The 'ReCCEL' toolbox: a response to carbon reduction challenges in the UK construction industry

MEETING NATIONAL NEEDS

Roberto Rossi

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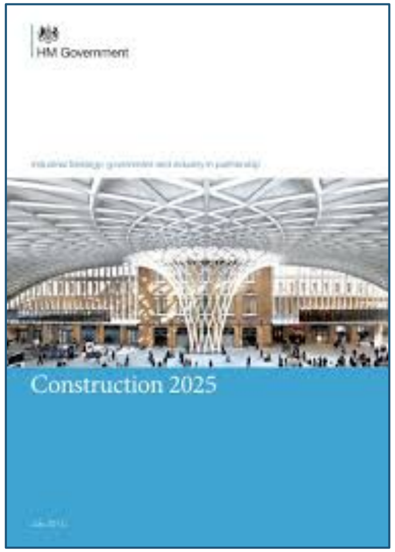
Business School

The ReCCEL Project

Aim:

We analyse the feasibility of low-carbon delivery of major infrastructure projects whilst ensuring compliance to schedule/budget and resilience to operational disruptions. The fragmented nature of construction logistics currently represents a challenge to these aspirations.



Scope:

In ReCCEL, by focusing on a portfolio of Costain's major infrastructure projects, we

- mapped current construction processes and elicited barriers to the fully integrated, low-carbon construction supply chain;
- road mapped scenarios based on our blend of solutions and related enabling business models; and
- provided and disseminated return on investment recommendations.

EPSRC

Innovate UK
Technology Strategy Board

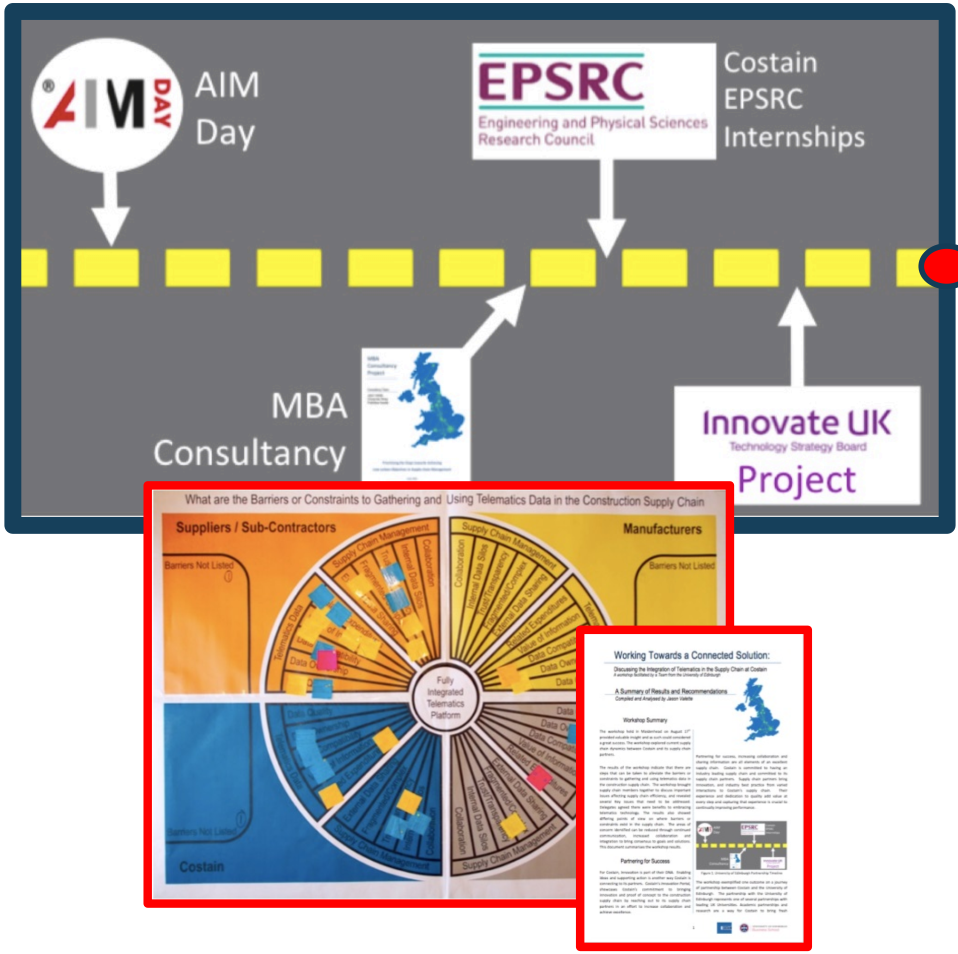
ReCCEL Project Partners

Project Consortium

External Partners

The ReCCEL Timeline

prep/groundwork



1st Oct 15 – project starts

2nd Nov 15 – telematics workshop

29th Jan 16 – Workshop 1

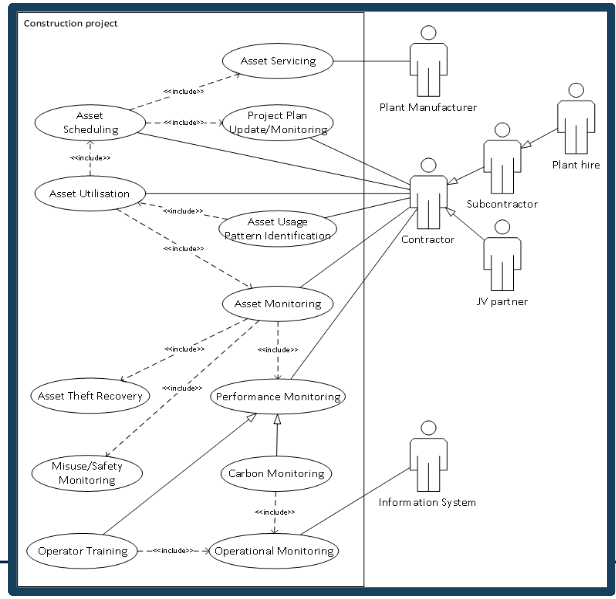
25th Feb 16 – Workshop 2

22nd Apr 16 – workshop 3

EURO 2016

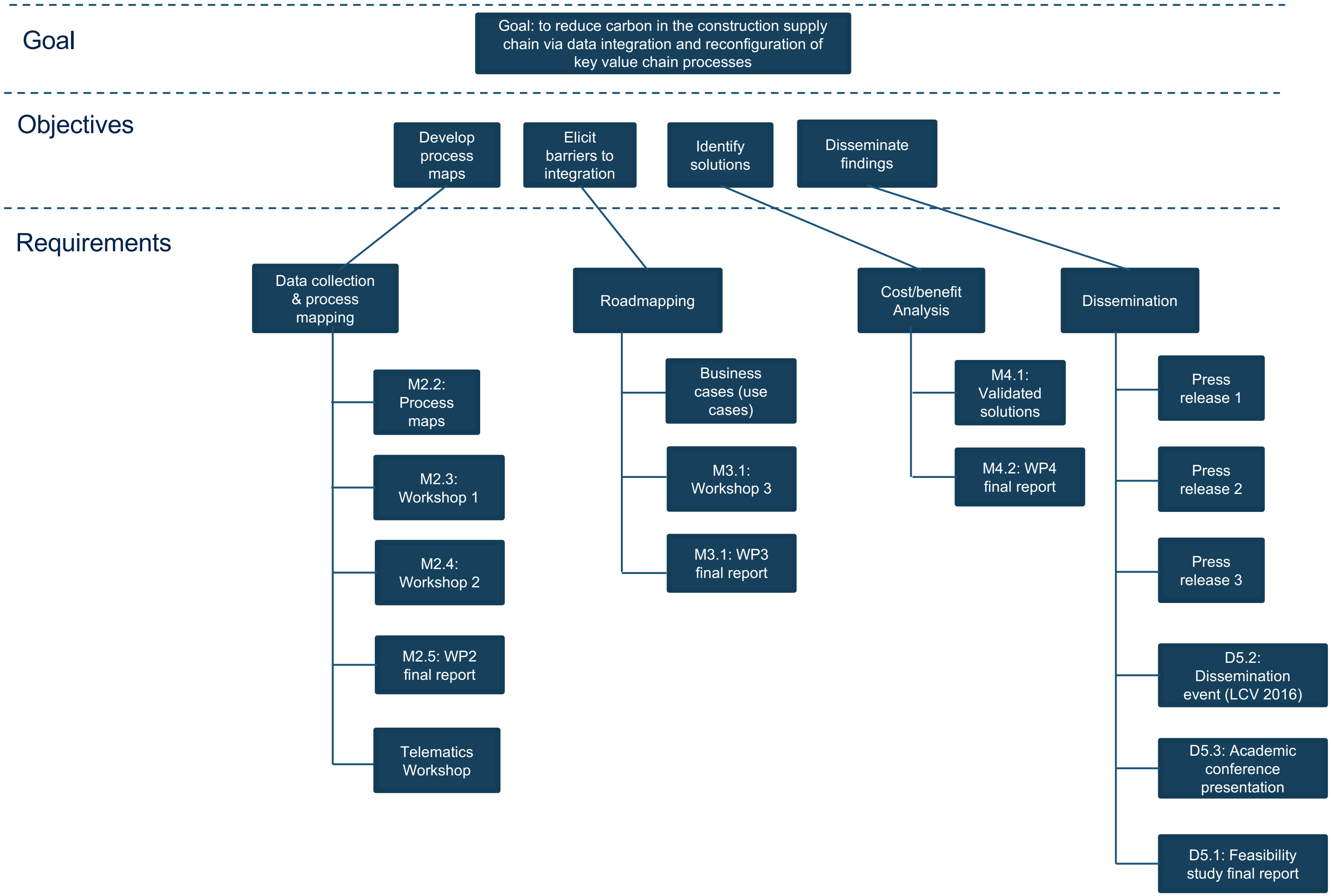
LCV 2016

ReCCEL use cases



ReCCEL toolbox development

ReCCEL Project Overview



Data Collection and Process Mapping

During months 1-3 of ReCCEL, partners focused on **data collection** across the Costain sites listed below.

Site	Business partners	Business Context	Business Processes	Telematics	Carbon
A1+	X				
A14	X				
C610	X	X	X	X	
Heysham				X	
Shieldhall	X	X			X
Tideway					X
Woolston	X				

The goal was to obtain information on business partners and supply chain structure.

Following this data collection exercise, two of the sites were singled out, **Shieldhall** and **C610 - Systemwide**, to perform a more in-depth business context analysis.

Site Visits

The **Shieldhall tunnel** is a 3.1 mile-long wastewater tunnel in the south of Glasgow as part of the biggest upgrade of the city's waste water network in more than a century.

