Networks and Optimal Control for a Circular Economy

Summary of Week-Long Workshop at the Isaac Newton Institute

10 – 14 Feb 2020

This document details the outputs of a workshop at the Isaac Newton Institute. This workshop was designed as a “co-creation” activity so that industry representatives with ambitions in the circular economy and UK mathematical scientists can find synergies in their problems to develop a cutting edge programme of activity to be support by UKRI. The workshop was structured so that future ideas could be formed on a project basis between individuals. These projects would be abstracted so that common themes could be identified and could be packaged together in a larger, challenge-based theme. Ultimately, the benefits of linking these challenge themes together to provide ‘more than the sum of its parts’ was discussed to propose a Big Idea into UKRI. We also include in our report output of a study by the mathematical sciences around challenges in food redistribution.

Table of Contents

Foreword

In 2019, the UK Government made a bold (and legally binding) commitment to reducing greenhouse gas emissions to net-zero by 2050. In our journey to net-zero, moving to renewables across the globe will only address 55% of greenhouse gas emissions. To tackle the remaining 45%, transitioning to a circular economy, diet shift, emerging innovations and carbon capture and storage are all required [1].

This transition from a linear to a circular economy offers a wide range of potential benefits (to the environment and economy):

- Increased - sustainable use of resources, resource efficiency, material security, business resilience, net job creation, robust supply chains
- Reduced - pollution (with associated health benefits), CO_2 emissions, reduced waste.

This requires ability to configure whole-systems, change practices and behaviour, deploy appropriate solutions, AND understand how these impact the system [2]. A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources [3].

Within this larger 'system of systems' are multiple subsystems or organisational systems where whole value chains exist and interlink. At present, organisations that are redesigning themselves to be circular through product and service design, within their own operations and across their value chain can only go so far as we still exist within a linear economy. No organisation, region or country has achieved 100% circularity yet. There is a fine balance between transforming the wider system from a linear to a circular one whilst unlocking the circular potential across these subsystems that are interlinked.

Collectively, there is a need to use a wide variety of tools and instruments to create the right environment for this systemic shift such as finance, policy, education, alternative business models. The mathematical sciences are a broad set of approaches and methods that can be

1 https://www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change
2 P. Hopkinson. Isaac Newton Institute for Mathematical Sciences (2020)
3 https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail

used to help unlock and de-risk the commercialisation and deployment of some of these business models such as last leg logistics for example.

The mathematical sciences are unique in their adaptability in tackling challenges at sub-system, component-level and broader, systems-level challenges; and providing the language which unites them.

Sometimes a broader mathematical framework for describing systems-level can open our eyes to how system-level dynamics behave. For example, complexity science applied to interacting relationships, or entropy arguments used to describe holistic resource flows, or the language of mathematical uncertainty to account for behaviour and stochastic processes. At the sub-system level, the mathematical sciences can provide a rigorous quantitative backbone for modelling logistics in circular cascades, or rationalising design decisions in new product/process offerings.

Matt Butchers, Emma McKenna (July 2020)

Building-blocks for a Circular Economy

We begin here by overviewing the building blocks for a circular economy (adapted from [4]) – comprising both value creation and capture leveraging. Input from the mathematical sciences should look to address the pain points list below the building blocks and more broadly. It should be noted however that none of the conversation fell into the last bullet point below.

- **Skills in circular product design and production**
  - Premature obsolescence
  - Limited degree of modularisation
  - Materials chemically contaminated

- **New business models**
  - Low customer incentives to return products after usage
  - Limited control of manufacturers / retailers over post-sale value chain

- **Skills in building cascades / reverse cycle**
  - Subscale and thus expensive reverse operations
  - Lack of quality (lots of dead on arrivals)

- **Enablers to improve cross-cycle and cross-sector performance**
  - Misaligned incentives
  - Lack of standards
  - Lack of investments
  - Lack of capabilities

The Cambridge sessions took contributions from leading businesses on the circular economy aspirations and translated these into statements which are amenable to the mathematical sciences. Additionally, over a three-day session in June 2020 relevant challenges for the charity FareShare added additional context to this report. In the following document, we list these against the circular economy "building blocks: in an attempt to provide a coherent narrative to the utility of the mathematical sciences in developing a strong UK capability in the underpinning methods for a circular economy.

