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

MEETING NATIONAL NEEDS

Roberto Rossi
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.
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

Goal

Goal: to reduce carbon in the construction supply chain via data integration and reconfiguration of key value chain processes.

Objectives

- Develop process maps
- Elicit barriers to integration
- Identify solutions
- Disseminate findings

Requirements

Data collection & process mapping
- M2.2: Process maps
- M2.3: Workshop 1
- M2.4: Workshop 2
- M2.5: WP2 final report
- Telematics Workshop

Roadmapping
- M3.1: WP3 final report

Cost-benefit Analysis
- M4.1: Validated solutions
- M4.2: WP4 final report

Dissemination
- Press release 1
- Press release 2
- Press release 3
- D5.2: Dissemination event (LCV 2016)
- D5.3: Academic conference presentation
- D5.1: Feasibility study final report

Business cases (use cases)
- M3:1 Workshop 3

Telematics Workshops

Goal: to reduce carbon in the construction supply chain via data integration and reconfiguration of key value chain processes.
During months 1-3 of ReCCEL, partners focused on data collection across the Costain sites listed below.

<table>
<thead>
<tr>
<th>Site</th>
<th>Business partners</th>
<th>Business Context</th>
<th>Business Processes</th>
<th>Telematics</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1+</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A14</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C610</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Heysham</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Shieldhall</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Tideway</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Woolston</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
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, Pollock 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.
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.
Visited **Crossrail C610 site** on January 22, 2016
Data Collection and Process Mapping

Shieldhall Collaboration Diagram and Business Context Model
C610 Collaboration Diagram and Business Context Model
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.
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- Disseminate findings

**Requirements**
- Data collection & process mapping
- Roadmapping
- Cost benefit analysis
- Dissemination

**Task Breakdown**
- M2.2: Process maps
- M2.3: Workshop 1
- M2.4: Workshop 2
- M2.5: WP2 final report
- Telematics Workshop
- M3.1: Workshop 3
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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.
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.
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Activities:
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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**.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Supply Chain Integration</th>
<th>Type</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReCCEL Carbon Dashboard</td>
<td></td>
<td>Data</td>
<td>Single-site</td>
</tr>
<tr>
<td>Asset Scheduling/Servicing</td>
<td></td>
<td>Data + Process</td>
<td>Multi-site</td>
</tr>
<tr>
<td>Asset Routing/Refueling</td>
<td></td>
<td>Data + Process</td>
<td>Single-site</td>
</tr>
<tr>
<td>Asset Booking System</td>
<td></td>
<td>Data + Process</td>
<td>Multi-site</td>
</tr>
<tr>
<td>Asset Requirement Document (ARD)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

Fuel consumption of different assets
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.

<table>
<thead>
<tr>
<th>Asset</th>
<th>$\lambda$</th>
<th>Jump size distribution</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCB 540-170</td>
<td>0.502645</td>
<td>Poisson(0.602257)</td>
<td>0.91558</td>
</tr>
<tr>
<td>JCB 540-170</td>
<td>0.774271</td>
<td>Poisson(0.684164)</td>
<td>0.449291</td>
</tr>
<tr>
<td>JCB 540-170</td>
<td>0.3731890</td>
<td>Poisson(1.004940)</td>
<td>0.933036</td>
</tr>
<tr>
<td>JCB JS130</td>
<td>1.03892</td>
<td>Poisson(1.01056)</td>
<td>0.460517</td>
</tr>
<tr>
<td>JCB JS130</td>
<td>0.926141</td>
<td>Poisson(0.393873)</td>
<td>0.116692</td>
</tr>
<tr>
<td>JCB 86C-1</td>
<td>0.476964</td>
<td>Poisson(0.960902)</td>
<td>0.778792</td>
</tr>
<tr>
<td>JCB 531-70</td>
<td>0.283428</td>
<td>Poisson(0.0516331)</td>
<td>0.516138</td>
</tr>
</tbody>
</table>

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.
Data Analysis

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.
We generated a portfolio of site topologies that are representative for single and multi-site scenarios.
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.
Asset Routing/Refuelling

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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.
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.

```plaintext
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];
```

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

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

EURO 2016 – Poznan, Poland

LCV 2016 – Millbrook, UK

LCV 2016
The Low Carbon Vehicle Event 2016
The UK’s Premier Low Carbon Vehicle (Technology Showcasing & Networking) Event
The Dynamic Bowser Routing Problem

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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 **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.
Appendix: Mathematical Programming Models