The £100m tunnel commissioned by Scottish Water will be constructed from Craigton Industrial Estate and will run under Bellahouston Park, Pollok Park, along Titwood Road to Queen's Park where it ties into the existing sewer network.

The project will improve water quality in the River Clyde and its tributaries and reduce flooding issues at key locations.

Site Visits

Visited **Shieldhall** on December 1, 2016

Site Visits

C610 - Systemwide is one of the last and largest contracts to be let by Crossrail. The consortium ATC involves three main partners: ALSTOM, TSO and COSTAIN.

With a project value at £400m ATC are responsible for the fit out of 21km of twin bored tunnels.

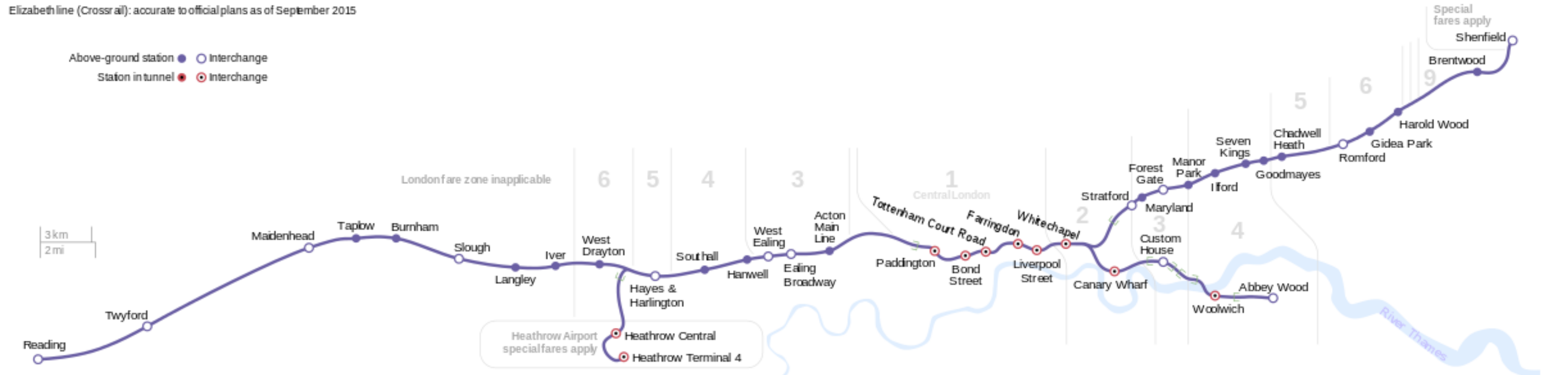
The main works involve the installation of track, overhead electric conductor rails to power the trains, ventilation, drainage, lighting, over 40km of walkways and 30km of fire mains.

The scale of C610 and the variety of materials used throughout the project presents some significant challenges in environmental performance.

In order to meet the project target of an 8% reduction in ATC's carbon footprint the team must continually seek innovative solutions to the daily operational needs.

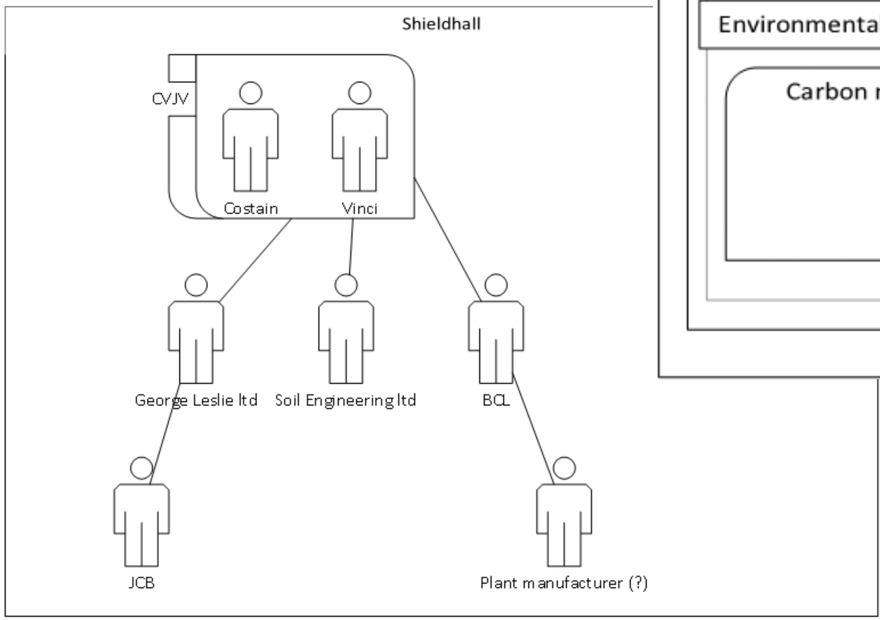
Site Visits

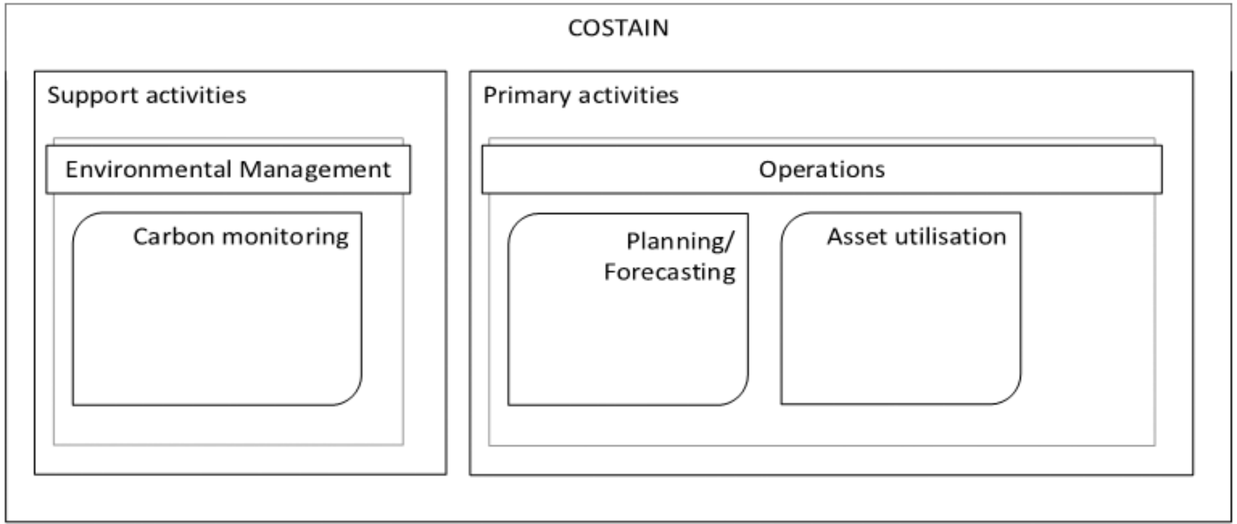
Visited **Crossrail C610 site** on January 22, 2016



Data Collection and Process Mapping

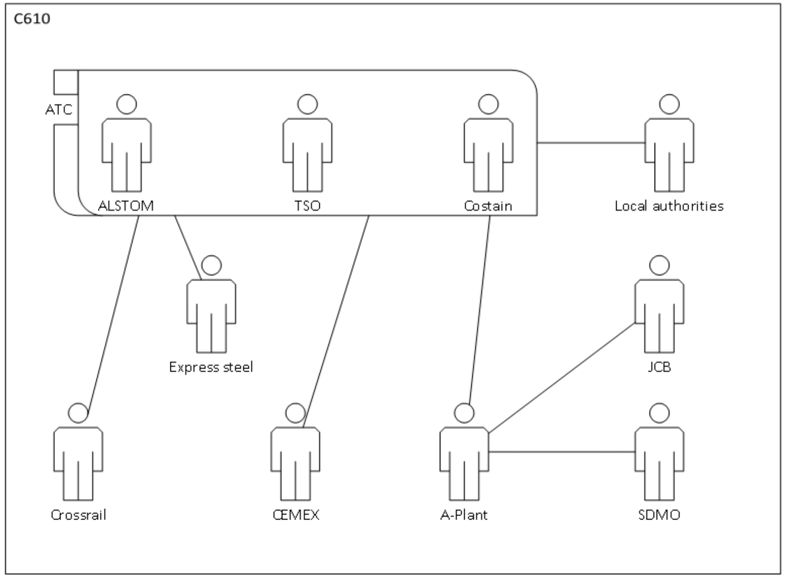
Shieldhall **Collaboration Diagram** and **Business Context Model**

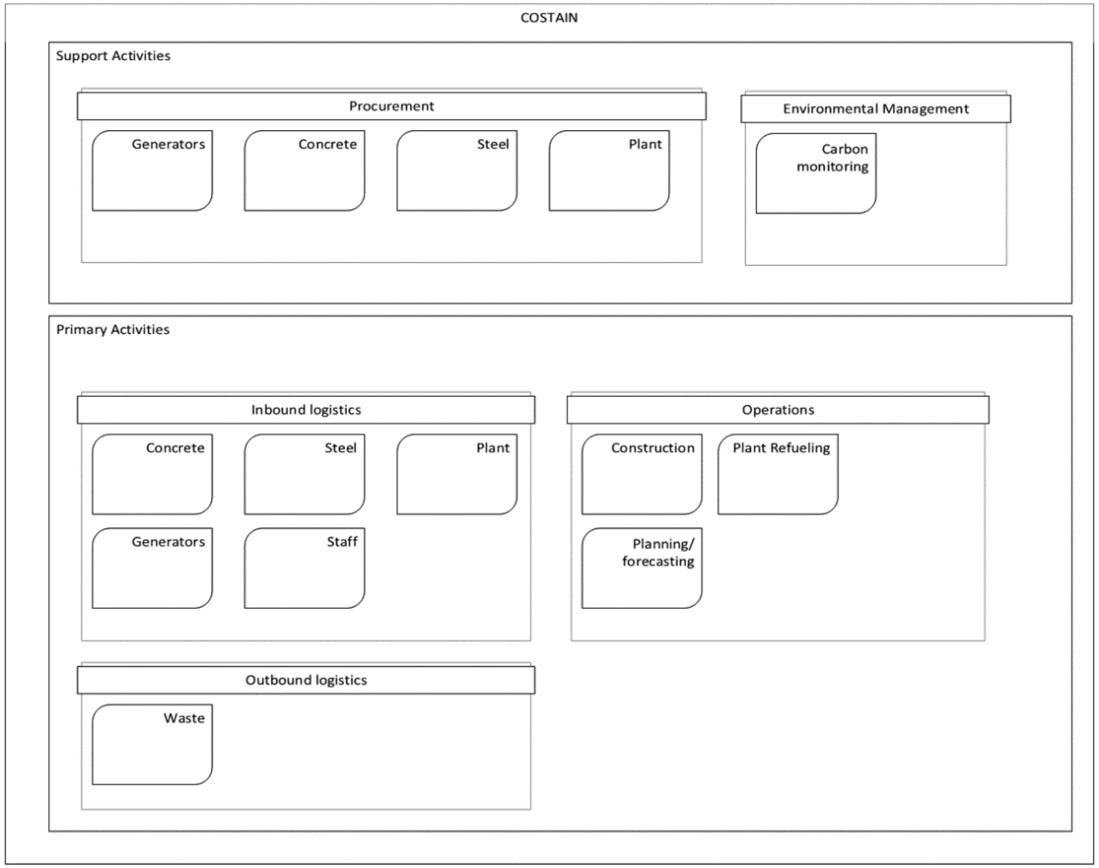




Data Collection and Process Mapping

C610 **Collaboration Diagram** and **Business Context Model**





Data Collection and Process Mapping

In the time span between Workshop 1 and Workshop 2, while we carried out our site visits, we developed two reports:

Report 1 - Carbon Auditing in Construction

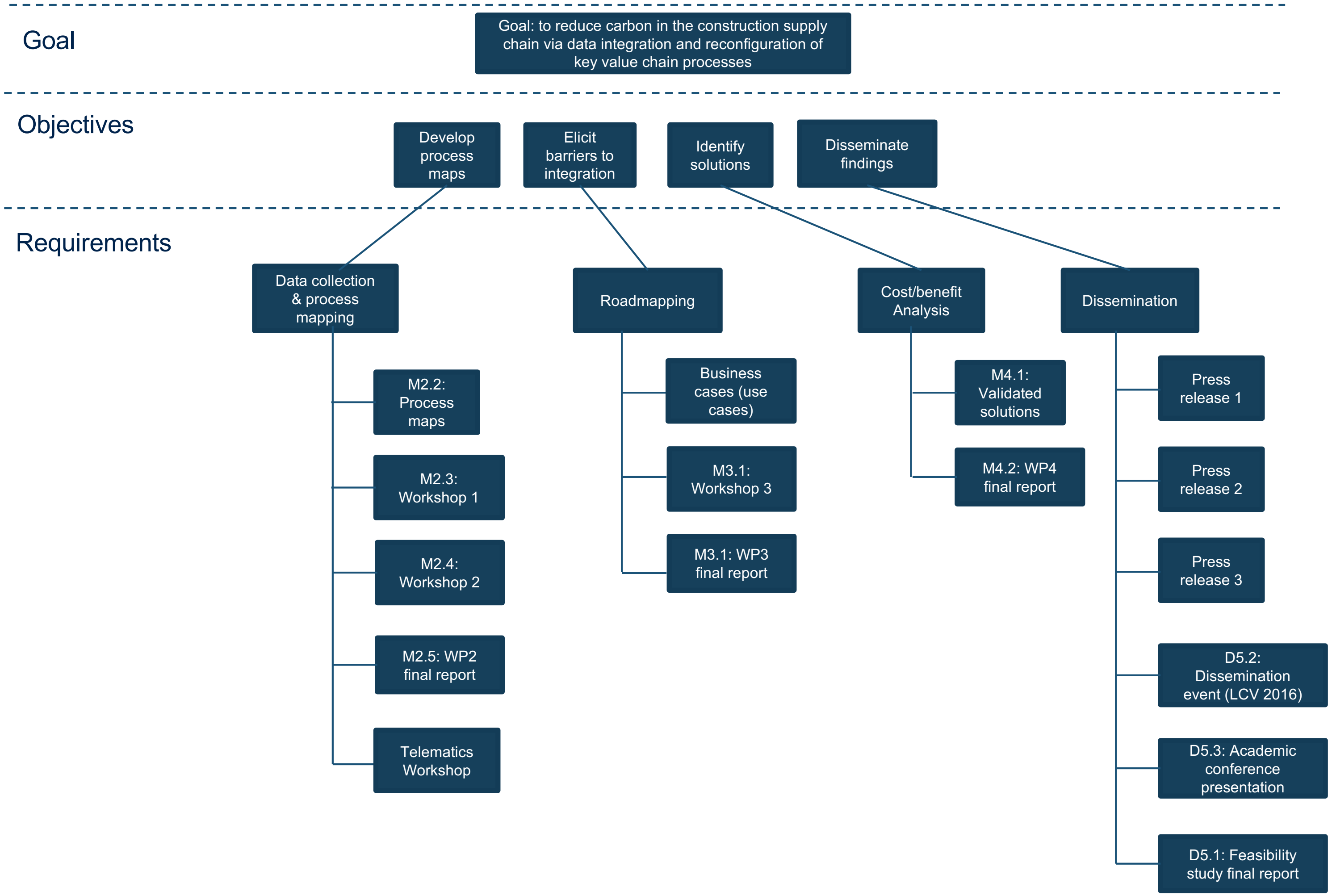
Report 2 - Telematics Asset Monitoring in Construction

surveying **carbon auditing practices**, and **telematics systems** in the construction sector, respectively. These reports informed Workshops 2 and 3.

In the period between Workshops 1 and 2, UoE received support from JCB and obtained access to three **JCB telehandlers** located at the C610 Systemwide Crossrail site.

Thanks to this synergy with JCB, it has been possible to automate data collection by using the **JCB LiveLink system**.

ReCCEL Project Overview

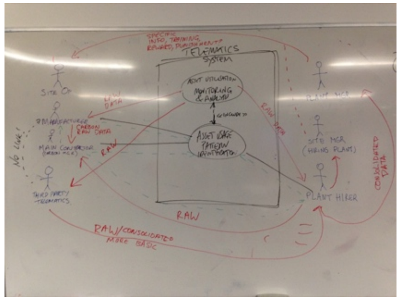


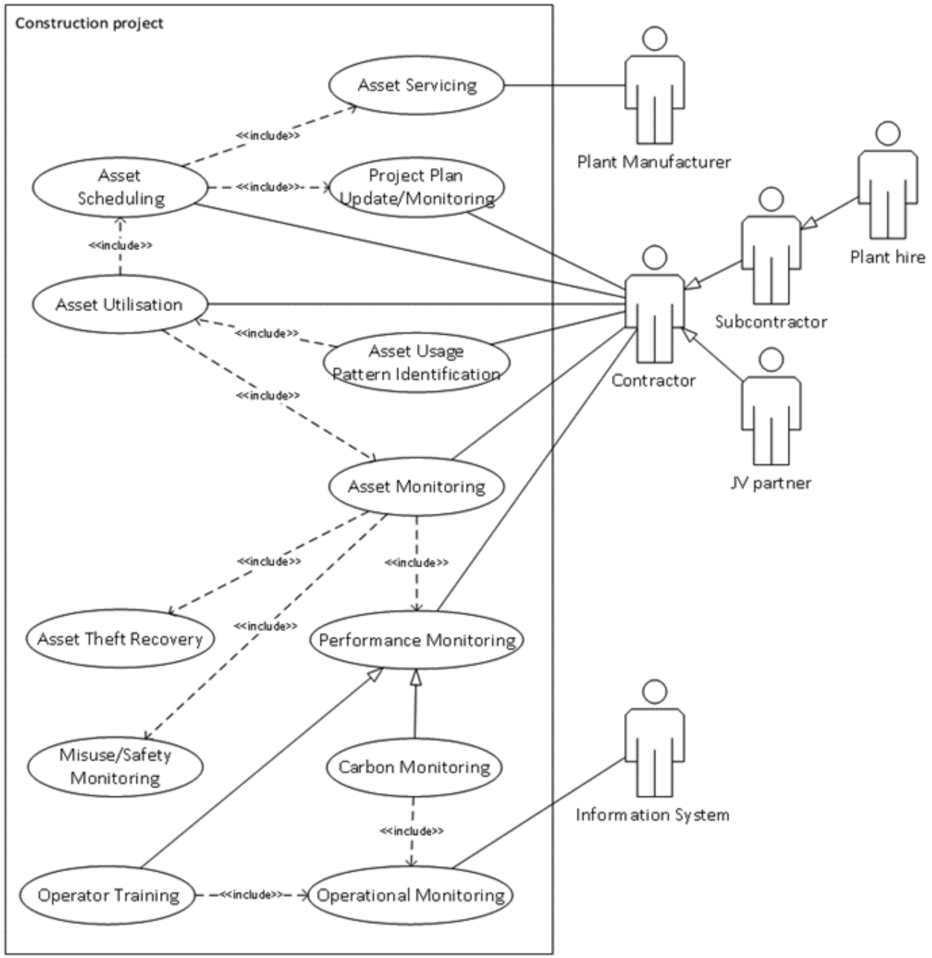
Use Cases

By building upon our process maps, we developed a number of **Use Cases** to address challenges identified in the area of **Asset Monitoring** and **Asset Scheduling**.

Use Cases were validated in the context of Workshop 1.

In Workshop 2 we focused on current **barriers to data and processes integration** in the supply chain, and in particular to telematics-driven intelligent systems.





Use cases

Barriers Identified - Telematics

Carbon reporting requirements differ across sites; there are heterogeneous practices in place and standardisation is a requirement. It is possible, that this should take into account existing reporting standards in other fields (further discussion on this in M2.5 Appendix A6).

Joint ventures (JV) tend to be contract-oriented; therefore, if certain data (e.g. telematics data) are required or certain reporting practices need to be implemented, it is necessary to design specific contract clauses to ensure compliance. Contracts are not predefined, they are flexible and the choice of solutions can vary from time to time.

JVs tend to set their own planning standards; these may be in line with past practices or customs or with stakeholder requirements. Generally, the partner with the highest stake owns the plan and sets reporting standards. Team experience and composition tend to influence tools adopted.