---

4 Zils, M. Circular Economy – linear value leakage vs. circular value creation (2019)

1. Skills in circular product design and production

Here we detail conversations around mathematical science topics and skills required to design circular principles into a product or process at the beginning of its life.

Bill of material decomposition and revalorisation challenge

This conversation was inspired by a presentation from Exeter Business School. The challenge has 2 elements:

(1) For “legacy” items - items that were not designed with a view to being part of a circular economy, but have now reached the end of their serviceable life - how do we decide how to disassemble them, and which parts go back through the different loops of the circular economy?
(2) How do we design new items in a way that maximizes their recoverable value?

How does it relate to the building blocks? Designing products which have circular economy principles designed in and also methods which enable legacy products to enter the circular value stream.

Mathematical science responses: For challenge (1) we need to think of the disassembly as a tree of stages, each of which takes an input component and has the option of disassembling it to produce some smaller output components, which may then be the input to other stages. At each stage of that disassembly process we have options that we need to decide between, and one of those options is not to disassemble any further. So the choice we need to make is a maximization with:

value of component = max(value as-is, Σ value of disassembled components) – (cost of disassembly)).

This is a recursive definition: we need to bottom it out as well as defining cost. In bottoming it out, we need to think of any component that is output from the disassembly process being fed into the appropriate loop of the “technosphere” part of the circular economy diagram; Fig. 1 (e.g. whether the component is repairable, reusable, can be used in remanufacture, is recyclable, or is waste).

So its value needs to be its value to those processes, or a negative value if it is waste (e.g. representing taxes and other costs of waste-disposal). The disassembly costs need to include: financial cost, energy cost, time, environmental costs, human costs, etc. As usual there is the huge issue of how to assess all these on a single linear scale.

