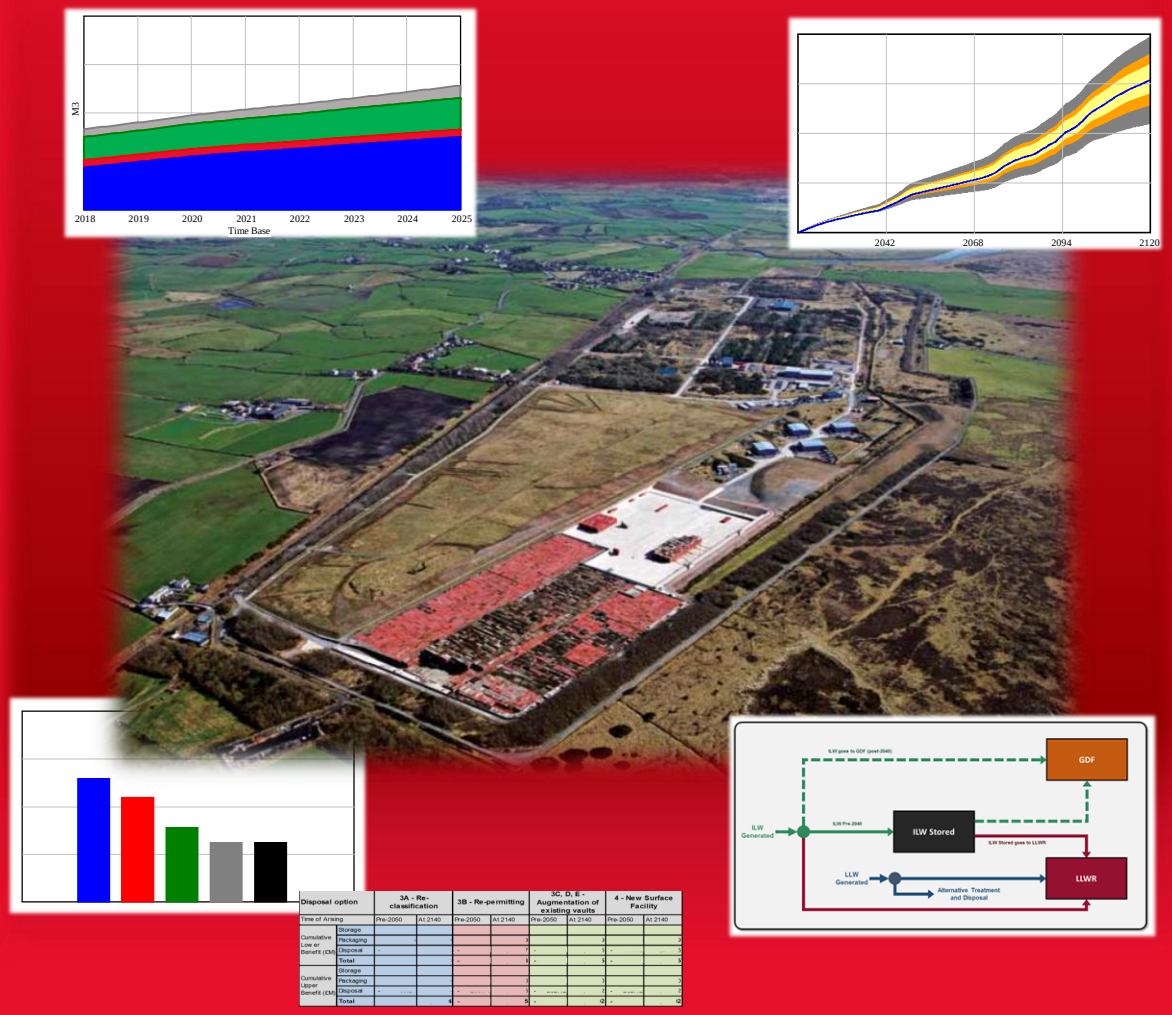

Simulation of the management and disposal of Low Level Radioactive Waste in the United Kingdom