Barriers Identified - Telematics

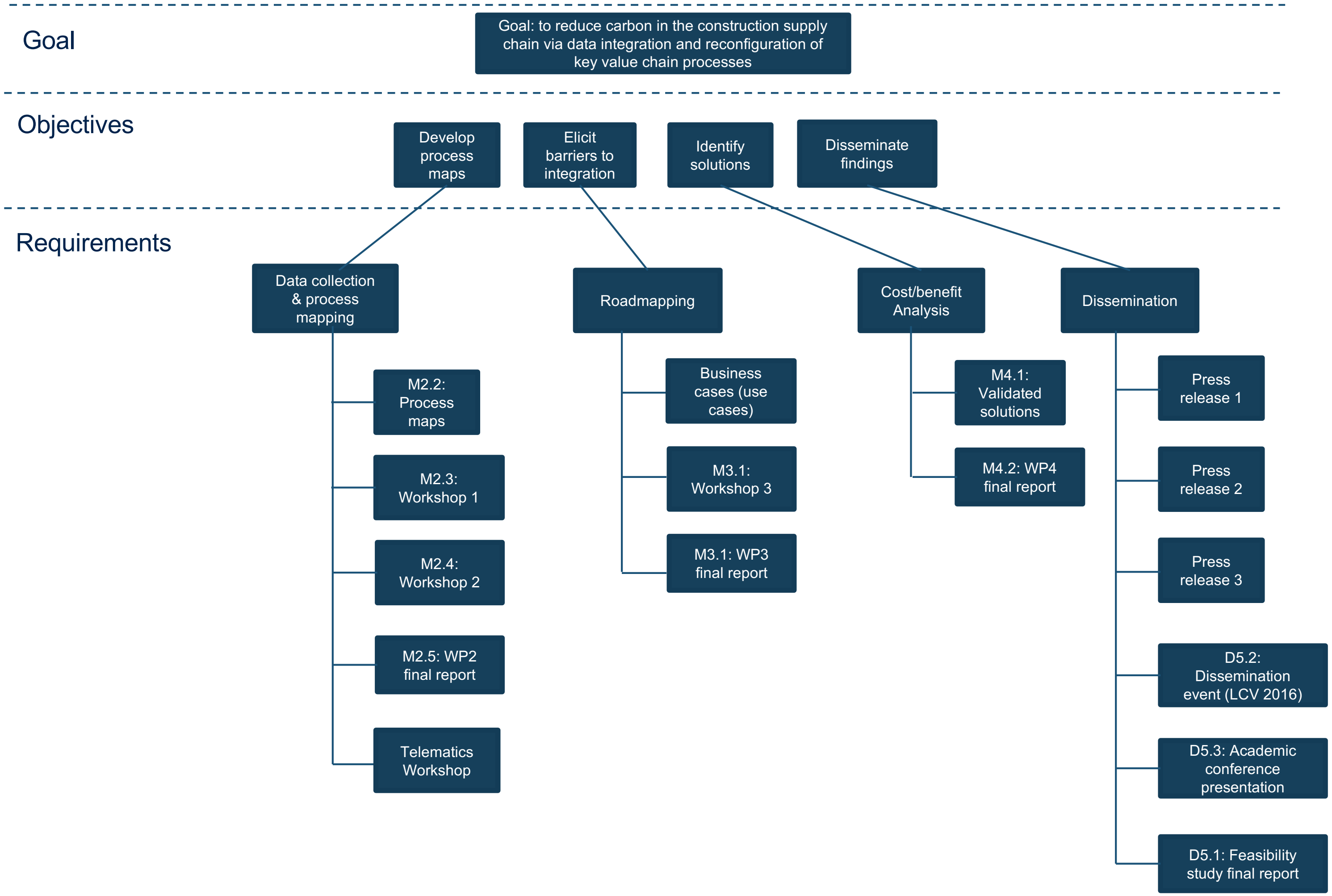
Following the plenary discussion there was a general concern on **data cascading and decision making**. Partners were concerned about data from monitoring use cases being shared with competitors (e.g. rental rates for plant). There was also a concern with early commitments to planning decisions: if a plan is shared, who can see it? Furthermore, when are decisions “frozen”?

There was a general consensus on the relevance of the use case “asset monitoring” and on the fact that participants would like to have better visibility of assets on sites (plant, generators, etc.) and their utilization; e.g. **develop “site heat maps”** to visualize hot spots in terms of emissions, idling etc.

Information on asset utilisation should be fed into automated reasoning algorithms to **optimize activities such as asset refuelling**. At the moment there is no integration.

There was a consensus on the need to develop an **asset booking system** to match assets to jobs across partners. Asset requirement could be utilised in a **centralised asset scheduling system** owned by the plant hire firm to coordinate plant scheduling and servicing and to enhance visibility on asset location/availability at a given time.

ReCCEL Project Overview



Solutions Developed – ReCCEL Toolbox

By leveraging on automated data collection and on business partner input received during ReCCEL Workshops, UoE outlined the “ReCCEL Toolbox,” a set of solutions whose aim is to tackle supply chain integration and carbon reduction across Costain sites.

The Toolbox features a number of solutions that aim to tackle the two use cases originally identified: **Asset Monitoring** and **Asset Scheduling**.

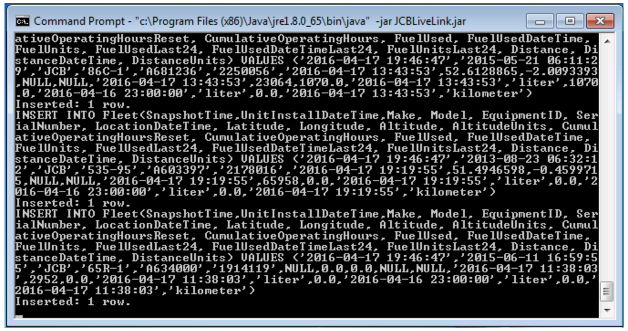
Tool	Supply Chain Integration	
	Type	Level
ReCCEL Carbon Dashboard	Data	Single-site
Asset Scheduling/Servicing	Data + Process	Multi-site
Asset Routing/Refueling	Data + Process	Single-site
Asset Booking System Asset Requirement Document (ARD)	Data + Process	Multi-site

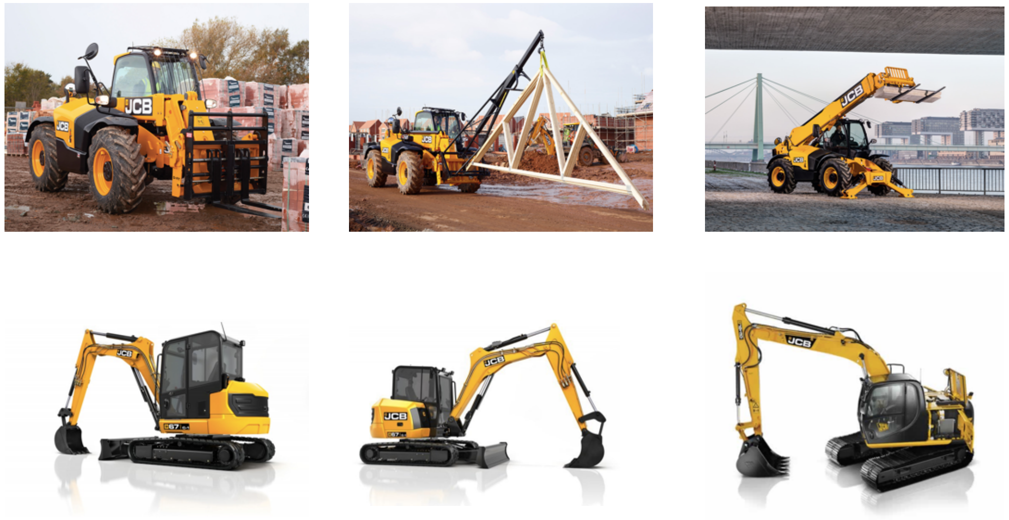
Due to time constraints we focused on delivering an **Asset Monitoring Dashboard** and a decision support system for **Asset Routing/Refuelling**.

Solutions Developed – ReCCEL Toolbox

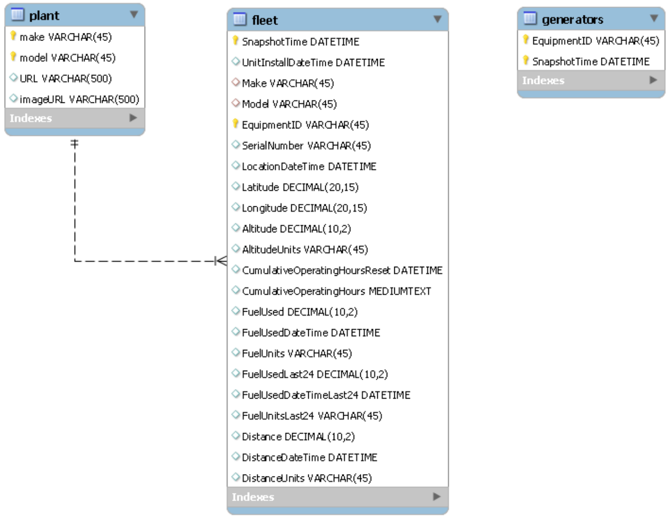
Asset Monitoring Dashboard

By leveraging on JCB LiveLink and on the AEMP standard we tracked 99170 records between 2016-02-22 23:30:45 and 2016-04-17 19:34:44 (sampling rate: 5 minutes).





