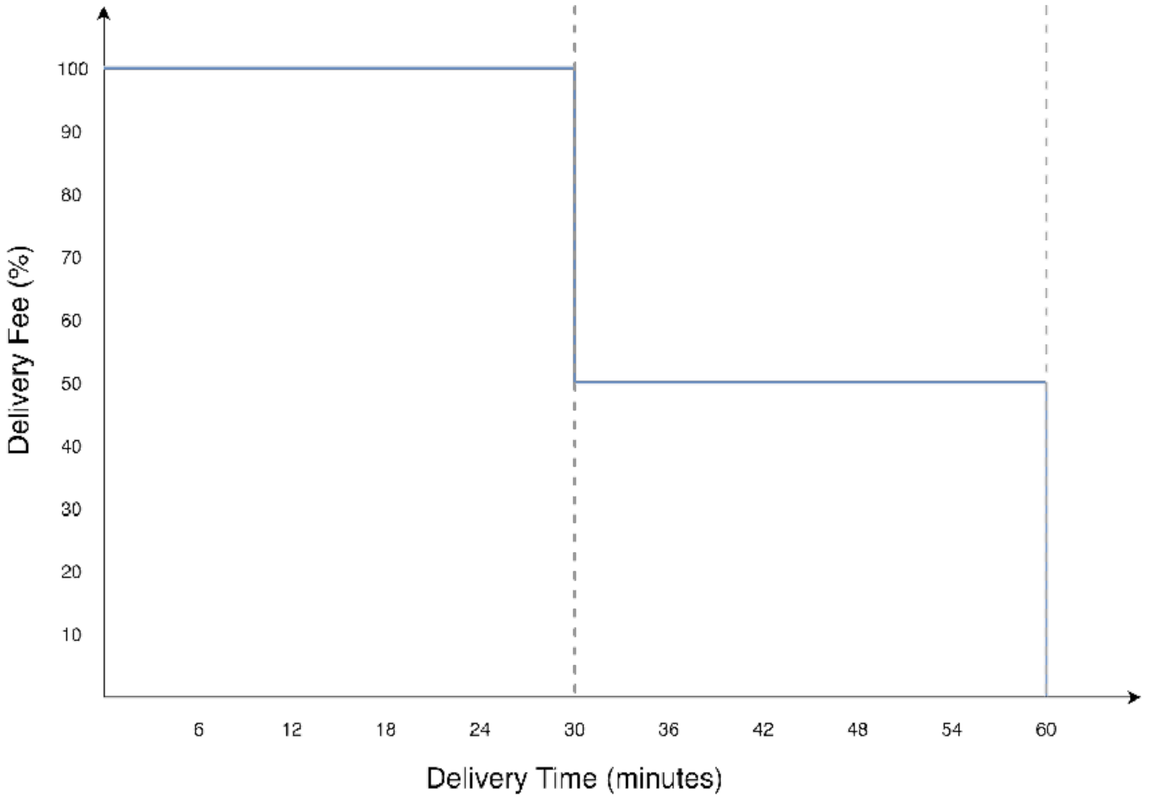
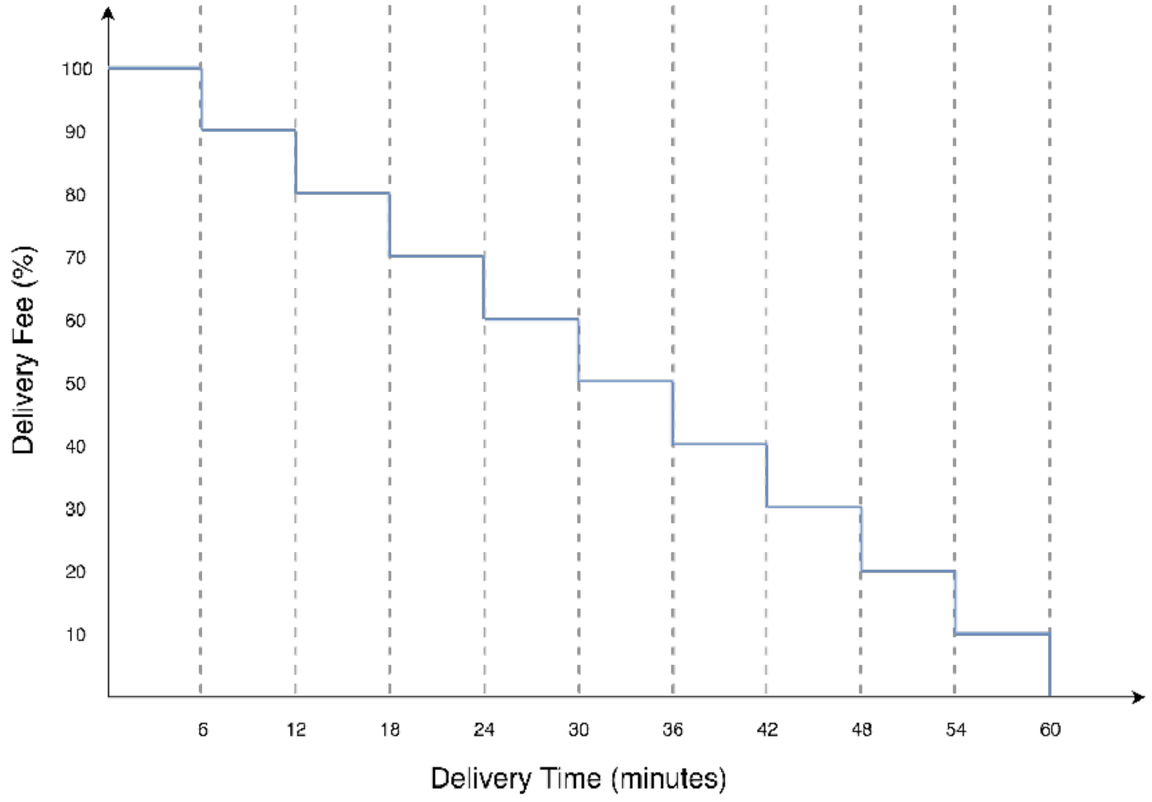


Stepwise Decrease



Package Type

Packaging Type *(Packaging Weight - grams)*	**Dimensions** *(cm)*	**Outbound Shipping Weight*** *(g)*	**Fee**
Small Letter[1] *(8 g)*	≤ 23 x 15.5 x 0.4 cm	0 - 100 g	£0.60
Large Letter[1] *(25 g)*	≤ 30 x 22 x 2.4 cm	0 - 250 g	£0.80
Small Envelope *(20 g)*	≤ 20 x 15 x 1 cm	0 - 100 g	£1.09
Standard Envelope *(40 g)*	≤ 33 x 23 x 2.5 cm	0 - 100 g	£1.21
		101 - 250 g	£1.34
		251 - 500 g	£1.54
Large Envelope *(40 g)*	≤ 33 x 23 x 5 cm	0 - 1,000 g	£1.77
Standard Parcel *(100 g)*	≤ 45 x 34 x 26 cm	0 - 250 g	£1.73
		251 - 500 g	£1.79
		501 - 1,000 g	£1.84
		1,001 - 1,500 g	£2.26
		1,501 - 2,000 g	£2.48
		2,001 - 3,000 g	£3.32

Package Priority

STANDARD

PRIORITY

URGENT

SUPER PRIORITY

Package Type	Weight (g)	Delivery Fee (£)			
		Standard	Priority	Urgent	Super Priority
Small Letter	0 - 100	0.60	0.90	1.35	2.03
Large Letter	0 - 250	0.80	1.20	1.80	2.70
Small Envelope	0 - 100	1.09	1.64	2.45	3.68
Standard Envelope	0 - 100	1.21	1.82	2.72	4.08
	101 - 250	1.34	2.01	3.02	4.52
	251 - 500	1.54	2.31	3.47	5.20
Large Envelope	0 - 1000	1.77	2.66	3.98	5.97
Parcel	0 - 250	1.73	2.60	3.89	5.84
	251 - 500	1.79	2.69	4.03	6.04
	501 - 1000	1.84	2.76	4.14	6.21
	1001 - 1500	2.26	3.39	5.09	7.63
	1501 - 2000	2.48	3.72	5.58	8.37
	2001 - 3000	3.32	4.98	7.47	11.21

Each levels costs 50% more than the previous

Order Generation

ID
unique, sequential integer

Destination
random non-NFZ point

Package Info
type and weight of package

Time Value Function
function + priority

Order Generation

ID
unique, sequential integer

Destination
random non-NFZ point

Package Info
type and weight of package

Time Value Function
function + priority

Example Order

271711

(1000, 0, 1000)

Parcel (1871g)

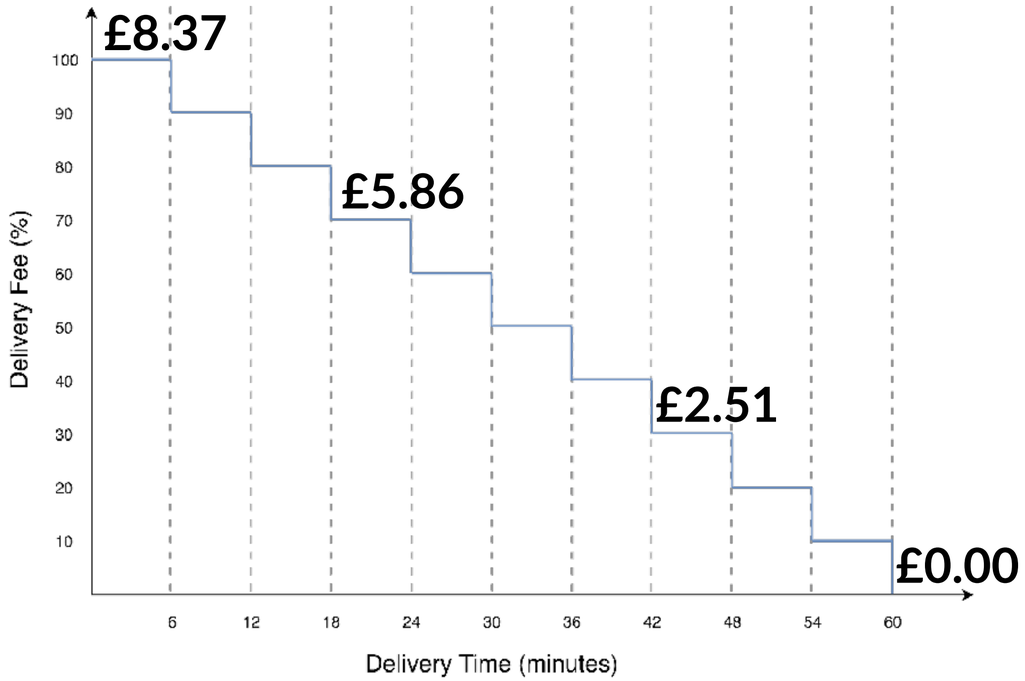
Stepwise + Super Priority

Example Order

Parcel (1871g)