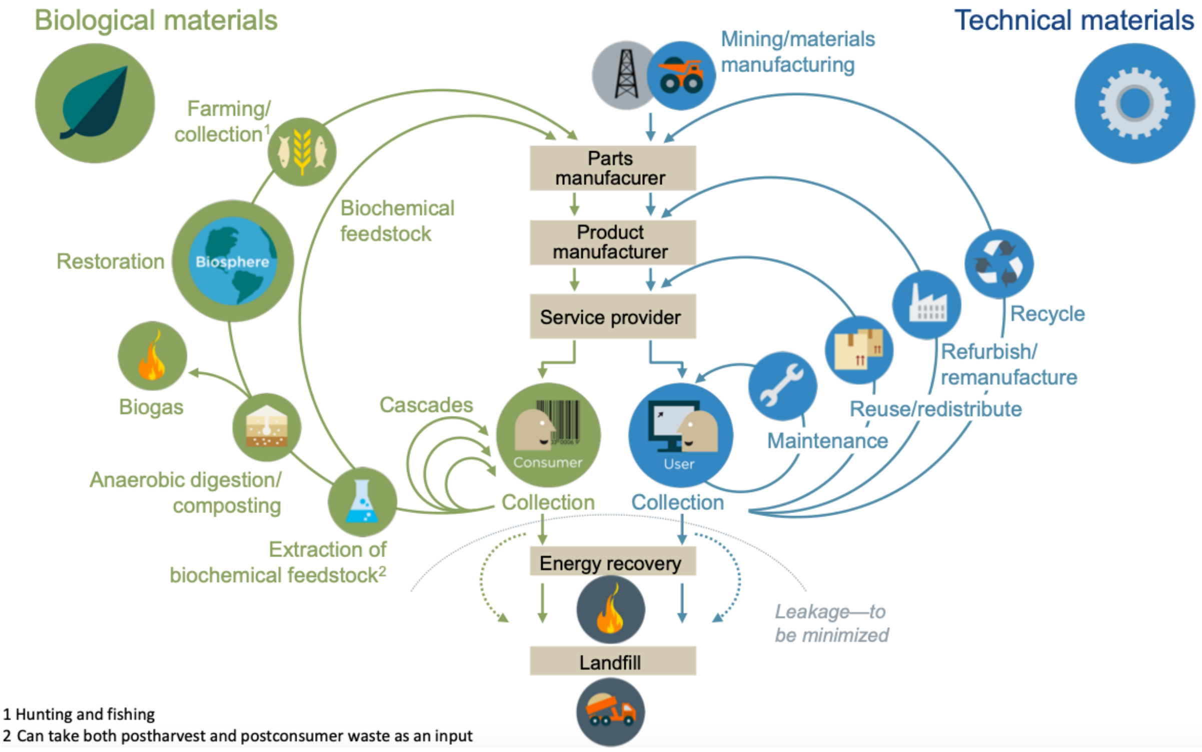

Figure 1. Source Ellen MacArther Foundation Circular Economy team drawing from Braungart & McDonough and Cradle to Cradle (C2C)

Nominally identical components may take different routes through decision (1) because they may have widely different states of wear, and the decision depends on that state. So uncertainty needs to be built in to this system: instead of a *known* value of a disassembled component we have an expected value of a disassembled component.

Coxian phase-type models could be used for the progress of items through a system like this. In order to calculate the expectation we would ideally need to have models for survival rates and degradation rates of the different components (and these might need to depend on conditions of use). These survival and degradation rate models would need to be built on some combination of: data from existing telemetry equipment (e.g. for condition monitoring, predictive maintenance, and warranty purposes), data from similar pieces of equipment, data built up in the revalorisation process itself, expert judgement.

For legacy items, design for revalorisation is a massive multidisciplinary optimization with an objective function that needs to be the overall value function arising from the first challenge.

Associated ideas: assessing costs on a single linear scale. One could make an entropic argument around component disorder [5]; clearly this is not going to be thermodynamic entropy or Shannon information theory entropy but some yet-to-be-determined measure of disorder. People need to be rewarded for entropy that is reduced by human labour or by renewable energy. If entropy is reduced using energy derived in other ways then the entropy cost of that energy production needs to be included in the calculation.

Conclusions:

Maths can play a role in designing products which have circular economy principles built in. The overall aim would be to assess the process by estimating the value reclaimed compared to wasting the original item, and by helping design metrics and 'values' associated with different process decisions. Probabilistic definitions of value could help account for uncertainty by defining 'expected' values. Statistical models could be used to model the evolution of value through life. These models could be informed by data or by structured expert judgment. There are existing ideas on assessing costs using entropy, for this scenario some as-yet undefined measure of disorder.

5 Information Theory, Inference and Learning Algorithms. David Mackay (2003) ISBN-13: 9780521642989 | ISBN-10: 0521642981

2. New business models

Here we detail conversations around mathematical topics in new business models and skills required to design economic value capture from circular principles

New product introduction programme decisions to better manage the transition to a circular economy

This conversation was inspired by a presentation from Rolls-Royce. The aerospace industry will have to increasingly adopt the principles and practices of a circular economy in order to minimise the use of valuable resources and the creation of waste, noise and carbon emissions. This inevitably means that conventional technologies such as gas turbines to power aircraft will need to be replaced wholly or in part by new technologies, such as hybrid or fully electric power systems.

Introducing, however, such radical change raises significantly the technical risks associated with a product development programme: there are a great many unknowns with regards to the capabilities and emergent behaviours of such new technologies that mean that planning and execution of an engine development programme and also the management of a fleet of aircraft after entry into service will be radically different to what has gone before. The underpinning challenge here is:

> How does a high technology organisation, like Rolls-Royce make defensible judgments about future business decisions when faced with epistemic uncertainties? Existing frameworks for handling uncertainty in complex engineering design projects are well adapted to deal with aleatory uncertainties, through robust optimization approaches etc. [6]

How does it relate to the building blocks? Methods and frameworks by which shifting business models can be modelled and validated.