11 assets tracked of different types

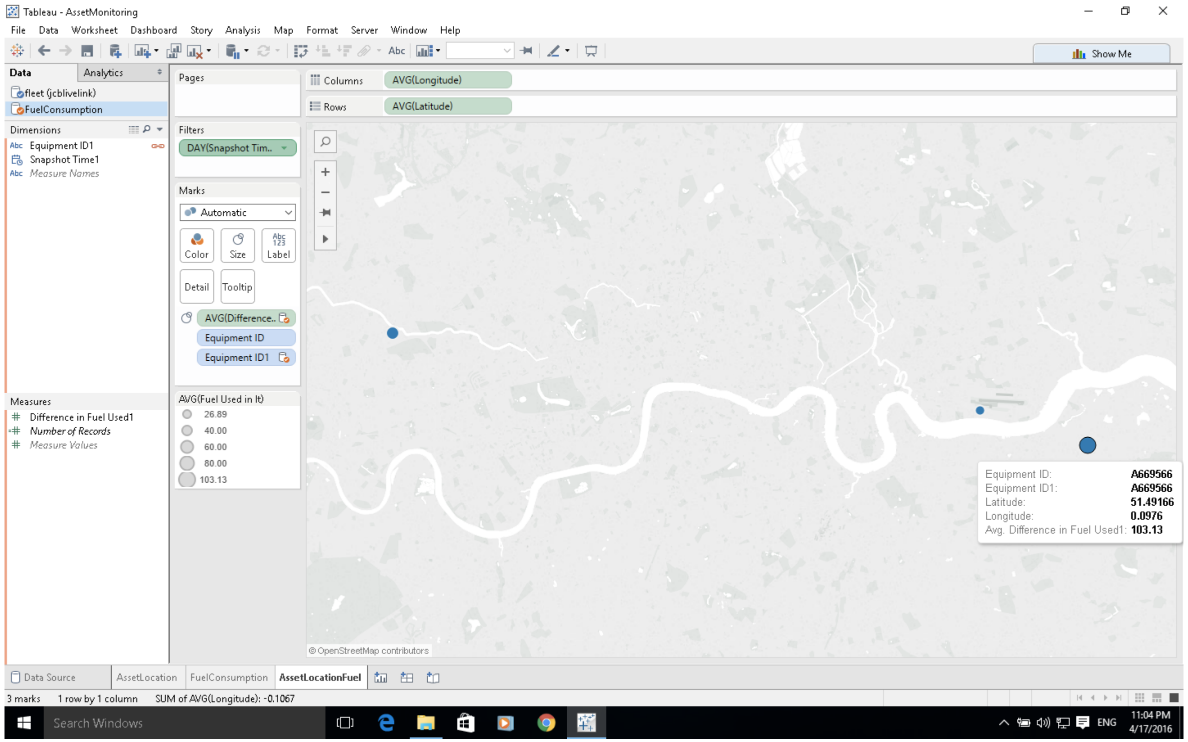


E/R model of the database

Solutions Developed – ReCCEL Toolbox

Asset Monitoring Dashboard

Data can be accessed and analysed with off-the-shelf tools such as Tableau



Average daily fuel consumption per asset between 22 and 27 February 2016 at C610

Solutions Developed – ReCCEL Toolbox

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Asset Monitoring Dashboard

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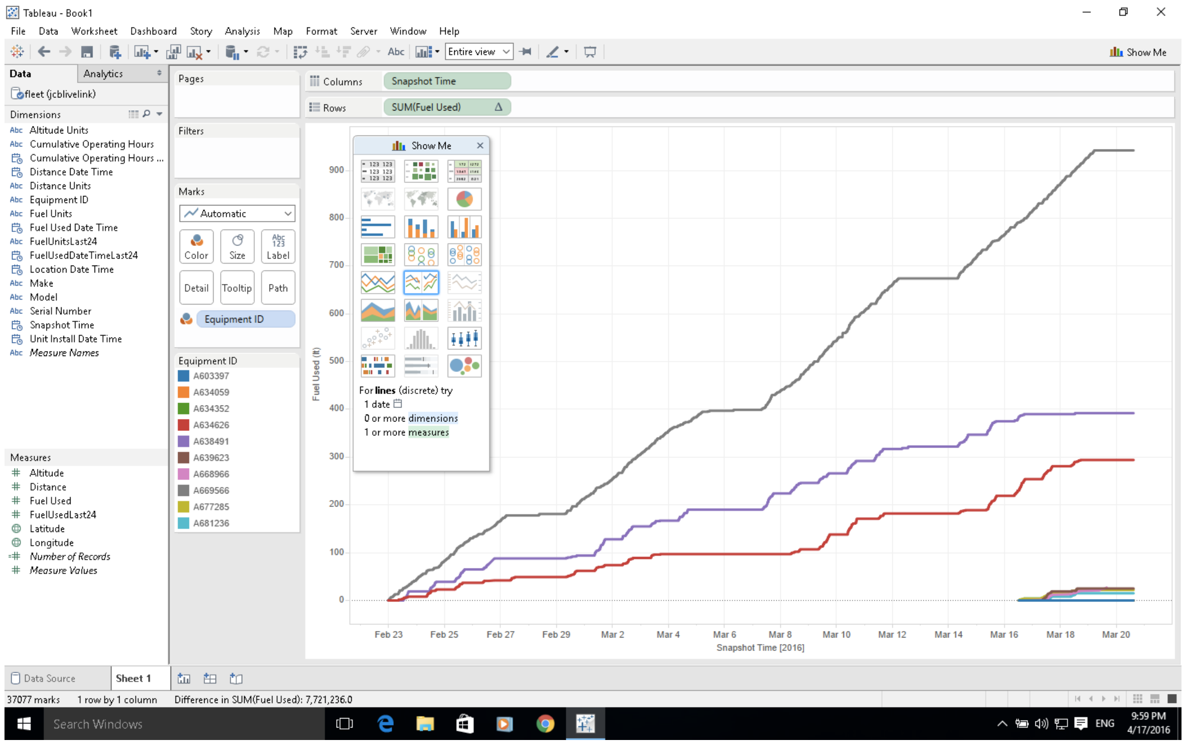
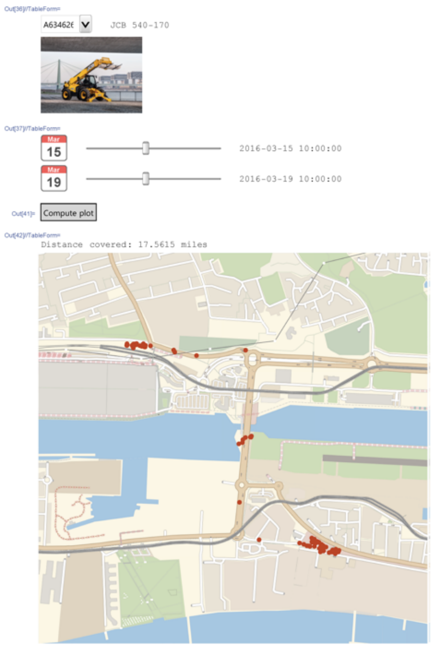


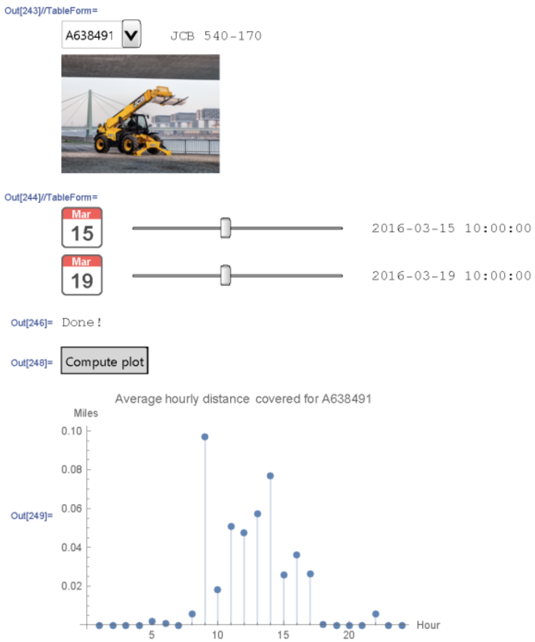
Fuel consumption of different assets

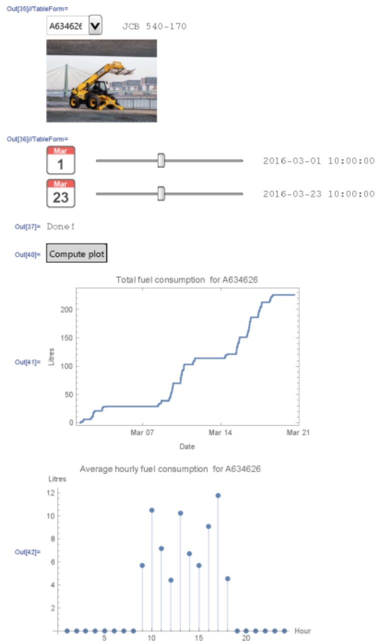
Solutions Developed – ReCCEL Toolbox

Asset Monitoring Dashboard

We developed a dedicated monitoring dashboard in Mathematica™ for advanced data visualization and statistical analysis







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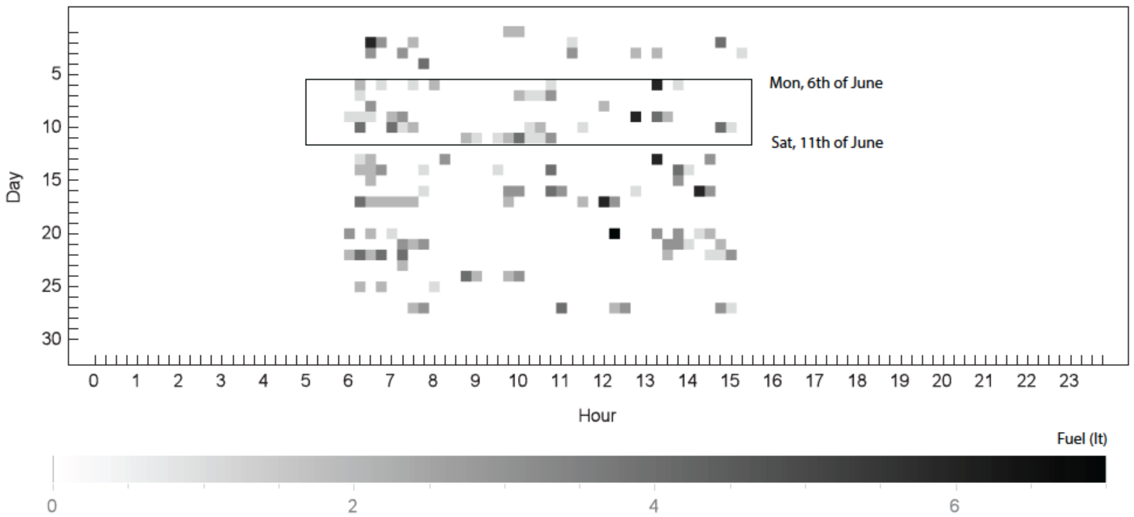


Monthly fuel consumption heat map for a JCB 540-170 at C610, June 2016

Data Analysis

By leveraging on the data we collected via our **Asset Monitoring Dashboard** we generated a set of asset consumption profiles that are representative of real-world scenarios.

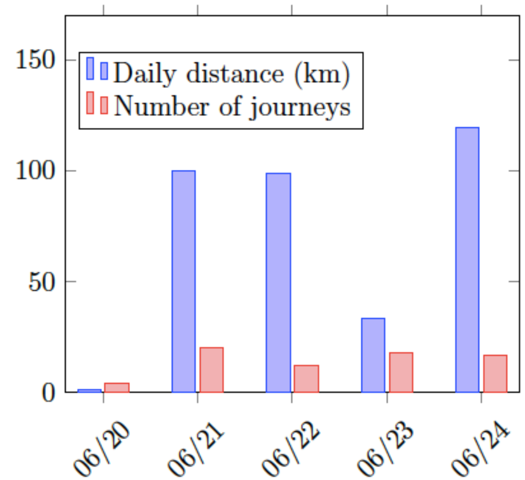
	Compound Poisson		
Asset	λ	jump size distribution	p-value
JCB 540-170	0.502645	Poisson(0.602257)	0.91558
JCB 540-170	0.774271	Poisson(0.684164)	0.449291
JCB 540-170	0.3731890	Poisson(1.004940)	0.933036
JCB JS130	1.03892	Poisson(1.01056)	0.460517
JCB JS130	0.926141	Poisson(0.393873)	0.116692
JCB 86C-1	0.476964	Poisson(0.960902)	0.778792
JCB 531-70	0.283428	Poisson(0.0516331)	0.516138

Table 1: Fitted distribution for a selection of JCB assets deployed on Crossrail sites in June 2016; the distribution represent the fuel consumption over a 15 minutes time bucket.