Parcel	0 - 250	1.73	2.60	3.89	5.84
	251 - 500	1.79	2.69	4.03	6.04
	501 - 1000	1.84	2.76	4.14	6.21
	1001 - 1500	2.26	3.39	5.09	7.63
	1501 - 2000	2.48	3.72	5.58	8.37
	2001 - 3000	3.32	4.98	7.47	11.21

Stepwise + Super Priority



Wow, pure profit!

~~Wow, pure profit!~~

Energy Consumption

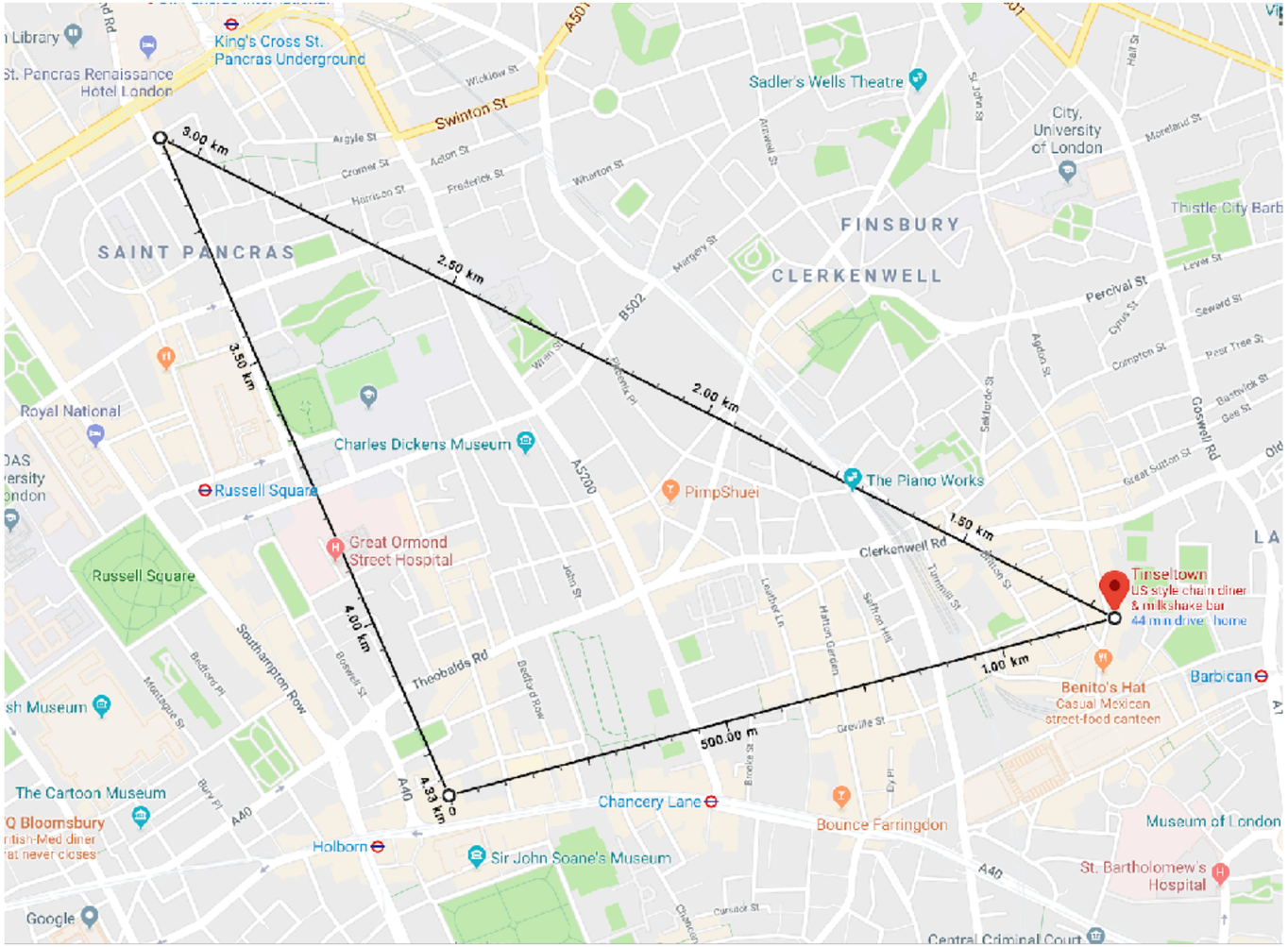
£55 per MWh

Motion: 8355 W
Hover: 670 W

Drones update their energy usage every 0.25 seconds

cost = energy*0.0055/3600
(pence)

Energy Consumption



4.33 km

4330 / 10 = 433 s

433 seconds moving
20 seconds hovering

Motion: 3617715 Ws
Hover: 13400 Ws
Total: 3631115 Ws

Energy Consumption

£55 per MWh

Motion: 8355 W
Hover: 670 W

cost = energy*0.0055/3600
(pence)

Total: 3631115 Ws

Total cost of delivery
=
3631115 * 0.0055 / 3600
=
5.547536806 pence

Cost ~ 5.48p

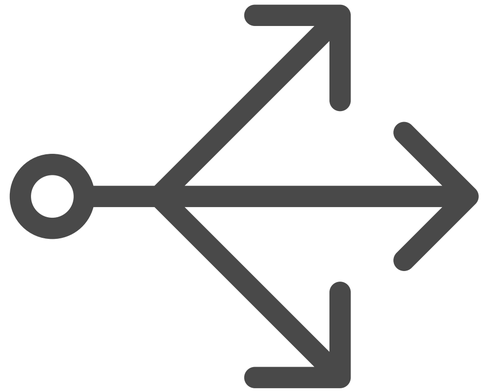
Almost pure profit!

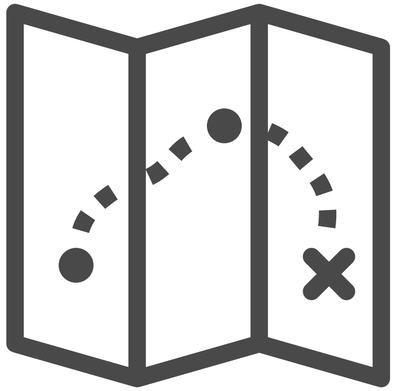
Extra Penalties

£5 penalty for not delivering a confirmed order

Costs of getting a truck to retrieve a drone

£400 penalty per drone for Collisions





Improved Scheduling

Least Lost Value (LLV)

Inspired by time-value of data

Adapted from Big Data use-case

Suited to the time-value revenue model

Outperforms most other TVD-based algorithms

How does it work?

$$EV(j_i, t_c) = \int_{t_0}^{\infty} V_i(t) \,.f_i(t - t_c)\ dt$$

$$PLV(j_i) = \sum_{j_k \in J,\ k \neq i,\ k-1}^{n} (EV(j_k, t_c) - EV(j_k, t_c + p))$$

$$PGV(j_i) = EV(j_k, t_c) - EV(j_k, t_c + \bar{p}_i)$$

$$NLV(j_i) = PLV(j_i) - PGV(j_i)$$

How does it work?

$$EV(j_i, t_c) = \int_{t_0}^{\infty} V_i(t) \,.f_i(t - t_c)\; dt$$

$$PLV(j_i) = \sum_{j_k \in J,\; k \neq i,\; k-1}^{n} (EV(j_k, t_c) - EV(j_k, t_c + p))$$