Mathematical science responses: One might consider that an organisation should recognise potential failure modes (and their possible consequences) to the adoption of disruptive technologies such as: a catastrophic event in service, leading to litigious action, damage to

6 Epistemic uncertainty arises from lack of knowledge, whilst aleatoric uncertainty arises from random processes.

reputation, loss of confidence in the business, legislative action, etc. and attempt to adopt design strategies that are robust to these. Of particular interest are: the role of technology innovation; the failure to adapt as a failure mode (and the possible outcome of the business failing); collaborate or compete (game theory and the prisoners dilemma) as possible development strategies.

Mathematical science topics: Bayesian belief networks; survival modelling; probabilistic model of impact of (and sensitivity to) change – decision support of a complex linear process; (N,K) fitness landscape model of a complex product; discrete event simulation with mutation to model introduction of innovation / disruptive market rules; models with disruptive rules; systems dynamics; control theory; non-linear discrete event simulations; stochastic differential games; simulation optimization.

How might one design trials for re-use rollout at scale?

This conversation was inspired by a presentation from Waitrose. Given the ambition in plastic reduction which Waitrose has set, the central question here is:

> **How might one create a systematic experimental design to provide Waitrose with confidence that a re-use[7] rollout at scale would be effective and efficient? The key idea is that there are many unknowns that can only be quantified through a full-scale rollout.**

How does it relate to the building blocks? Can the process be designed, trialled, modified etc at the design stage to have confidence in its feasibility and uptake in deployment.

Mathematical science response: Fundamentally, the main unknown that affects whether the scheme is viable or not is the return rate: both the percentage return rate and the average delay time between purchase and return. These are things that could be addressed in a trial using the membership scheme on existing products in certain stores in a return/recycle scheme which is much cheaper to run than a return/refill scheme. Such a trial could also use a design of experiments approach to test the significance of various factors on the return rate.

7 The feasibility of this in a post-Covid-19 society is an interesting aspect.

Mathematical science topics: experimental design to enable confidence through statistically significant trials.

What would a membership business model look like?

This conversation was inspired by a presentation from Waitrose. Waitrose wishes to reduce packaging by a third by 2023 and reduce single-use plastic by 20 % by 2021. Waitrose also wishes to lead the way on reusables.

> For products which require plastic packaging, this then raises an interesting challenge in who owns the packaging? Two possible options are via a membership model, whereby the consumer rents the package, or a non-membership model in which they own it. How could these be modelled and validated?

How does it relate to the building blocks? How to design business models and comparatively assess their efficacy.

Mathematical science response: For the membership model, it doesn't particularly matter if people keep the boxes, and damaged ones can be replaced for free. In this model, Waitrose would know where the boxes are, and can collect them (e.g. using empty delivery vans), in combination with RFID tags, this might provide insight into customer behaviour and would work well for online shopping. There are many sustainability benefits of this model, material, psychological, not to mention brand loyalty.

For a non-membership model, the boxes would be on open shelves. It raises the question of how do you get them back? How might one incentivise return? What knock-on effect would low return rates have on the business; price of food increasing? How would this work for people who are not loyal to Waitrose? How would this work if other supermarkets don't join in?

There is also the question of reverse logistics of re-usable food containers. There may be some uncertainty in the availability and type of container to be collected (e.g. because the customer is still using them, or lost, or not in an acceptable state). This uncertainty would need to be modelled. Furthermore, we may be able to predict when customers should have their containers ready for collection; this means that we could actively contact those customers who very likely have returnable containers. Customer behaviour modelling could help here to predict what potential collection time would be attractive to the customer. In addition, one could envision a system whereby customers notify the retailer that their containers can be collected, along with booking of a suitable time slot.