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1. Background
2. System Dynamics Model
3. Model Impact
4. Conclusions
5. Bibliography

1. Background

Radioactive waste management

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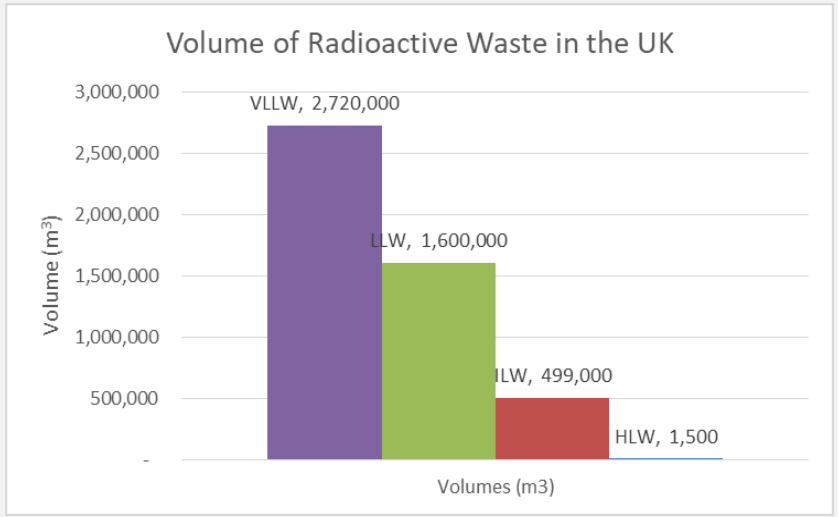
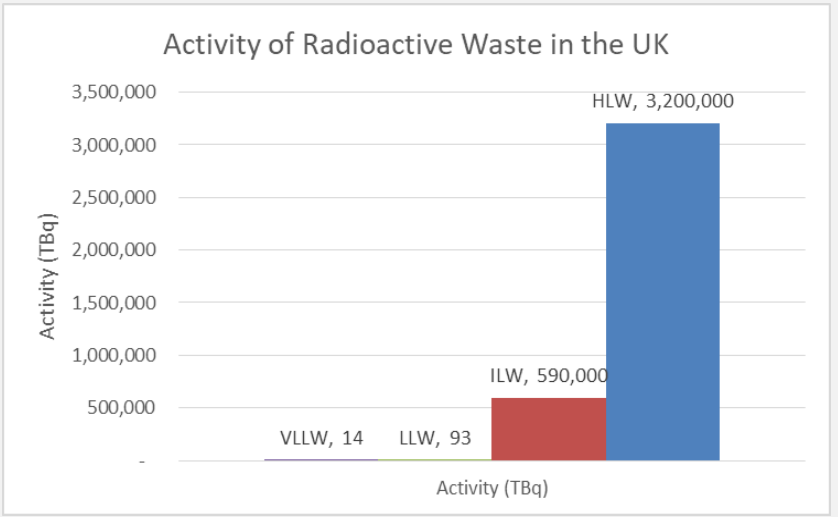
- Nuclear material has a wide range of applications in the UK.
- Radioactive waste is a by-product of these activities and much be treated and managed appropriately to ensure safe disposal
- Radioactive waste is categorised into four categories, based on radioactivity:
  - High Level Waste (HLW)
  - Intermediate Level Waste (ILW)
  - Low Level Waste (LLW)
  - Very Low Level Waste (VLLW)
- The current long-term management policy for all ILW is for it to be disposed of at a Geological Disposal Facility (GDF).
- The current planning assumption is that the GDF will be available in 2040.

Radioactive Waste in the UK

- Every 3 years the NDA collects data from waste producers and publishes an inventory of the radioactive waste currently in storage and predicted to arise over the next 100 years.
- The inventory data shows that VLLW makes up more than half of the radioactive waste in the UK but over 80% of the radioactivity is contained in a relatively small volume of HLW.