MEETING NATIONAL NEEDS

Roberto Rossi
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>number of time periods;</td>
</tr>
<tr>
<td>$A$</td>
<td>number of assets;</td>
</tr>
<tr>
<td>$N$</td>
<td>number of nodes in the overlay network (i.e. $N =</td>
</tr>
<tr>
<td>$d_{i,j}$</td>
<td>distance between node $i$ and node $j$ in the overlay network, if $i = j$, $d_{ij} = 0$;</td>
</tr>
<tr>
<td>$\delta_{i,j}$</td>
<td>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;</td>
</tr>
<tr>
<td>$l_{i,i}^a$</td>
<td>a binary variable that is set to one if an only if asset $a$ is at node $i$ during time period $t \in T$;</td>
</tr>
<tr>
<td>$f_t^a$</td>
<td>fuel consumption of asset $a$ in time period $t \in T$ denoting the node in the overlay network;</td>
</tr>
<tr>
<td>$F$</td>
<td>total fuel consumption for all assets across all time periods;</td>
</tr>
<tr>
<td>$c_a$</td>
<td>tank capacity of asset $a$;</td>
</tr>
<tr>
<td>$s_a$</td>
<td>initial tank level of asset $a$;</td>
</tr>
<tr>
<td>$c_b$</td>
<td>bowser tank capacity;</td>
</tr>
<tr>
<td>$s_b$</td>
<td>initial bowser tank level;</td>
</tr>
</tbody>
</table>
# Asset Refuelling / Bowser Routing

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_t^i$</td>
<td>A binary variable that is set to one if and only if, at time $t$, the bowser is at node $i$;</td>
</tr>
<tr>
<td>$T_t^{i,j}$</td>
<td>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 $t$.</td>
</tr>
<tr>
<td>$Q_t^a$</td>
<td>The quantity of fuel delivered to asset $a$ at time $t$;</td>
</tr>
<tr>
<td>$B_t$</td>
<td>The quantity of fuel transferred from the cistern to the bowser at time $t$.</td>
</tr>
</tbody>
</table>
A bilinear formulation

\[
\min \sum_{t=2}^{T} \sum_{i=1}^{N} \sum_{j=1}^{N} V^i_{t-1} V^j_t d_{i,j}
\]

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

\[ V^1_1 = 1. \]

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

\[ B_t \leq V^1_t C_b, \quad t = 1, \ldots, T. \]

The following constraint enforces bowser capacity

\[ s_b + \sum_{k=1}^{t} B_k - \sum_{k=1}^{t} \sum_{a=1}^{A} Q^a_k \leq C_b, \quad t = 1, \ldots, T. \]
A bilinear formulation

We next introduce inventory conservation constraints for the bowser

\[ s_b + \sum_{k=1}^{t} B_k - \sum_{k=1}^{t} \sum_{a=1}^{A} Q_k^a \geq 0, \quad t = 1, \ldots, T. \] (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

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

\[ \sum_{k=1}^{T} \sum_{a=1}^{A} Q_k^a \leq s_b + \sum_{k=1}^{T} B_k. \] (7)
A bilinear formulation

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

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

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

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

We introduce inventory conservation constraints for asset tanks

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

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

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

(12)

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

(13)

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

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

(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

\[
\min \sum_{t=2}^{T} \sum_{i=1}^{N} \sum_{j=1}^{N} T_{t-1}^{i,j} d_{i,j}.
\]  

(15)

The following channeling constraint links variables \( T_{t}^{i,j} \) and variables \( V_{t}^{i} \),

\[
T_{t-1}^{i,j} \geq V_{t-1}^{i} + V_{t}^{j} - 1, \quad t = 2, \ldots, T; \ i, j = 1, \ldots, N.
\]  

(16)

Constraint 9 can be replaced by the following constraints

\[
\sum_{j=1}^{N} T_{t}^{i,j} \delta_{i,j} = V_{t}^{i}, \quad t = 1, \ldots, T - 1; \ i = 1, \ldots, N.
\]  

(17)

\[
\sum_{j=1}^{N} T_{t}^{i,j} = V_{t}^{i}, \quad t = 1, \ldots, T - 1; \ i = 1, \ldots, N.
\]  

(18)

Finally, the safety restriction can be rephrased as follows

\[
T_{t}^{i,i} = 0, \quad t = 2, \ldots, T; \ i = 2, \ldots, N.
\]  

(19)
MILP reformulation: example

• Working example:
  • 10 assets
  • 30 nodes
  • 50 periods

• IBM ILOG CPLEX
  Opt Studio, v 12.6
  • Solves in 190 s