Mathematical science topics: collection scheduling; discrete choice mode of market share for the membership model; data analytics around the box flows (if trackable); optimising transport and storage space (what type / size of box); customer behaviour modelling; box return probability and condition (initial and steady state); design of an objective function which minimises overall carbon footprint, plastic pollution and food waste, whilst maximising brand loyalty.

Prediction of potential surplus

This conversation was inspired by a presentation from FareShare. In incentivising redistribution charities to be the first port of call for possible surplus, the central question here is:

> How to identify where and when secondary material flows exist to enable FareShare to pre-empt, and effectively react to, offers of food surplus from primary producers? Such strategies might also help FareShare identify producers with whom it would be beneficial to build a relationship.

How does it relate to the building blocks? Identifying where and what secondary material flows exist allowing circular economy organisations to create predictive methods for materials.

Mathematical science response: The primary approach involves the acquisition and systematic analysis of data from FareShare's connections and from publicly available sources. While being of direct use to FareShare, this information may also be of interest to producers, enabling them to make decisions to mitigate surpluses, and could, therefore, be used by FareShare to incentivise relationships with producers.

Mathematical science topics: machine learning; mathematical finance; data analytics.

Turning systems dynamics problems into simulation models.

This conversation was inspired by a presentation from Exeter Business School. Circular economy models regularly use diagrams with nodes and arrows to represent different flows.

For example, the fundamental model from the Exeter Business School involves material flows in a separate “technosphere” and “biosphere”.

> We often see flow diagrams that use systems dynamics. How can these diagrams be turned into simulation tools using law of mass action etc.? How can they help support business model innovation for the circular economy?

How does it relate to the building blocks? Graphical models to explain, explore and validate possible circular economy models.

Mathematical science response: Can we produce some toy models that capture certain aspects of a circular economy, for example taking one of the more specific problems, like bottle recycling versus refilling. Then we could use these to simulate to understand questions like whether they produce stable networks, what are the sensitivities to key parameters, what could a regulator do to stabilise this economy.

Mathematical science topics: Nash equilibria versus user equilibria; decision variables; the role of reverse logistics, and entropy in such models; multi-layered complex networks; money and product flows. Economies of scale need to be explicitly modelled as does uncertainty

Conclusions:

Designing and assessing business models would benefit highly from collaboration with those involved in managing epistemic risk and uncertainty. Decision support frameworks could provide a way to model key decision variables and provide actionable insight. Statistical tools in experimental design could provide confidence in trial rollouts of circular business models and provide frameworks for key data capture vital for validation.

Analytics will play a key part in monitoring processes and optimising circular economy approaches. Human behaviour modelling will be key to understanding how users will adopt these new business approaches. Machine learning and mathematical finance may have a role in understanding secondary material flows and availability.

More generalised modelling and learning from system dynamics could be turned into simulation tools to provide insight into holistic system-level challenges around complex networks, flow of entropy etc.

3. Skills in building cascades / reverse cycle

Here we detail conversations around mathematical topics in skills in building cascades / reverse cycle interpreted as skills required to enable the logistics infrastructure.

Best Market Design for Freight Exchange – “the empty leg problem”

This conversation was inspired by a presentation from Royal Mail and Waitrose. Royal Mail run the largest fleet of HGVs in Europe, operating around 3000 legs per day. Currently, there are many trips undertaken without a load (other than emptied foldable cages). Royal Mail see an opportunity in selling this spare capacity to third parties provided that pickup and drop-off locations do not deviate too much from the originally planned trip origin and destination.

Waitrose are interested in introducing re-useable food containers that are being used throughout the supply chain including the end user. These containers are envisioned to be foldable and/or stackable such that they could be stored efficiently. After use by the consumer, they would need to be returned to Waitrose, cleaned and checked in dedicated facilities, and then re-inserted into the supply chain

> How could organisations like Waitrose who have assets to distribute, re-capture, and redistribute access available capacity in the freight and logistics market?

How does this relate to the building blocks: designing approaches which allow dynamic pickup, delivery and routing.