Data Analysis

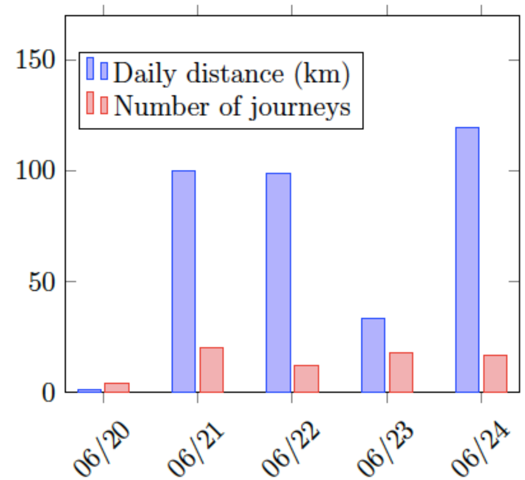
We also tracked a bowser truck over several days and analysed current refuelling activities.

Figure 8: A bowser journey from the Connaught bridge site in North Woolwich to the C610 site of Crossrail in Plumstead on Tue, 21th of June; the bowser covered 47.6km in 1h and 31 minutes.



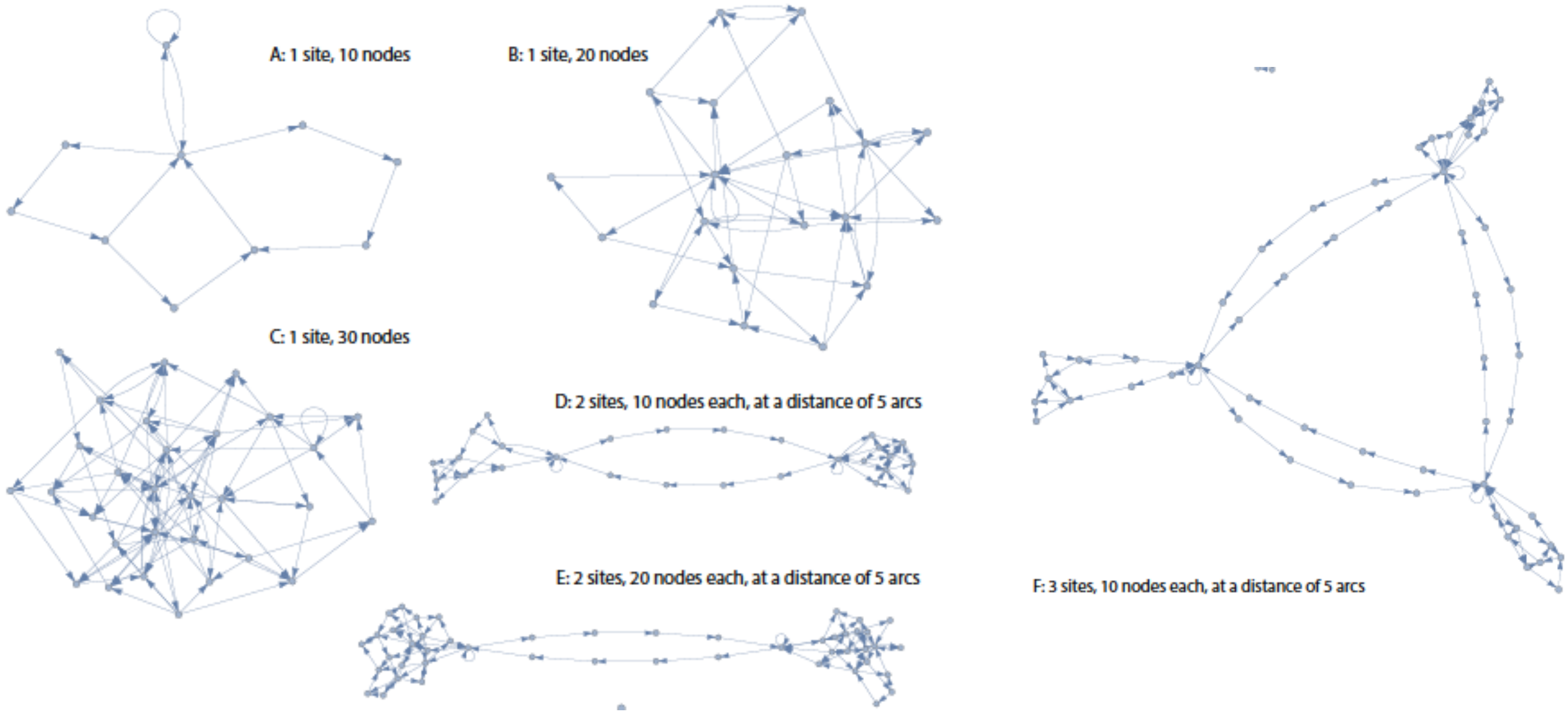
We also tracked a bowser truck over several days and analysed current refuelling activities.

Figure 9: Two short on-site journey at Crossrail C610 site; the first journey (on the left hand side) covered 1.3km in 44 minutes and comprises four stops of less than five minutes each; the second journey (on the right hand side) covered 1.7km in 37 minutes and comprises five stops of less than five minutes each.



Data Analysis

We generated a portfolio of site topologies that are representative for single and multi-site scenarios



Solutions Developed – ReCCEL Toolbox

Asset Routing/Refuelling

We developed a **decision support system** for scheduling asset replenishment operations; the model relies on live asset location and consumption data obtained from the JCB LiveLink™ system.

Solutions Developed – ReCCEL Toolbox

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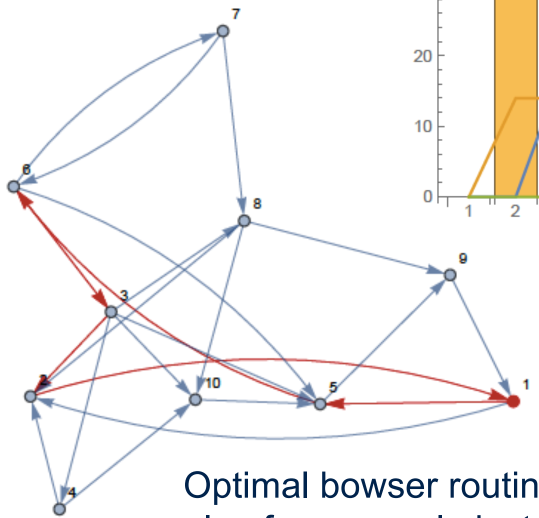
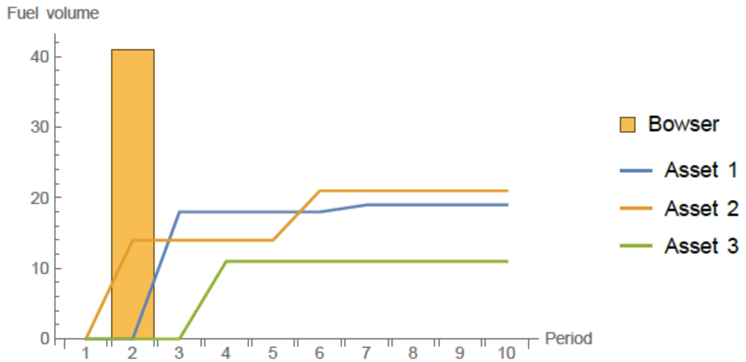
Sample site network for the Connaught bridge Crossrail site in London; triangles represent assets.



Optimal bowser routing plan for a sample instance analysed in our working paper



Bowser and asset refuelling plan

Solutions Developed – ReCCEL Toolbox

Our solutions are based on **Mathematical Programming** (IBM ILOG OPL) and on **Dynamic Programming** (jsdp); the latter can also tackle situations in which fuel consumption and/or asset location are uncertain.

A sketch of our OPL model

```
/*********************************************
* IBM ILOG OPL 12.6.0.0 Model
* Author: Roberto Rossi
* Creation Date: Apr 12, 2016 at 4:02:27 PM
*********************************************/
/* Assume machine 1 is the cistern */

int T = 5;
int M = 4;
range time = 1..T;
range machines = 1..M+1;
float distance[1..T-1][machines][machines] = ...;
int fuelConsumption[machines][time] = ...;
float initialTankLevel[machines] = ...;
float tankCapacity[machines] = ...;

dvar int visit[machines][time] in 0..1;
dvar int transit[machines][machines][time] in 0..1;
dvar float+ qty[machines][time];
dvar float+ bowserRefuel[time];
dvar float+ bowserLevel[time];

minimize sum(m1 in machines, m2 in machines, t in 2..T) transit[m1][m2][t-1]*distance[t-1][m1][m2];
```

https://www-01.ibm.com/software/commerce/optimization/modeling/

jsdp is a brand new open source general purpose library that has spun off as a side effect of our project!

http://gwr3n.github.io/jsdp/

ReCCEL Toolbox – Cost/benefit Analysis

Asset Routing/Refuelling

The routing and refuelling model was thoroughly tested against existing practices currently used for on-site asset refuelling.

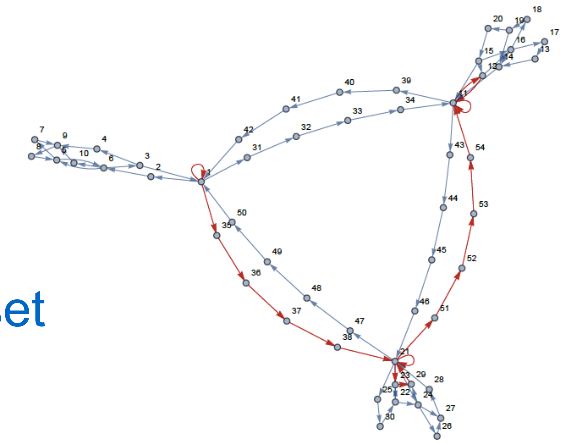


Figure 14: Optimal bowser routing plan.

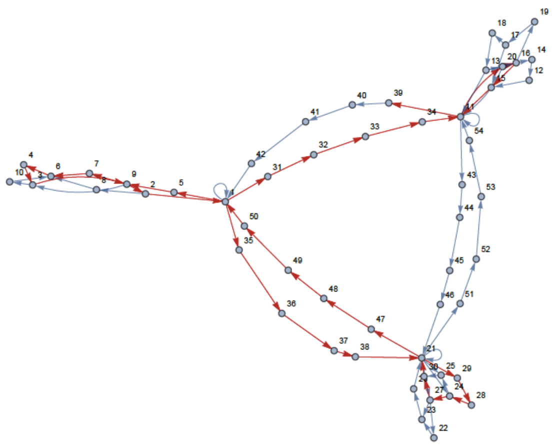


Figure 17: Heuristic bowser routing plan.