$$PGV(j_i) = EV(j_k, t_c) - EV(j_k, t_c + \bar{p}_i)$$

$$NLV(j_i) = PLV(j_i) - PGV(j_i)$$

EV uses a duration distribution

PLV is sum value of jobs not taken

PGV is difference in processing job now vs later

NLV = PLV - PGV

Job with lowest NLV is selected

Adapting LLV

Fixed durations, no distributions

Don’t know all future jobs, adapting to incoming jobs

Eviction of low-priority elements

Queue implementation

Re-sorting queue on each dequeue request

Shortest Job First

Occasionally beats LLV in some test cases

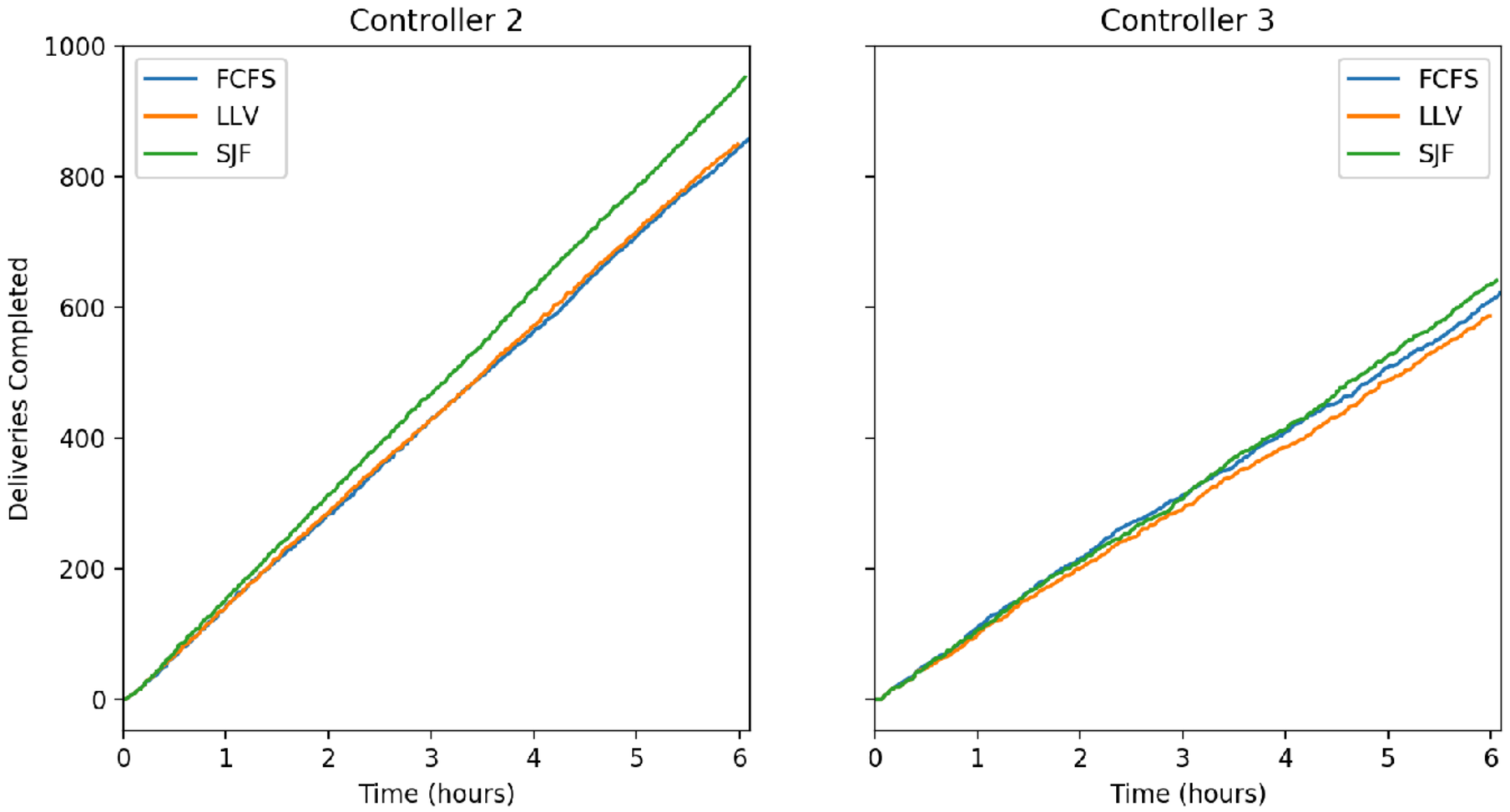
Very simple to implement

No need to re-sort queue regularly

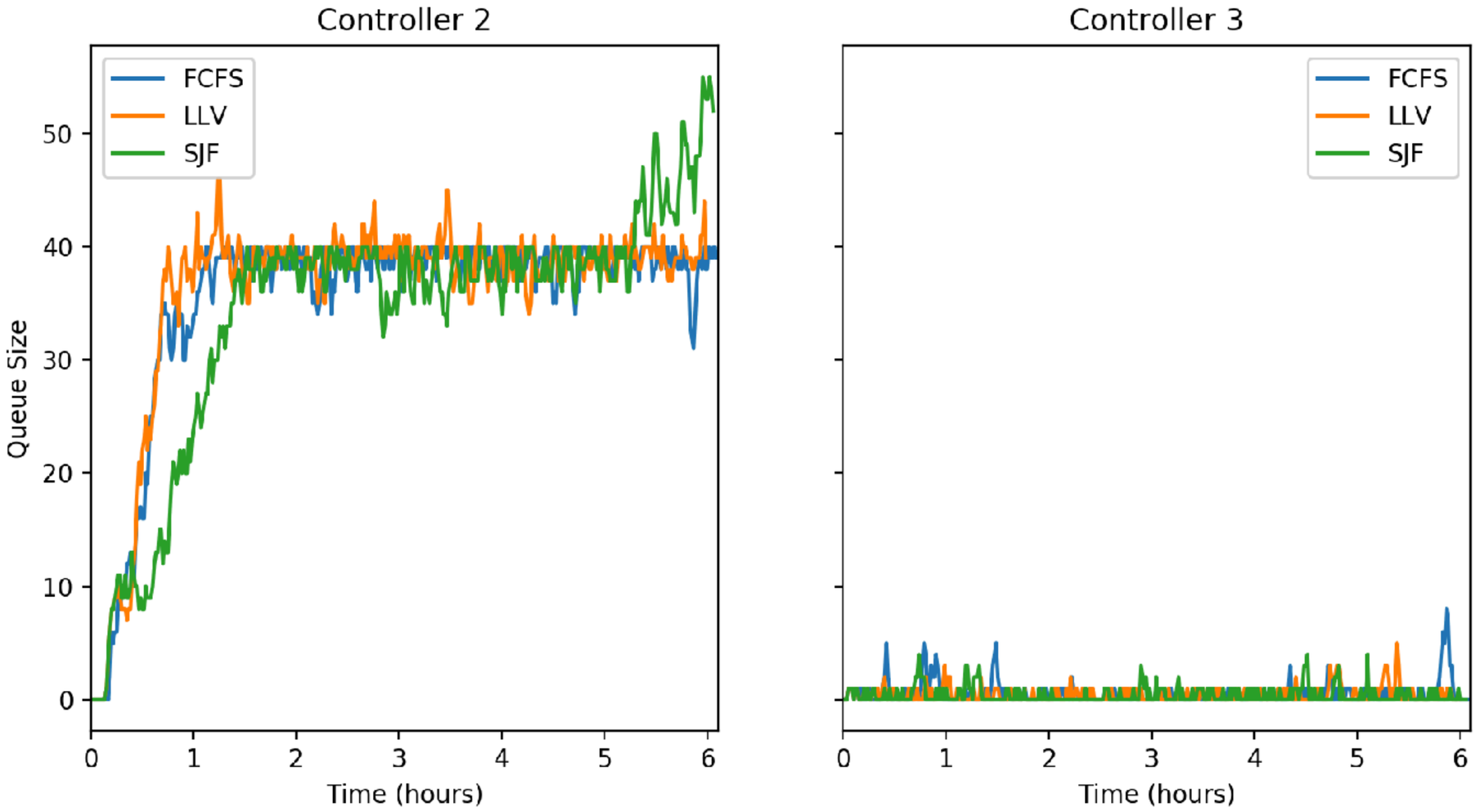
Viable strategy for drone deliveries

So, how did they do?