Mathematical science response: The basic underpinning problem is a pickup and delivery vehicle routing problem with time windows. The problem has several interesting new features as discussed below

1. *Risk quantification:* This new business model comes with a number of risks: most importantly, reliance on a third party increases the risk of delays (e.g. due to unavailability of sufficiently many loaders to load or off-load the vehicle at the third party’s sites), which may lead to costly knock-on effects over the day. Missing delivery targets due to delays can result in severe financial penalties. Furthermore, the risk of (partial) loss of cargo needs to be accounted for. Reputational damage may result from transporting certain cargo. Traffic conditions on the deviated route may lead to delays.

These risks need to be quantified so as to assess the business opportunity and as input to a pricing mechanism (e.g. to calculate a risk surcharge).
Finally, allowing certain other types of cargo entails the risk of misloading the vehicles since there are certain rules to obey on how to balance the load over the axes. This risk could be addressed by adding appropriate constraints to a packing optimisation algorithm (assuming that all required information would be available at the time of booking).

2. *Bidding mechanism:* It is an open question on how to best design a marketplace for such spare transport capacity that would act as an enabler for this concept. A possible design would be a platform that allows commercial customers to place bids including origin, destination, time constraints and load specifications. These bids then would need to be matched with available "empty" legs that are sufficiently close (subject to suppliers' specifications of allowable deviations) in their original start and end locations as well as fitting with the time constraints.

   A pricing mechanism would need to determine the price of a given provider for this given request. This should ideally reflect the opportunity cost of accepting the request (i.e. the direct additional transportation costs, additional expected costs derived from the risk distributions as discussed above, and possibly the expected value of foregoing potential other requests that may have arisen in the future). Since these some of these costs are only visible to the individual supplier, it seems sensible that this pricing mechanism would be under the control of the supplier (rather than the platform).

   However, this is just one potential scenario of what this market could look like; there may be other designs worth looking into. The question is which design would be best.

   This pricing mechanism is closely linked to the transportation problem not only in terms of the corresponding additional transportation or risk-related costs, but also because the sequencing of loading and off-loading cargo needs to be taken into consideration (since it will require longer off-loading times if the cargo has not been loaded in the correct sequence).

   The mechanism could also be studied under the angle of cooperation between companies, e.g. in the form of a loose alliance.

3. We may be able to predict when customers should have their containers available; one could envision to target customers with likely available containers to offer them a collection time when we are anyway in the area to collect or to deliver. Customer behaviour modelling could help here to predict whether the potential collection time would be attractive to the customer. In addition, one could envision a system whereby customers notify the retailer that their containers can be collected, along with booking of a suitable time slot.

4. Under a scenario where there is a shared standard set of containers across retailers, how would one share the cost of collection between retailers in a fair manner? In other words, what compensation would retailer A get for collecting retailer B's containers?

It would be highly valuable to study historical data of transportation schedules of, say, two transport providers with regard to the potential of increasing load factors (and revenues). Under reasonable assumptions, this could serve as a basis to gain support for this concept from senior decision makers in companies and run trials.

Fleet Electrification in Logistics

The movement towards green infrastructure will be a vital component for enabling agile logistics networks, vital for the adoption of the circular economy. This comes with the challenges of vehicle routing, uncertainty, scheduling etc. The central question here is:

> What can the mathematical sciences say about placement of charging infrastructure for green, logistics networks?

How does this relate to the building blocks: providing systems level descriptions for green networks to enable the adoption of the circular economy.

Mathematical science response: Firstly, there is the demand of electricity over key periods of operation and how that can be coordinated with the grid, wholesale prices and forecasts. This in turn leads to business cases for battery-reinforcement over expensive periods of usage and cost mitigation via industrial solar and wind generation. Then there is the operational challenge presented by the periods of non- use for the vehicles and presenting a charging schedule to operational units which is the nonetheless compatible with the core operation demand.