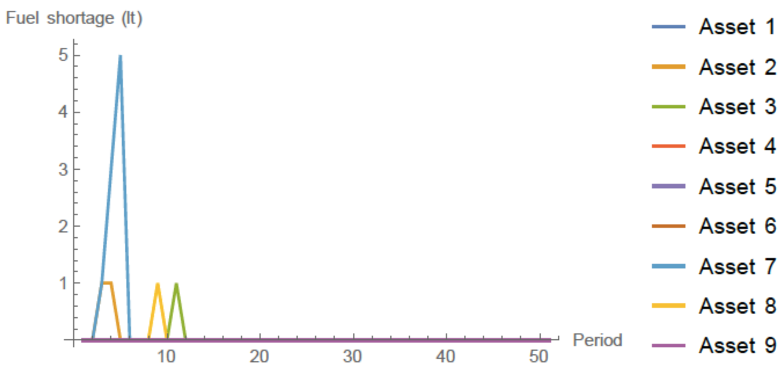


Figure 16: Planned shortages under an optimal plan.

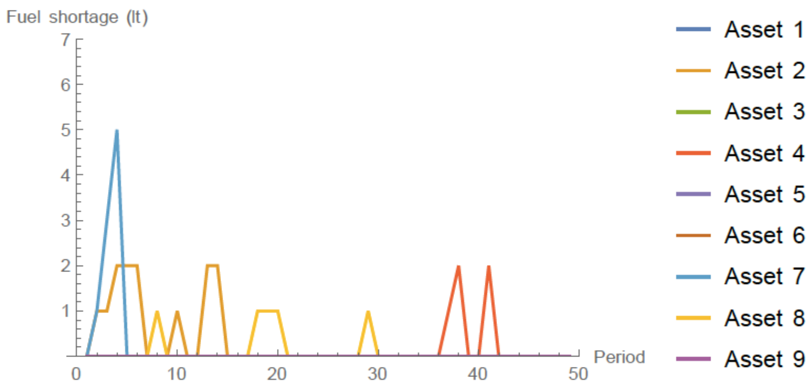


Figure 19: Planned shortages under a heuristic plan.

ReCCEL Toolbox – Cost/benefit Analysis

The routing and refuelling model was thoroughly tested against existing practices currently used for on-site asset refuelling.

Our analysis suggested that an integrated solution leads to:

an average **reduction of 80% for the distance covered by the bowser**

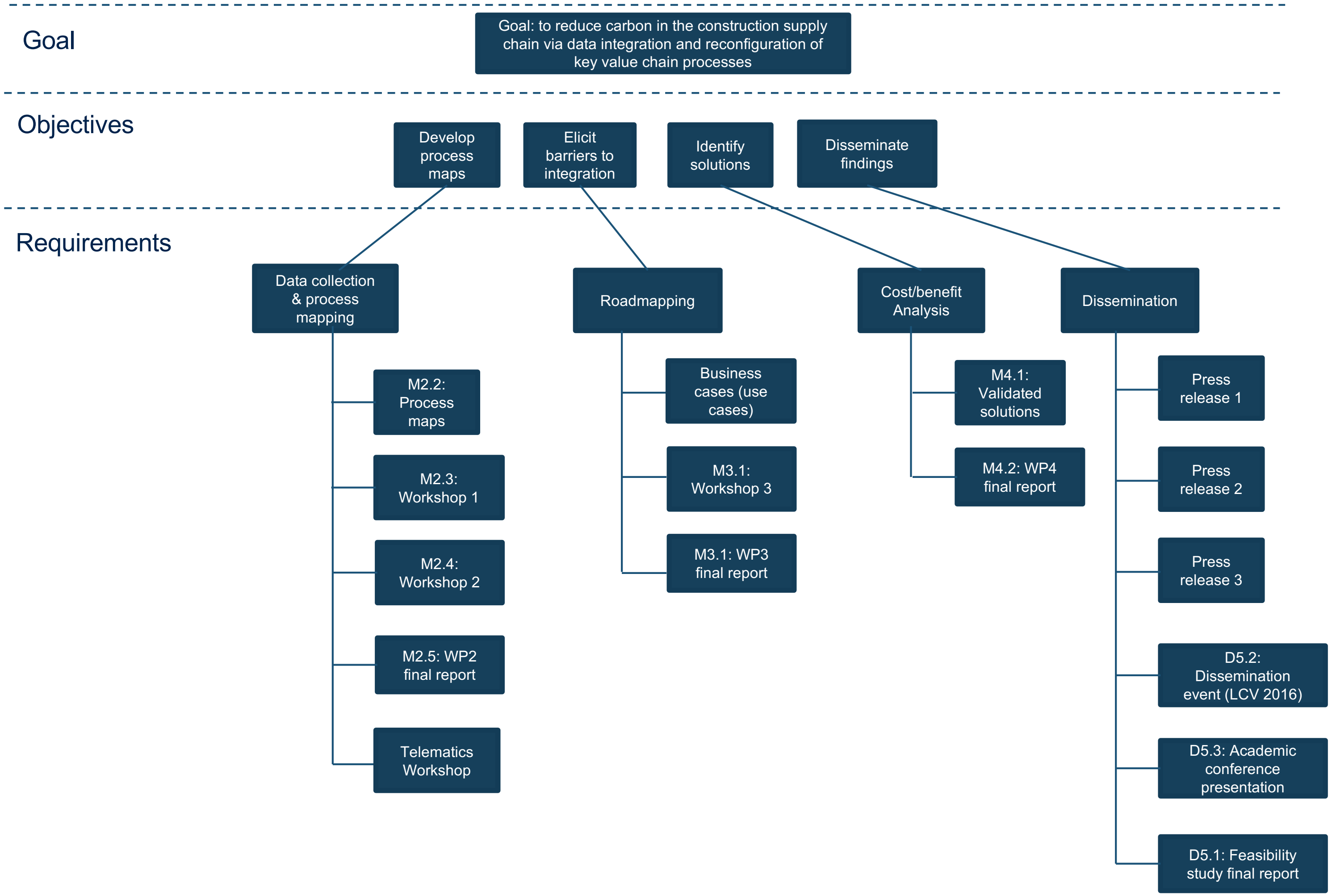
an average **reduction of 46% for asset fuel shortages**

with respect to the existing refuelling policy.

By exploiting asset fuel consumption information from our monitoring dashboard we also estimated the **cost of uncertainty in asset fuel consumption**, which is considerable and amounts to **17%.**

A comprehensive discussion of our decision support model for routing and refuelling is available as a working paper.

ReCCEL Project Overview



Dissemination – Conferences

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EURO 2016 – Poznan, Poland

EURO
THE ASSOCIATION OF EUROPEAN OPERATIONAL RESEARCH SOCIETIES

LCV 2016 – Millbrook, UK

LCV cenex

LCV2016
The Low Carbon Vehicle Event 2016
The UK's Premier Low Carbon Vehicle (Technology Showcasing & Networking) Event

Dissemination – Working Paper

The Dynamic Bowser Routing Problem

Roberto Rossi*[1], Maurizio Tomasella[1], Belen Martin-Barragan[1], Tim Embley[2], Chris Walsh[3], and Matthew Langston[4]

[1]Business School, University of Edinburgh, Edinburgh, UK

[2]Costain Group Plc., Maidenhead, UK

[3]Cenex Advanced Technology Innovation Centre, Loughborough, UK

[4]J C Bamford (JCB) Excavators Ltd., Rocester, UK

Dissemination – Press Releases

News > News releases > Telematics Solution For Carbon Emissions

SHARE

TELEMATICS SOLUTION FOR CARBON EMISSIONS

12 May 2016

Costain is working with the University of Edinburgh Business School and Cenex, the UK's first centre of excellence for low carbon and fuel cell technologies, to see how telematics can be used to reduce carbon emissions on major infrastructure projects.

Conclusions

This report showcases a number of **feasible options** we have identified to **enhance supply chain integration** and **reduce carbon emissions** in construction.

Our solutions, which leverage on on **telematics**, reduce fuel usage by improving efficiency of vehicle movement and enable **integrated decision making**.

The **next steps** would be to conduct a trial through which we can prove the savings hereby estimated.

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Appendix: Mathematical Programming Models

MEETING NATIONAL NEEDS

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Asset Refuelling / Bowser Routing

- Single construction site
- Multiple assets (plant, fleet, generators)
- Single fuel type
- Network of relevant locations on site
- All feasible pathways connecting any two locations
- Discrete time, finite horizon
- Single bowser truck
- Single cistern, infinite capacity

- Asset info, at any time *t*:
  - location
  - fuel consumption

Asset Refuelling / Bowser Routing

- Bowser moves b/w any two adjacent locations within a single time period
- Bowser does not go back to cistern if on its way to refuel an asset
- Refuelling an asset
  - takes negligible time
  - requires: bowser and asset in same location
- Time modelling: “large bucket”

Asset Refuelling / Bowser Routing

Parameter	
T	number of time periods;
A	number of assets;
N	number of nodes in the overlay network (i.e. $N = \|V\|$);
$d_{i,j}$	distance between node i and node j in the overlay network, if $i = j$, $d_{ij} = 0$;
$\delta_{i,j}$	a binary variable that is set to one if and only if it is possible to travel from node i to node j in one time period;
$l^a_{t,i}$	a binary variable that is set to one if an only if asset a is at node i during time period $t \in T$;
f^a_t	fuel consumption of asset a in time period $t \in T$ denoting the node in the overlay network;
F	total fuel consumption for all assets across all time periods;
c_a	tank capacity of asset a;
s_a	initial tank level of asset a;
c_b	bowser tank capacity;
s_b	initial bowser tank level;

Asset Refuelling / Bowser Routing

Decision variable	
V_t^i	a binary variable that is set to one if and only if, at time t, the bowser is at node i;
$T_t^{i,j}$	an auxiliary binary variable that is set to one if and only if the bowser transits from node i to node j by the end of period t.
Q_t^a	the quantity of fuel delivered to asset a at time t;
B_t	the quantity of fuel transferred from the cistern to the bowser at time t.

A bilinear formulation

$$\min \sum_{t=2}^{T} \sum_{i=1}^{N} \sum_{j=1}^{N} V_{t-1}^{i} V_{t}^{j} d_{i,j} \tag{1}$$

which captures the distance travelled by the bowser, which we aim to minimise.