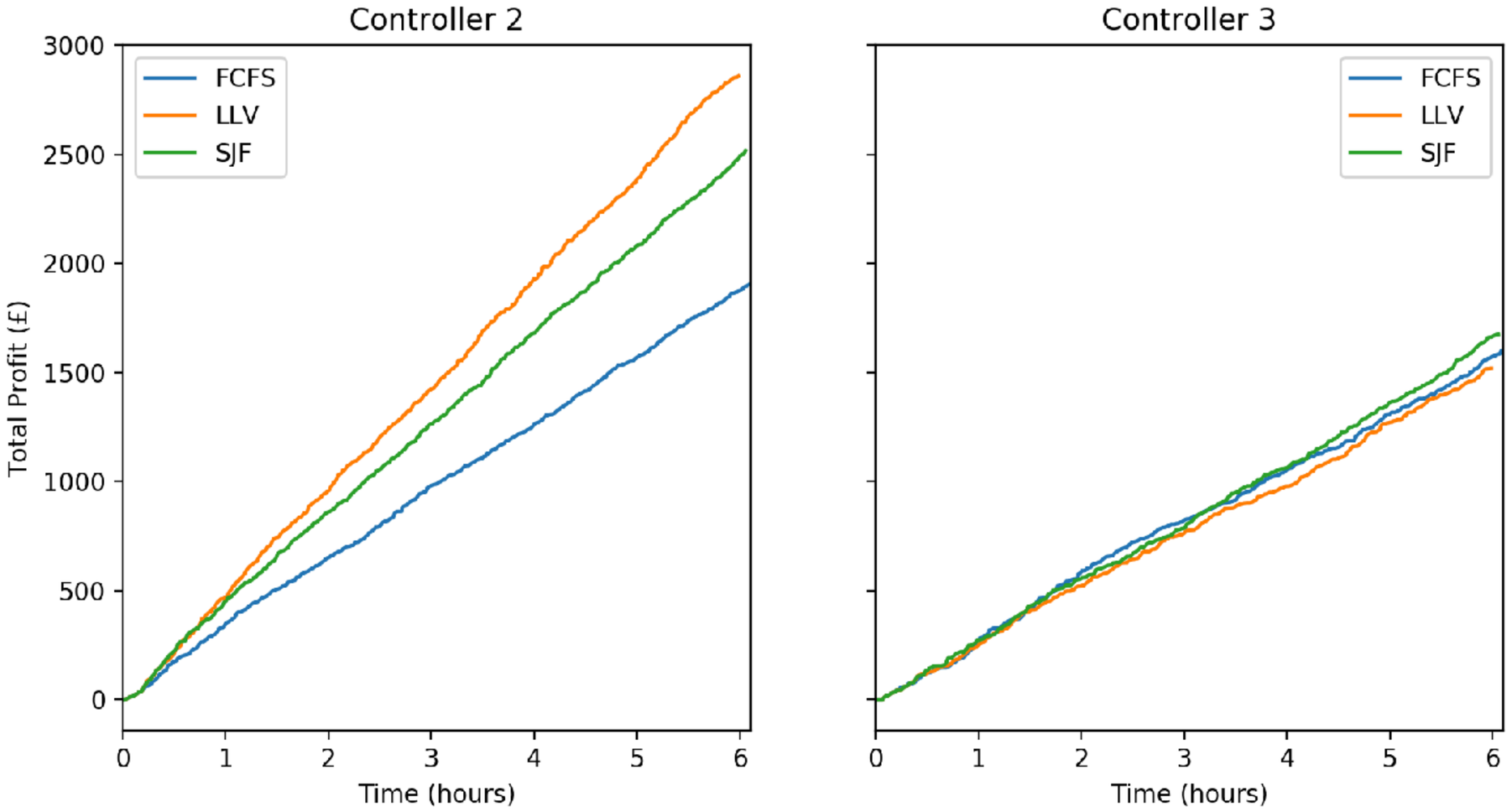
Deliveries Completed



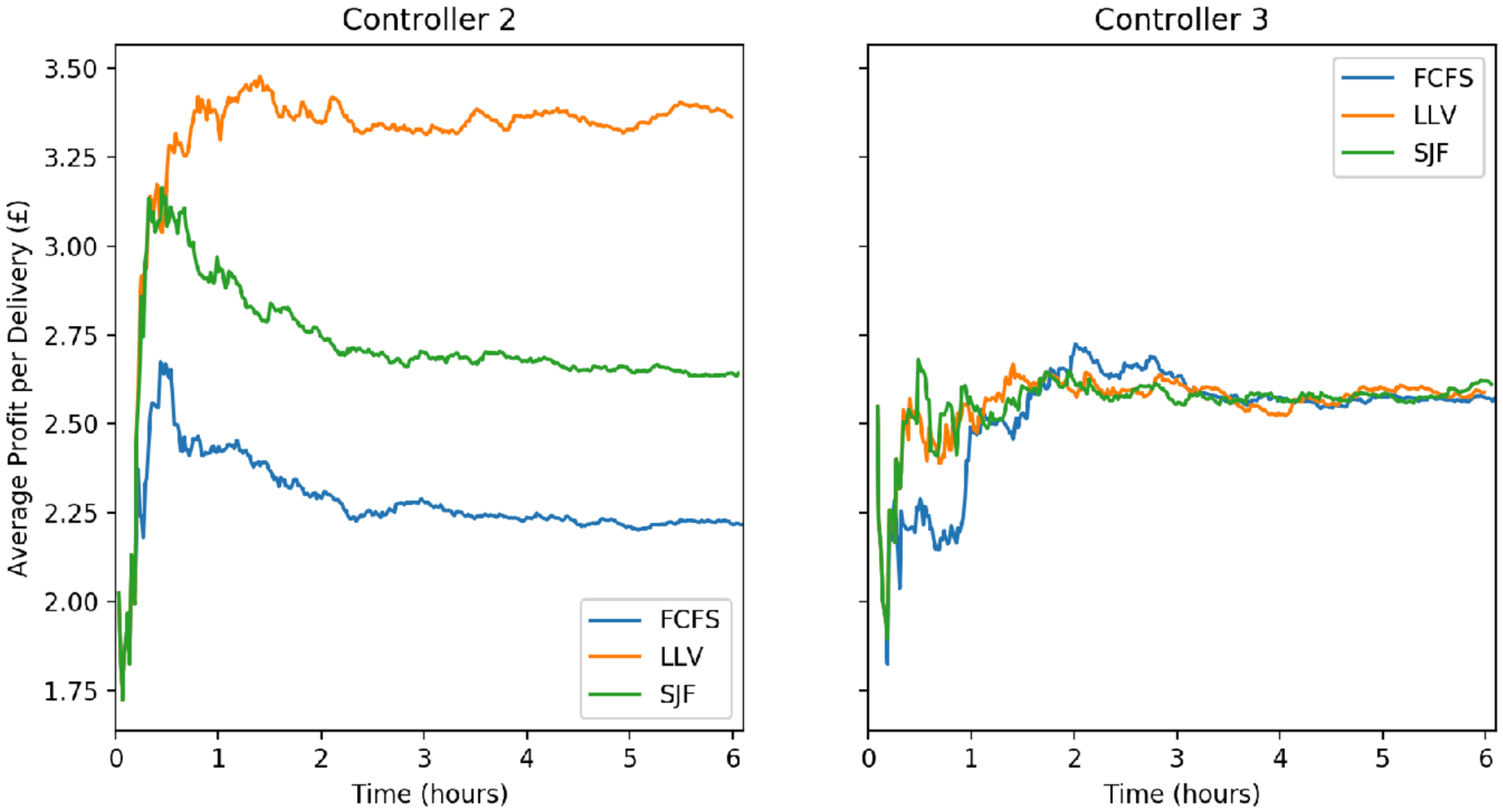
Queue Size


Controller 2
FCFS
LLV
SJF
Queue Size
0
10
20
30
40
50
0
1
2
3
4
5
6
Time (hours)
Controller 3
FCFS
LLV
SJF
0
1
2
3
4
5
6
Time (hours)

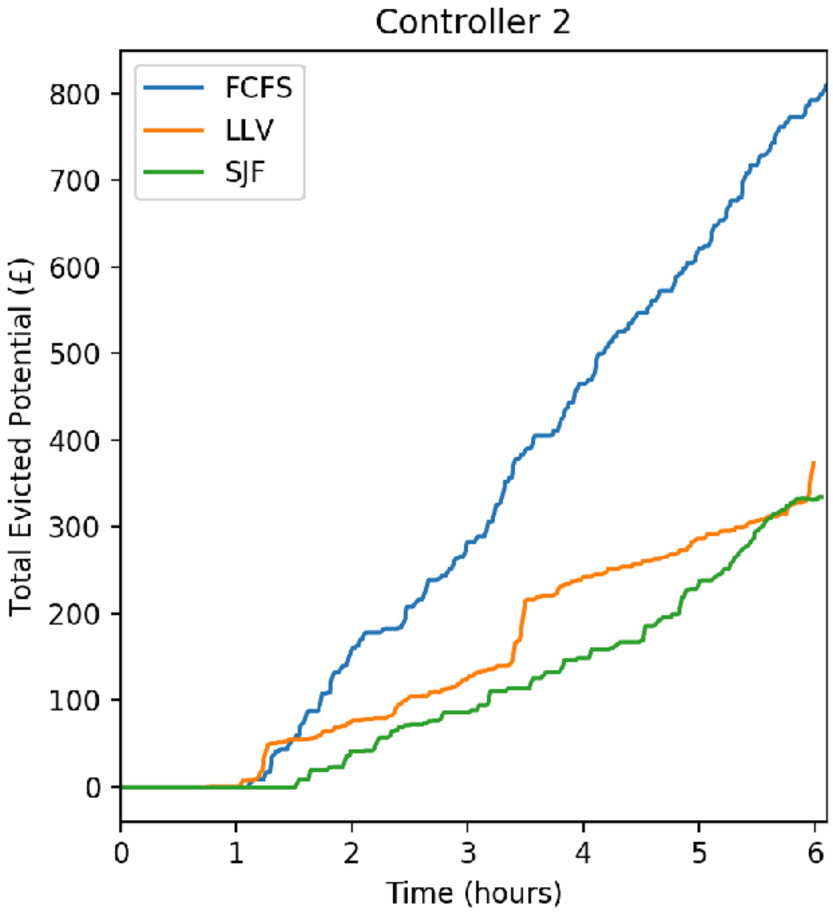
Total Profit



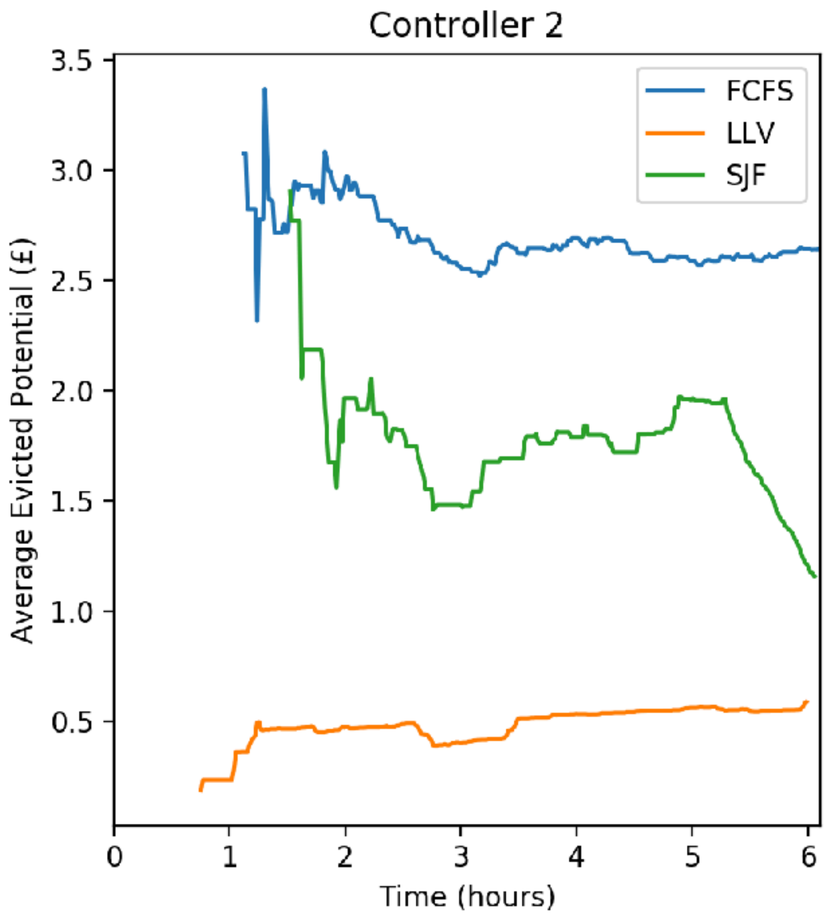
Average Profit per Delivery



Evicted Potential



Avg. Evicted Potential



Where next?