There is a fairly classic logistics problem about EV routing, with an interesting twist about finite range and accessing charging points. This challenge links to a major question in energy networks of how to share out the benefits and costs of electricity network upgrades, when investment is very lumpy, and thus standard marginal economic theory has little to say. As the capital planning problem is reasonably bounded, it looks as if conventional mathematical programming approaches are applicable; though there are interesting aspects of eliciting decision maker preferences and uncertainty in planning background, and a question about analysis of when to switch to a new technology. There are mathematical challenges associated with running a clearing house for spare van space in which multiple companies participate – there could be contributions from algorithmic game theory, stochastic networks or metaheuristic optimisation researchers.

Mathematical science topics: risk and uncertainty; optimal scheduling; game theory and incentive distribution; stochastic networks; metaheuristic optimisation.

Finding the optimal facility location

This conversation was inspired by a presentation from FareShare. FareShare currently receives surplus food from a variety of sources, including retailers and food manufacturers. Retail and manufacturers have sustainability commitments which require them to prioritise methods which reduce food waste. However, suppliers to FareShare have choices in what they do with their surplus, with redistribution being just one of these choices. Surplus could also go to anaerobic digestion or animal feed.

> How might the mathematical sciences be used to overcome barriers to redistribution? In particular how might we incentivise the supply of surplus by improving the methodologies used to decide where to put redistribution infrastructure and resource?

How does it relate to the building blocks? Providing an agile logistical infrastructure which would enable and incentivise secondary resource flows.

Mathematical science response: From discussions with FareShare, we identified the supply chain and specifically the location of the distribution centres as a key interest. The goal is to improve the agility of FareShare to deal with spikes in supply. We decided to model this problem as a classical facility location problem.

Incorporation of uncertainty would make this a large-scale stochastic simulation. The model could further be improved by better modelling of the capacities and product categories at the supply point. There is a link here with some of the other topics on last-leg logistics and a conversation around possible improvements associated with dedicated transport instead of relying on third party logistics companies. Costs and realistic network representations could be incorporated. Heuristic approaches involving clustering could be used for quick insight into evolving supply and demand.

Mathematical topics: mixed integer linear programming, stochastic simulation, uncertainty quantification, heuristics, clustering, graph theory

Can mathematics help us collect 100% of our packages?

This conversation was inspired by a presentation from Coca-Cola. The questions to consider here were:

> How could mathematics help us increase our recycling rates in a deposit-return market to 100%? When would be the right time to do this in the UK? How could we more effectively measure our return rate?

How does it relate to the building blocks? Similar to the Waitrose challenge.

Mathematical science response: Bringing together optimisation, UQ, decision-making (mathematicians do this in different ways to executive boards), an outside framework to assist with this – emotional vs rational response where profits/ reputation of brand are concerned. Is there enough information out there already to track bottles without introducing barcodes etc? Consider sales per year/ bottles damaged per year; use this to come up with an estimate of uses per bottle. A small project could investigate the estimate made on the back of the envelope during the workshop. Other ideas included tablet form Coca Cola – just add to water! How do you trace a batch – could use time-bound tags, e.g. world cup specials etc. Packaging is a major part of carbon footprint – may want to look at eliminating bottles completely. Crossover with empty leg idea.

Mathematical topics: uncertainty quantification; decision making frameworks.

Conclusions:

There are many classic logistics challenges in here - reverse logistics, last-leg optimisation, vehicle routing etc. - but with some interesting twists. Managing risk and uncertainty would make traditional approaches computationally challenging. Real-time data capture and designing optimal bidding mechanisms would be a required enabler for the concept. There are some topics in collaborative logistics which the mathematical sciences could provide some leadership on.

Locating infrastructure to underpin circular economy efforts is again a classical challenge where the mathematical sciences have a lot of heritage in operational research, stochastic simulations, clustering and graph theory.

Connecting for
Positive Change

Head Office

KTN
Suite 218 Business Design Centre
52 Upper Street
Islington
London N1 0QH

Telephone: 03333 403251
Email: enquiries@ktn-uk.org
ktn-uk.org
@KTNUK

Contact Person
Dr Matt Butchers
matt.butchers@ktn-uk.org