We assume that the bowser is at node 1 (the cistern) at the beginning of the planning horizon

$$V_1^1 = 1. \tag{2}$$

Fuel cannot be transferred from the cistern to the bowser unless the bowser is at node 1

$$B_t \leq V_t^1 C_b, \quad t = 1, \ldots, T. \tag{3}$$

The following constraint enforces bowser capacity

$$s_b + \sum_{k=1}^{t} B_k - \sum_{k=1}^{t} \sum_{a=1}^{A} Q_k^a \leq C_b, \quad t = 1, \ldots, T. \tag{4}$$

A bilinear formulation

We next introduce inventory conservation constraints for the bowser

$$s_b + \sum_{k=1}^{t} B_k - \sum_{k=1}^{t} \sum_{a=1}^{A} Q_k^a \geq 0, \quad t = 1, \ldots, T. \tag{5}$$

We denote as F the total fuel consumption for all assets across all time periods and introduce the following constraints which ensure the bowser does not carry more fuel than needed

$$\sum_{k=1}^{T} B_k \leq \max(0, F - \sum_{a=1}^{A} s_a - s_b); \tag{6}$$

$$\sum_{k=1}^{T} \sum_{a=1}^{A} Q_k^a \leq s_b + \sum_{k=1}^{T} B_k. \tag{7}$$

A bilinear formulation

The following constraint captures the fact that at each point in time the bowser must be somewhere in the network

$$\sum_{i=1}^{N} V_t^i = 1, \quad t = 1, \ldots, T. \tag{8}$$

The bowser can transit from node i to node j only of these are connected,

$$\delta_{i,j} \geq V_{t-1}^i + V_t^j - 1, \quad t = 2, \ldots, T;\ i, j = 1, \ldots, N. \tag{9}$$

We introduce inventory conservation constraints for asset tanks

$$s_a + \sum_{k=1}^{t} (Q_k^a - f_t^a) \geq 0, \quad t = 1, \ldots, T;\ a = 1, \ldots, A. \tag{10}$$

$$s_a + \sum_{k=1}^{t} (Q_k^a - f_t^a) \leq c_a, \quad t = 1, \ldots, T;\ a = 1, \ldots, A. \tag{11}$$

A bilinear formulation

The following constraint states that an asset can be refuelled only if it is located at the same node in which the bowser is found at a given time period

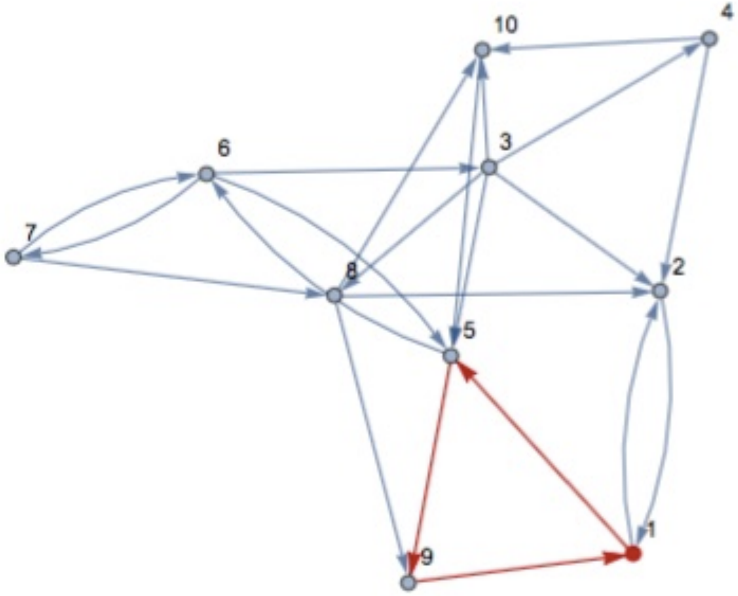
$$Q_k^a \leq c_a \sum_{i=1}^{N} V_t^i l_{t,i}^a, \quad t = 1, \ldots, T;\ a = 1, \ldots, A. \tag{12}$$

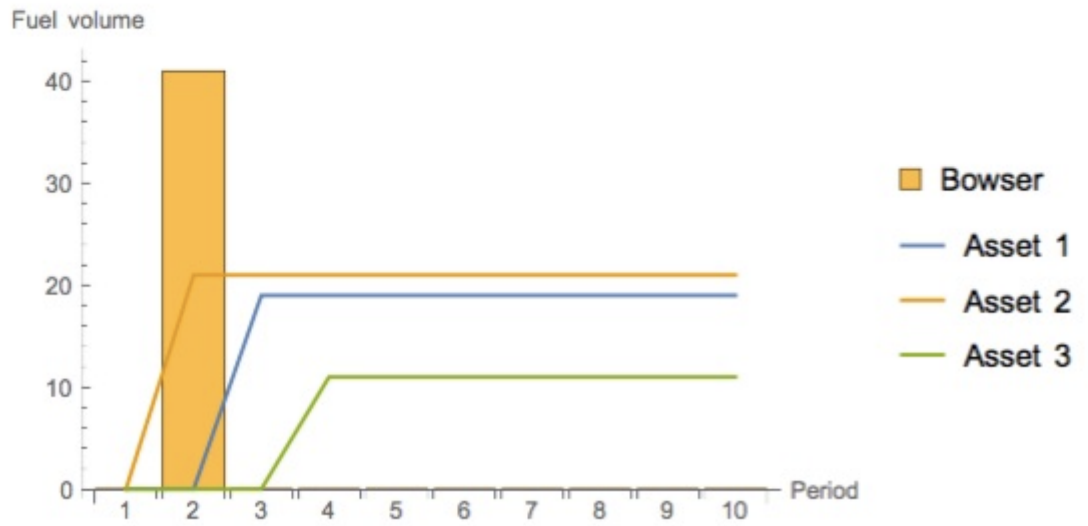
$$Q_k^a \leq \max\left(0, \sum_{k=1}^{T} f_k^a - s_a - \sum_{k=1}^{t-1} Q_k^a\right), \quad t = 1, \ldots, T;\ a = 1, \ldots, A;\ i = 1, \ldots, N. \tag{13}$$

Finally, we impose the following safety restriction: the bowser should only remain stationary at the cistern node

$$V_{t-1}^i + V_t^i \leq 1, \quad t = 2, \ldots, T;\ i = 2, \ldots, N. \tag{14}$$

Bilinear formulation: example





- Working example:
  - 3 assets
  - 10 nodes
  - 10 periods
- IBM ILOG CPLEX Opt Studio, v 12.6
- Solves in 0.8 s

MILP reformulation

$$\min \sum_{t=2}^{T} \sum_{i=1}^{N} \sum_{j=1}^{N} T_{t-1}^{i,j} d_{i,j}. \tag{15}$$

The following channeling constraint links variables $T_t^{i,j}$ and variables V_t^i,

$$T_{t-1}^{i,j} \geq V_{t-1}^{i} + V_t^{j} - 1, \quad t = 2, \ldots, T;\ i, j = 1, \ldots, N. \tag{16}$$

Constraint 9 can be replaced by the following constraints

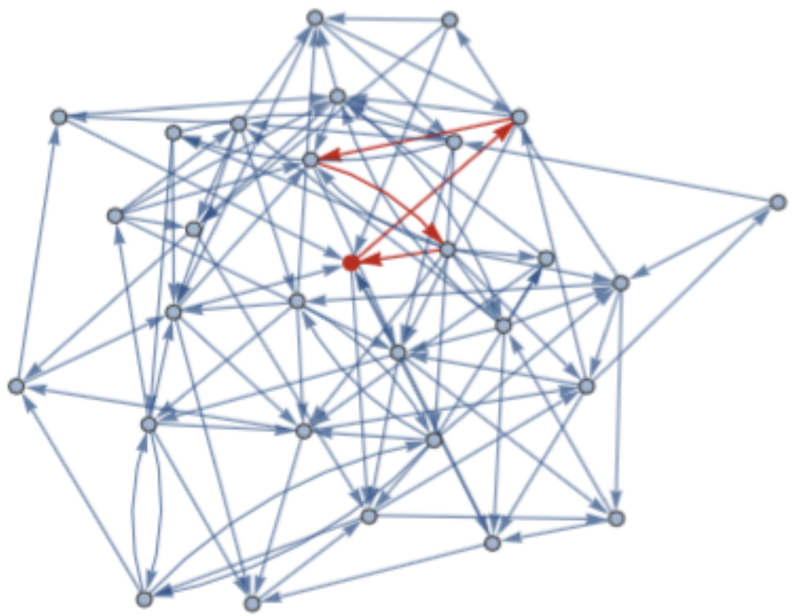
$$\sum_{j=1}^{N} T_t^{i,j} \delta_{i,j} = V_t^i, \quad t = 1, \ldots, T-1;\ i = 1, \ldots, N. \tag{17}$$

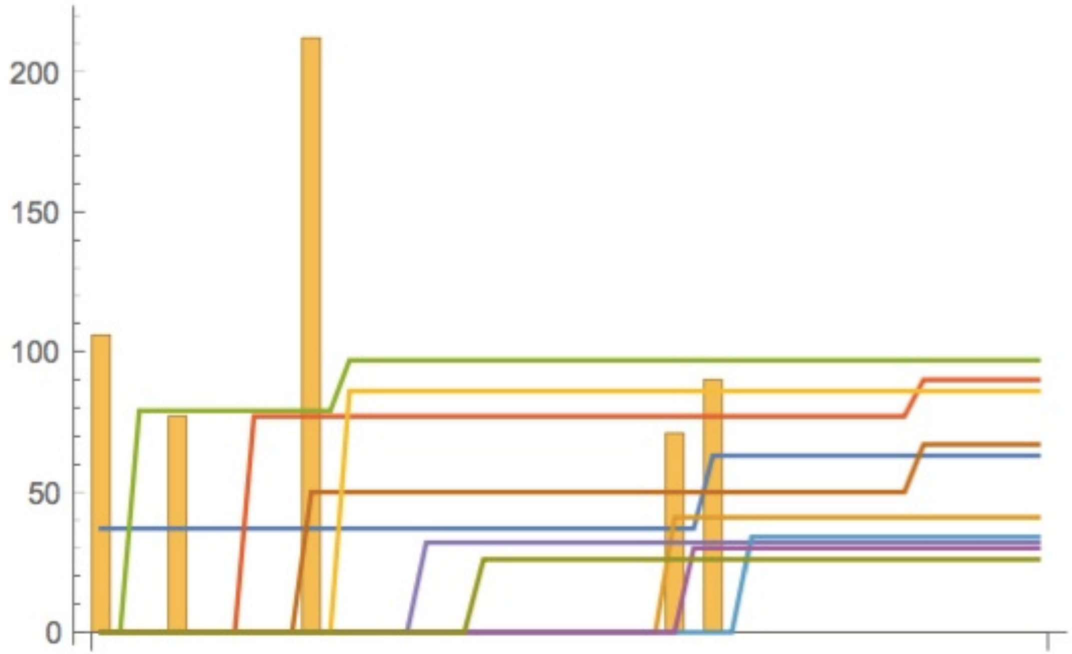
$$\sum_{j=1}^{N} T_t^{i,j} = V_t^i, \quad t = 1, \ldots, T-1;\ i = 1, \ldots, N. \tag{18}$$

Finally, the safety restriction can be rephrased as follows

$$T_t^{i,i} = 0, \quad t = 2, \ldots, T;\ i = 2, \ldots, N. \tag{19}$$

MILP reformulation: example





- Working example:
  - 10 assets
  - 30 nodes
  - 50 periods
- IBM ILOG CPLEX Opt Studio, v 12.6
- Solves in 190 s