Fix major bugs

Improved order generation

More time-value functions

Split scheduling

Inter-controller communication

Dynamic no fly zones

Interactive simulation

Submit results to ValueTools 2018 conference

Fix major bugs

Improved order generation

More time-value functions

Split scheduling

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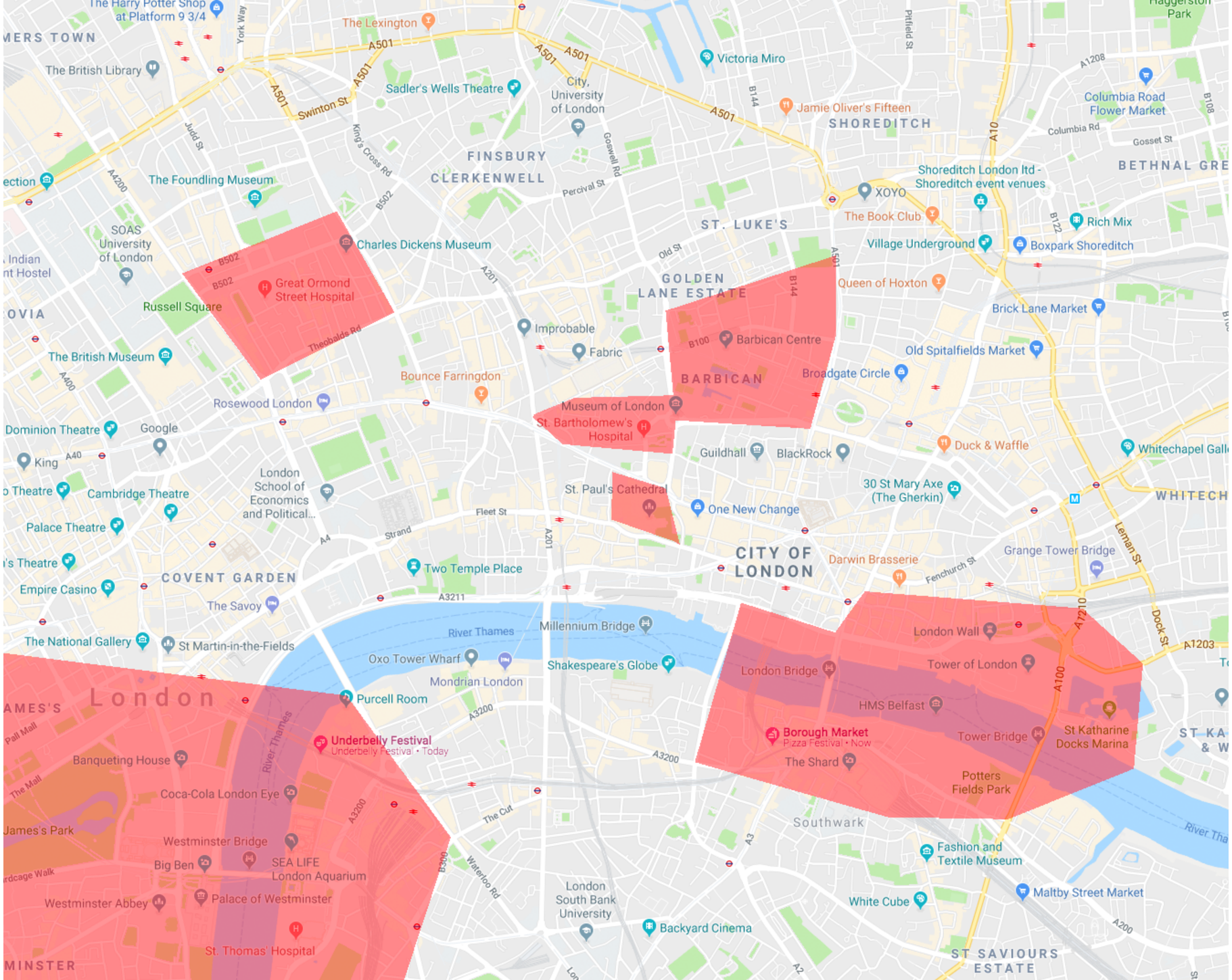
One more thing...


The Harry Potter Shop at Platform 9 3/4
The Lexington
Victoria Miro
The British Library
Sadler's Wells Theatre
City, University of London
Jamie Oliver's Fifteen
SHOREDITCH
Columbia Road Flower Market
FINSBURY CLERKENWELL
The Foundling Museum
Shoreditch London ltd - Shoreditch event venues
XOYO
The Book Club
Rich Mix
ST. LUKE'S
Village Underground
Boxpark Shoreditch
SOAS University of London
Charles Dickens Museum
Great Ormond Street Hospital
Russell Square
GOLDEN LANE ESTATE
Queen of Hoxton
Brick Lane Market
Improbable
Fabric
Barbican Centre
BARBICAN
Old Spitalfields Market
Broadgate Circle
The British Museum
Bounce Farringdon
Rosewood London
Museum of London
St. Bartholomew's Hospital
Duck & Waffle
Dominion Theatre
Google
Guildhall
BlackRock
Whitechapel Gall
King
Cambridge Theatre
London School of Economics and Political...
St. Paul's Cathedral
30 St Mary Axe (The Gherkin)
Palace Theatre
One New Change
WHITECH
Two Temple Place
CITY OF LONDON
Darwin Brasserie
Grange Tower Bridge
COVENT GARDEN
Empire Casino
The Savoy
The National Gallery
St Martin-in-the-Fields
River Thames
Millennium Bridge
London Wall
Oxo Tower Wharf
Shakespeare's Globe
London Bridge
Tower of London
Mondrian London
Purcell Room
London
Underbelly Festival
Underbelly Festival • Today
HMS Belfast
Borough Market
Pizza Festival • Now
Tower Bridge
St Katharine Docks Marina
Banqueting House
The Shard
Potters Fields Park
Coca-Cola London Eye
Westminster Bridge
Big Ben
SEA LIFE London Aquarium
Southwark
Fashion and Textile Museum
Westminster Abbey
Palace of Westminster
London South Bank University
Backyard Cinema
White Cube
Maltby Street Market
St. Thomas' Hospital
ST SAVIOURS ESTATE

Kenwood House
Highgate Cemetery
The Whittington Hospital
Finsbury Park
Springfield Park
Golders Hill Park
Hampstead Heath
FINSBURY PARK
STOKE NEWINGTON
Valentines Park
SEVEN KINGS
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Danson House
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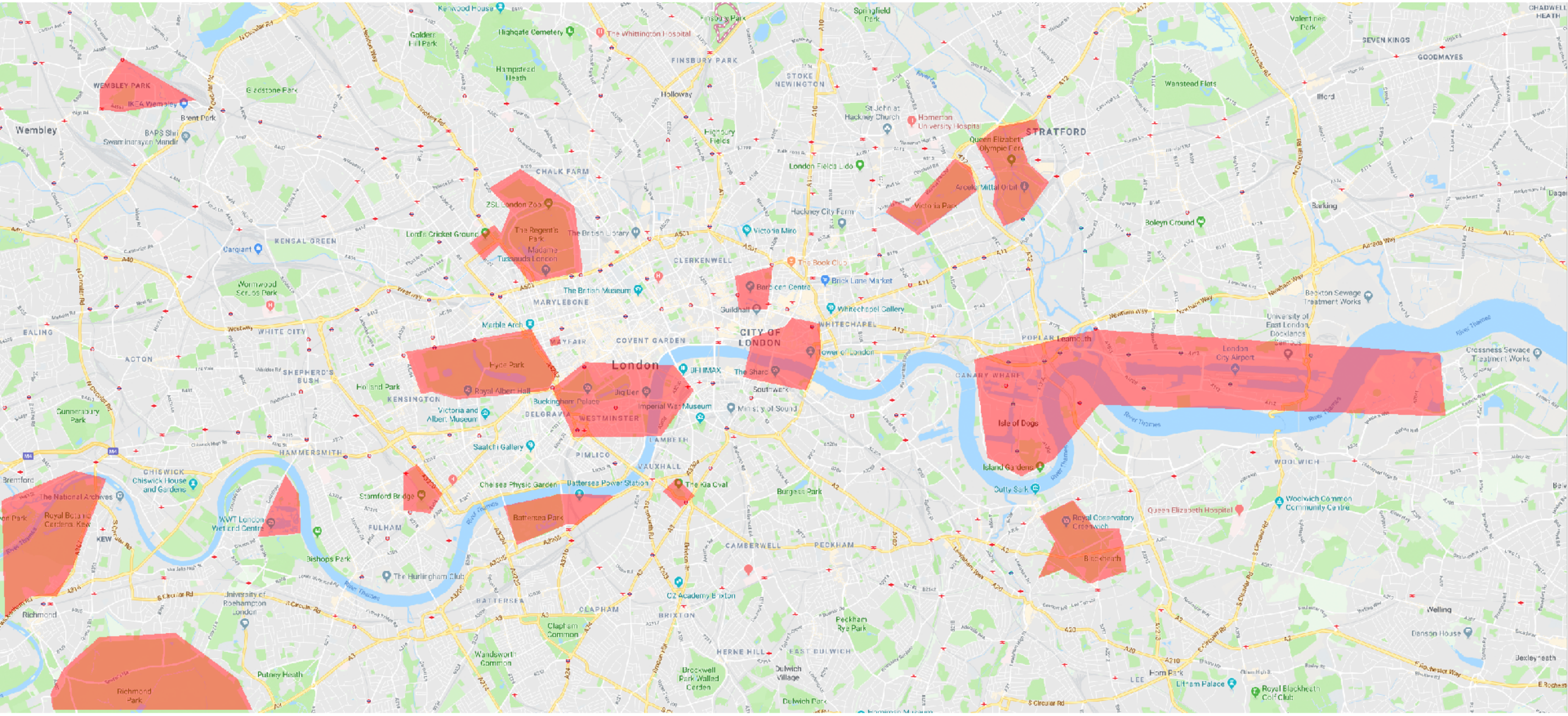
Wandsworth Common
Putney Heath
Brockwell Park Walled Garden
Dulwich Village
Horn Park
Bexleyheath
LEE
Eltham Palace
Royal Blackheath Golf Club
Richmond Park
Dulwich Park