Source: Radioactive Wastes in the UK: A summary of the 2016 Inventory

Low Level Waste Repository

- The Low Level Waste Repository in West Cumbria is the UK's principal national facility for the disposal of solid low level radioactive waste.
- It is managed and operated by the LLWR, a consortium of AECOM, Studsvik and Areva, on behalf of the NDA.
- In December 2017, the LLWR were required to present a Business Case to support the Third Term Contract Option.
- As part of the Business Case, the LLWR wanted to propose potential opportunities to be explored during the Third Term.

Scope of Analysis

- The primary purpose of the analysis was to determine an As-Is baseline cost estimate to inform the Business case.
- In addition, it has been identified that some Intermediate Level Waste near the LLW/ILW boundary could potentially be safely disposed of at the LLWR prior to the availability of the Geological Disposal Facility.
- Initial analysis was required to demonstrate if there are any potential cost savings to be realised from this opportunity and if further analysis is worth perusing during the Third Term.
- Decision Analysis Services Ltd were commissioned to develop a cost model to inform the value for money argument in the business case.

2. System Dynamics Model

Model Purpose

An initial high level cost model was required to support gaining economic approval for the LLWR's Third Term Contract Option Business Case. The Business Case includes development of potential options for enhancing the operations at the LLWR, which include the capability to dispose of some ILW at the LLWR.

- The model is required to enable **cost estimates** and **volume projections** associated with the baseline case and other potential disposal proposed options.
- The initial focus is on waste generated from **Sellafield, Harwell and Winfrith**
- The model timeframe is **2016 to 2140**.
- The model will allow for **"what-if"** calculations and enable the impact of the **uncertainty** associated with key parameters to be determined.
- The model must be **scalable** to allow greater levels of detail to be added to the model following the initial assessment of the alternative options.

Justification for using System Dynamics

- System Dynamics was selected to develop the economic model for the following reasons:
  - Long modelling time horizon,
  - Potentially large degree of segmentation, which may be increased in future model iterations,
  - Flexible and scalable modelling environment,
  - Continuous processes, such as radioactive decay, can be represented
  - Complex feedback processes, such as controls on disposal options can be incorporated,
  - Delays, for example time for treatment capacity to come on line can be included,
  - Monte Carlo and multiple scenario runs can be incorporated into system dynamics models to allow the evaluation of uncertainty,
  - Aggregation (for example of waste into different categories and transportation assets into types of assets is acceptable).