32 km x 14.5 km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Golders Hill Park
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GOODMAYES
CHADWELL HEATH
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Welling
Danson House
HERNE HILL
EAST DULWICH
Wandsworth Common
Brockwell Park Walled Garden
Dulwich Village
Dulwich Park
Putney Heath
Richmond Park
LEE
Horn Park
Eltham Palace
Royal Blackheath Golf Club
Dartford Crossing
Bexleyheath

32 km x 14.5 km

5 km
4 km
Wembley
WEMBLEY PARK
CHALK FARM
KENSAL GREEN
MARYLEBONE
CLERKENWELL
CITY OF LONDON
COVENT GARDEN
London
MAYFAIR
WESTMINSTER
KENSINGTON
HAMMERSMITH
FULHAM
BATTERSEA
CLAPHAM
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PECKHAM
VAUXHALL
PIMLICO
STRATFORD
POPLAR
CANARY WHARF
Isle of Dogs
WOOLWICH
Richmond
Richmond Park
Hyde Park
Battersea Park
Blackheath
London City Airport

Scaling SpatialOS

Chunk Size

50 —> 250

32k x 14.5k / 50 * 50
= 185,600 chunks

32k x 14.5k / 250 * 250
= 7,424 chunks

Scaling SpatialOS

Chunk Size

50 —> 250

32k x 14.5k / 50 * 50
= 185,600 chunks

32k x 14.5k / 250 * 250
= 7,424 chunks

Entity Interest Range

200 —> 25

Match the radius drones need to check

Minimise what is checked out by workers


Wembley
WEMBLEY PARK
IKEA Wembley
Brent Park
BAPS Shri Swaminarayan Mandir
Gladstone Park
Golders Hill Park
Highgate Cemetery
The Whittington Hospital
Hampstead Heath
Finsbury Park
FINSBURY PARK
STOKE NEWINGTON
Holloway
Highbury Fields
St John at Hackney Church
Homerton University Hospital
London Fields Lido
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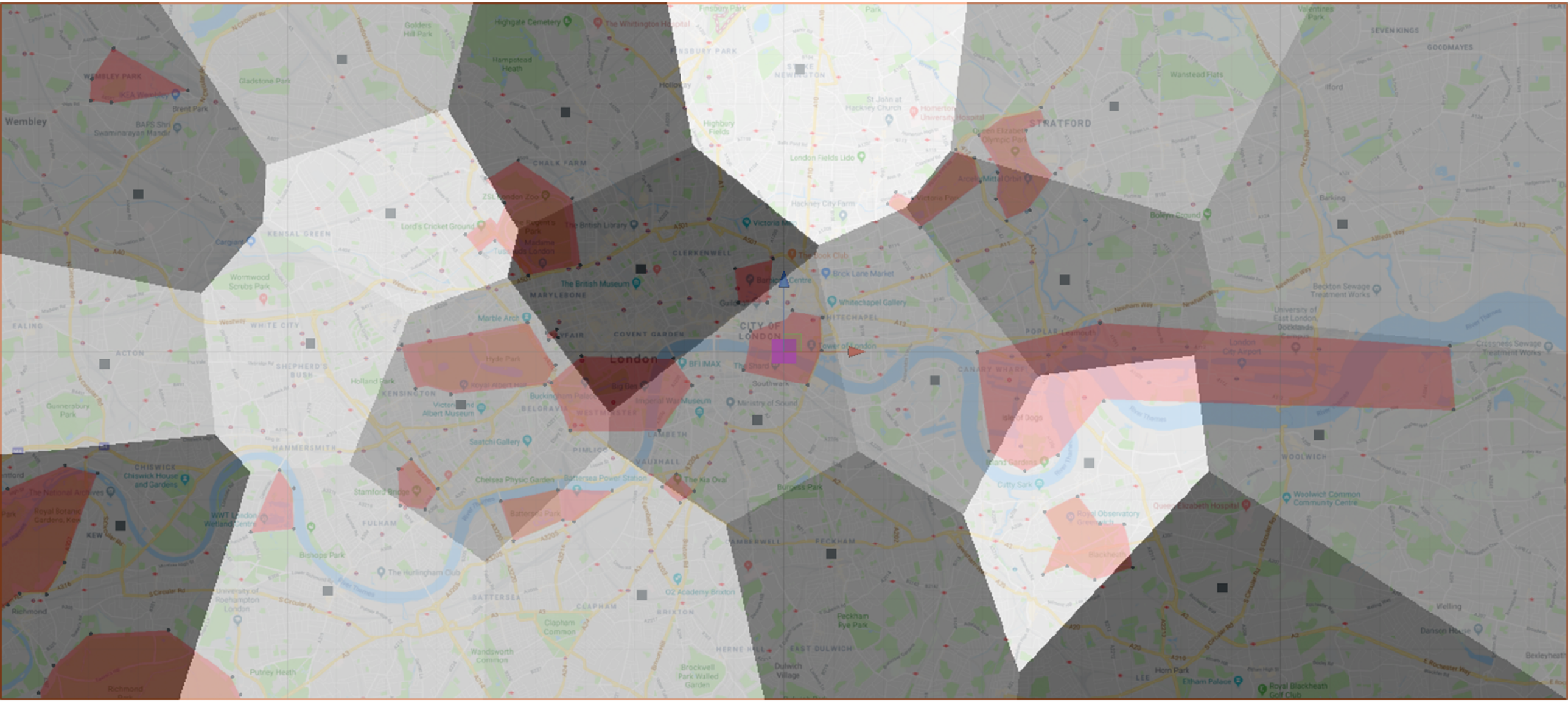
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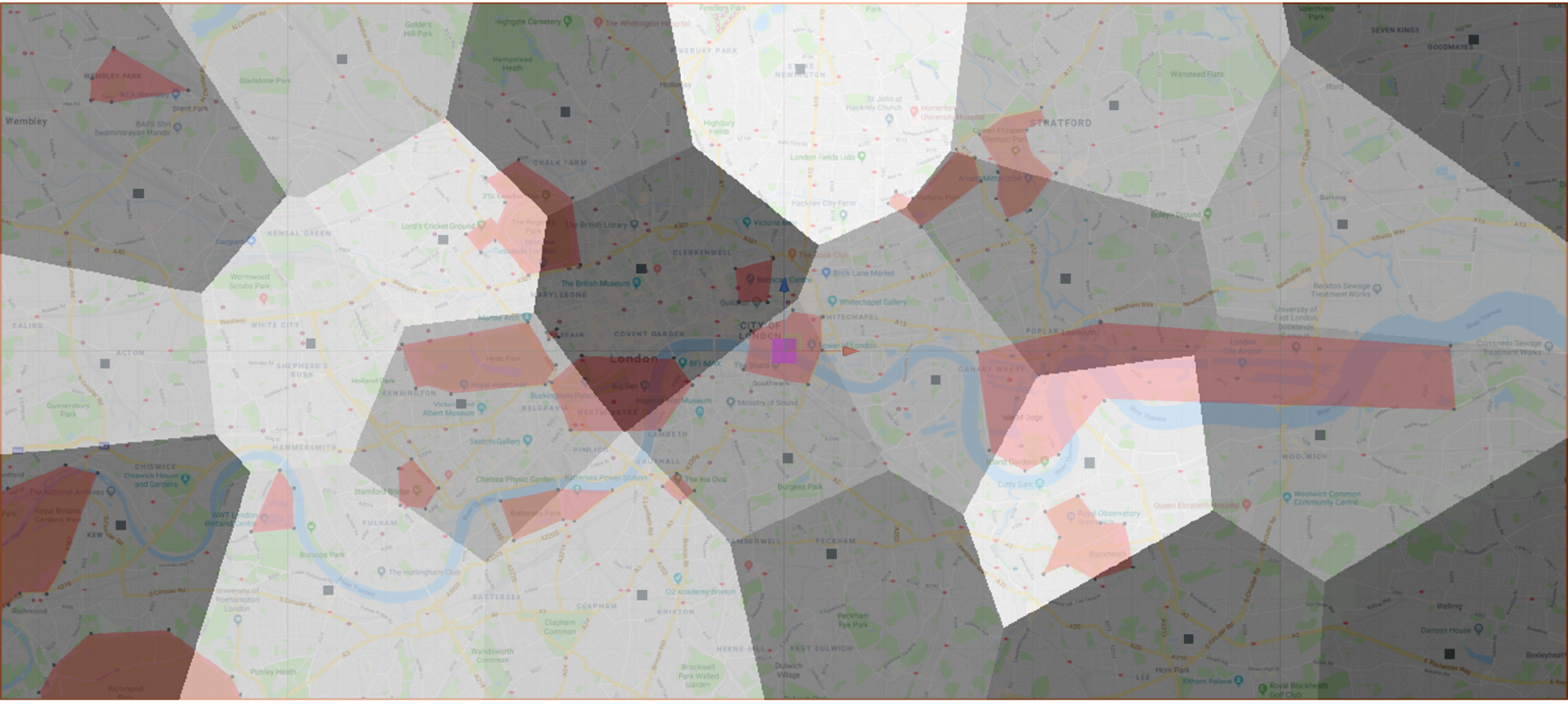
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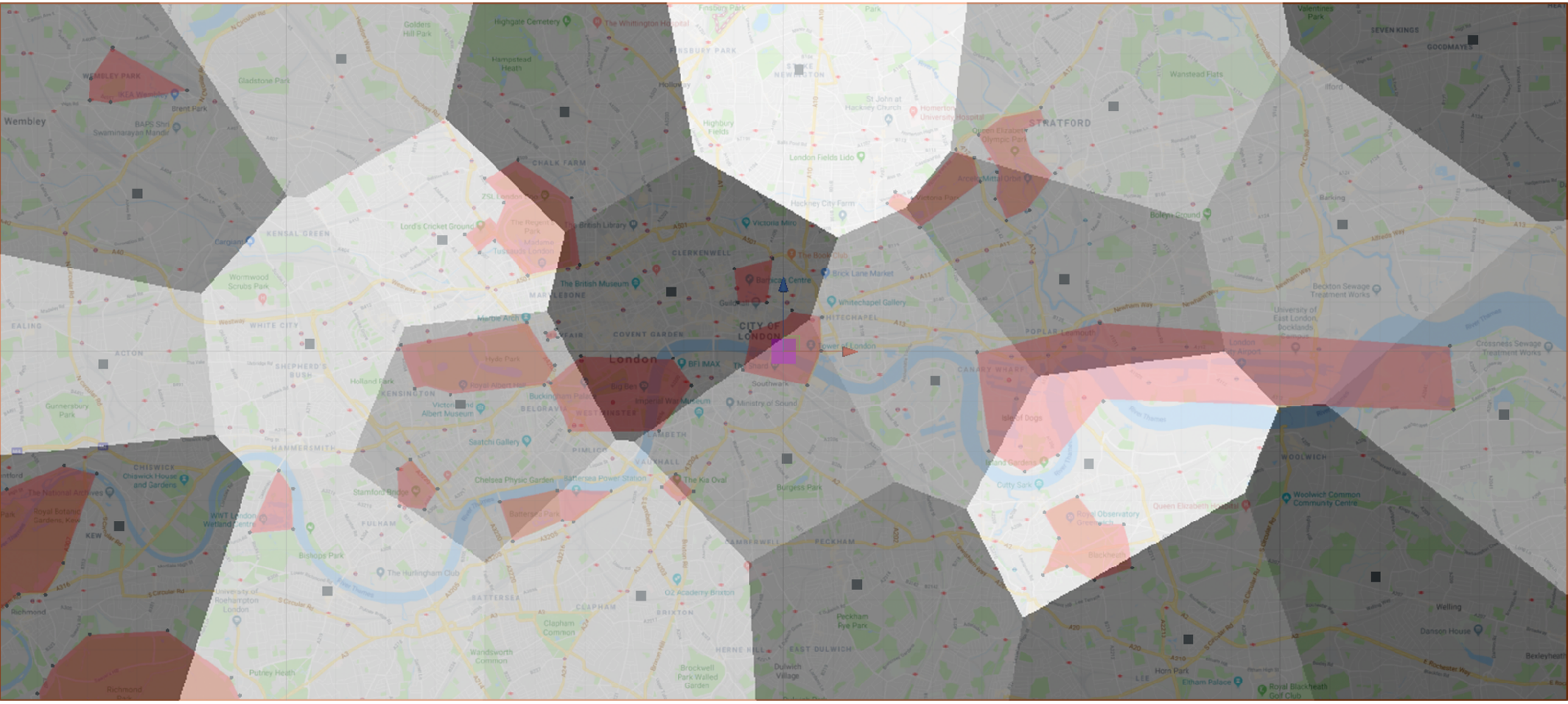
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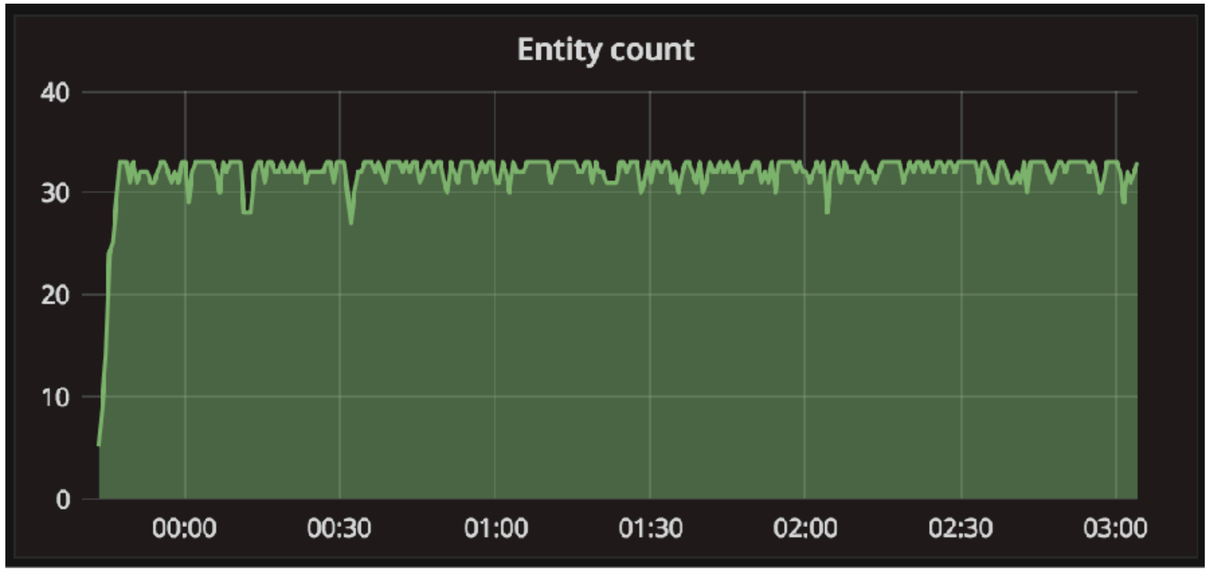
City of London
Tower of London
Barbican Centre
Guildhall
The Book Club
Brick Lane Market
Whitechapel Gallery
Hitechapel
Poplar
Canary Wharf
Isle of Dogs
Island Gardens
Cutty Sark
Royal Observatory Greenwich
Queen Elizabeth Hospital
Blackheath
Woolwich
Woolwich Common Community Centre
Welling
Danson House
Bexleyheath
Horn Park
Lee
Eltham Palace
Royal Blackheath Golf Club
University of East London Docklands Campus
London City Airport

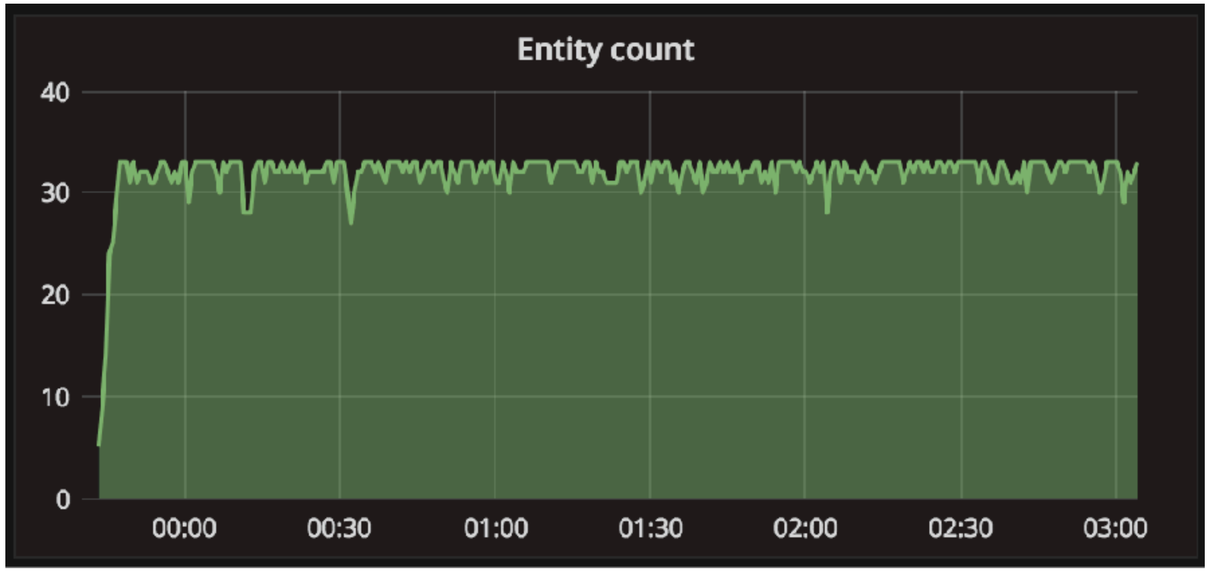
Scaling SpatialOS

Chunk Size	Entity Interest Range	Load Balancer
50 —> 250	200 —> 25	Point of Interest
32k x 14.5k / 50 * 50 = 185,600 chunks	Match the radius drones need to check	Feed controller locations
32k x 14.5k / 250 * 250 = 7,424 chunks	Minimise what is checked out by workers	Put each controller onto a different worker

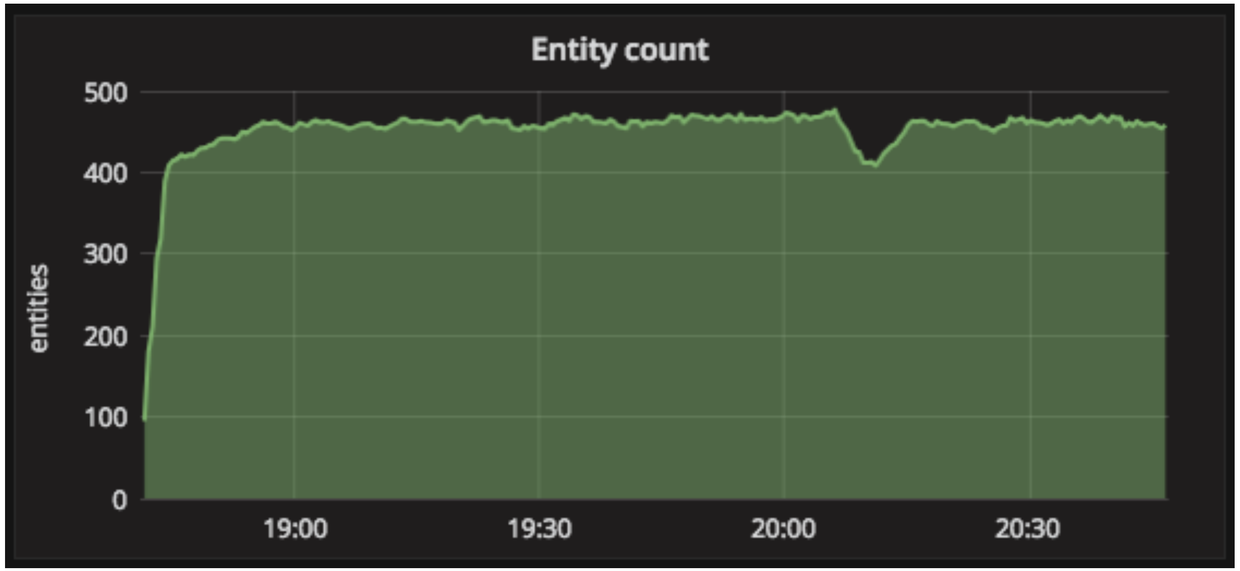
From this...



From this...



...to this!



bigger bugs appearing

bigger bugs appearing

23.2x larger world

bigger bugs appearing

23.2x larger world

11.5x more controllers

bigger bugs appearing

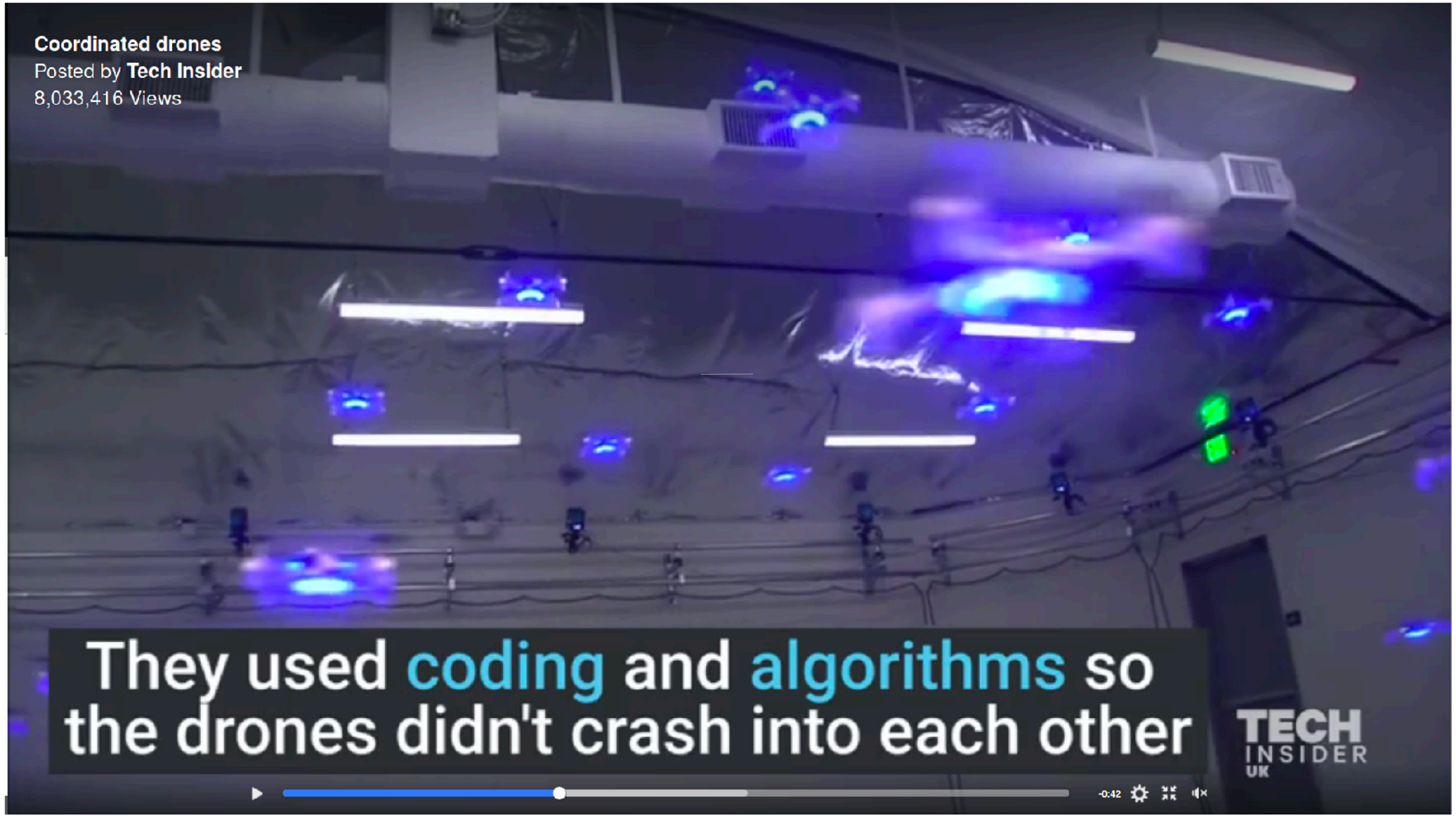
23.2x larger world

11.5x more controllers

14.7x more drones


Great Ormond Street Hospital
Improbable
Fabric
GOLDEN LANE ESTATE
B100
Barbican Centre
BARBICAN

Questions?



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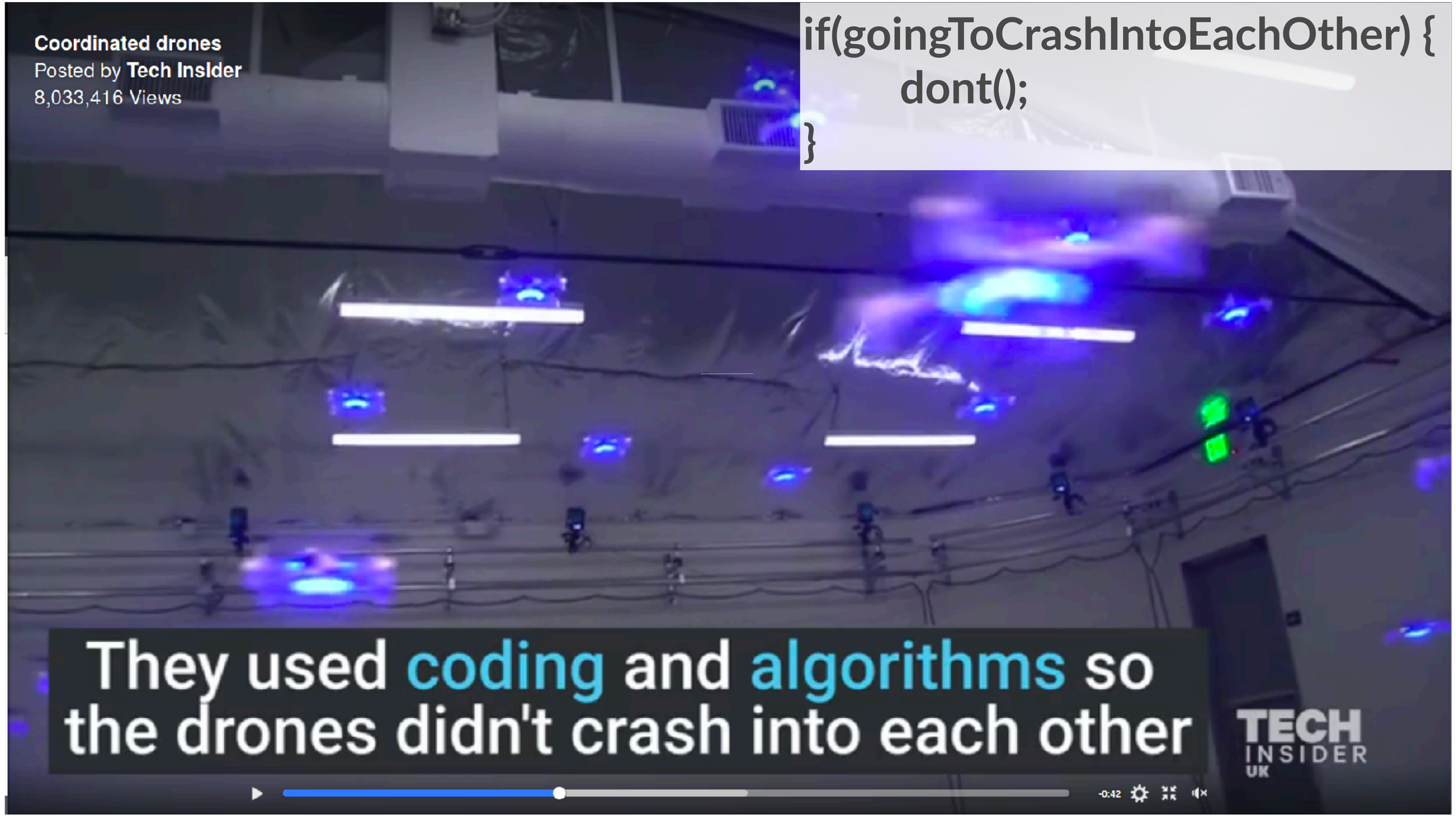

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