Model Development

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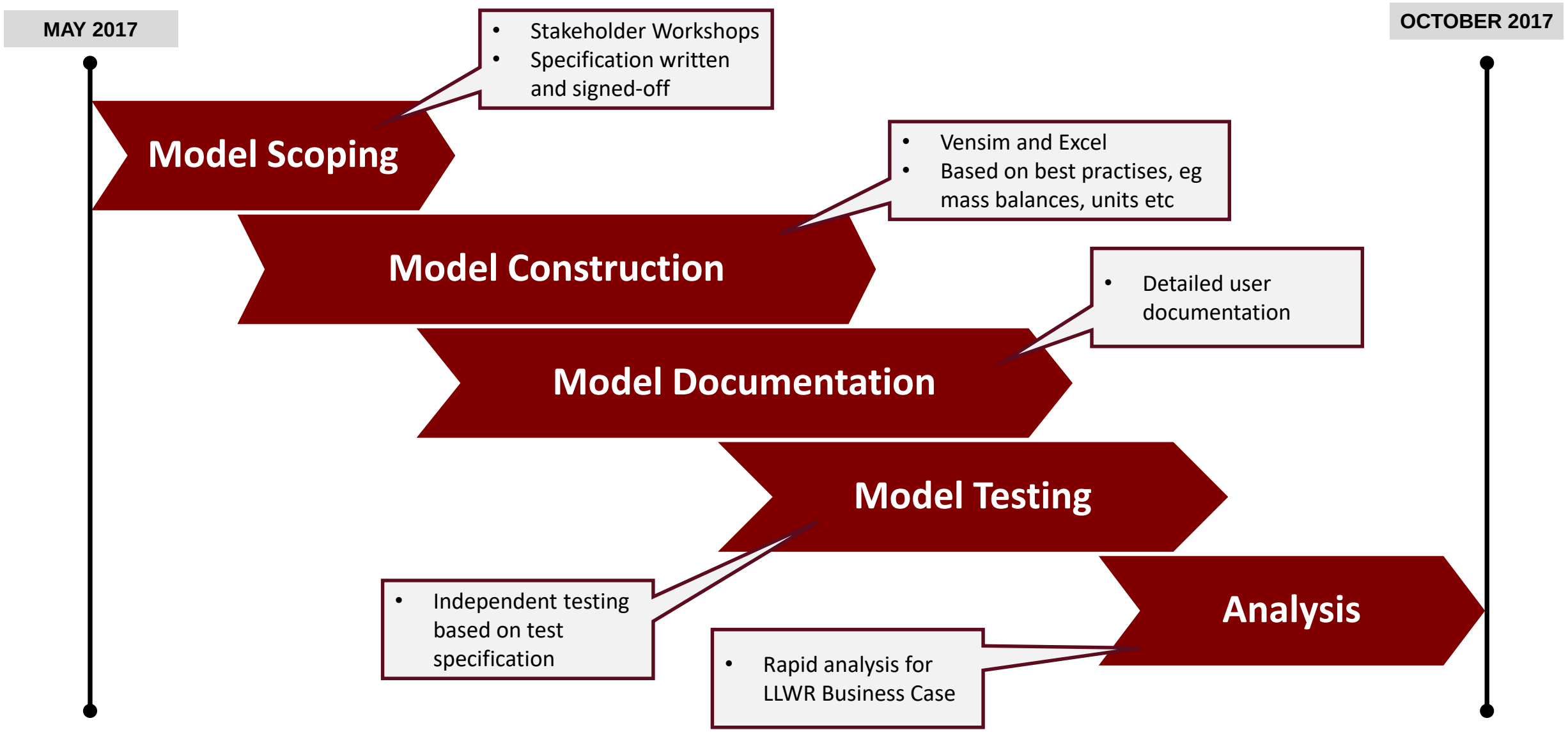
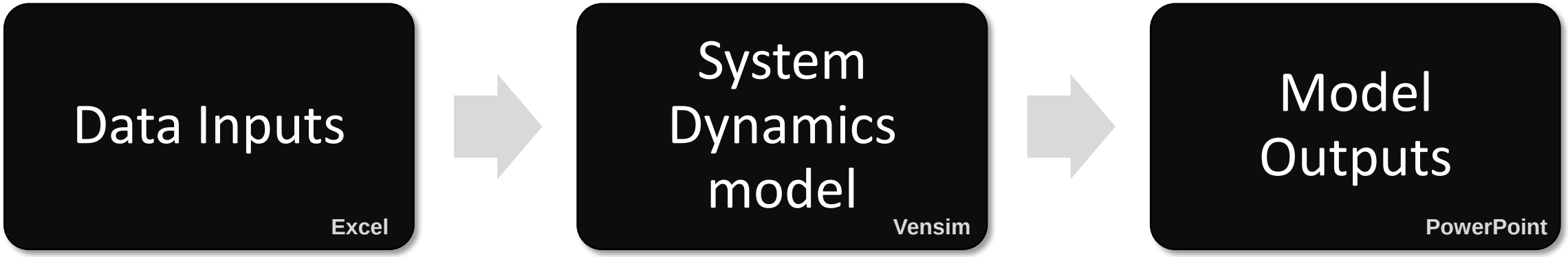
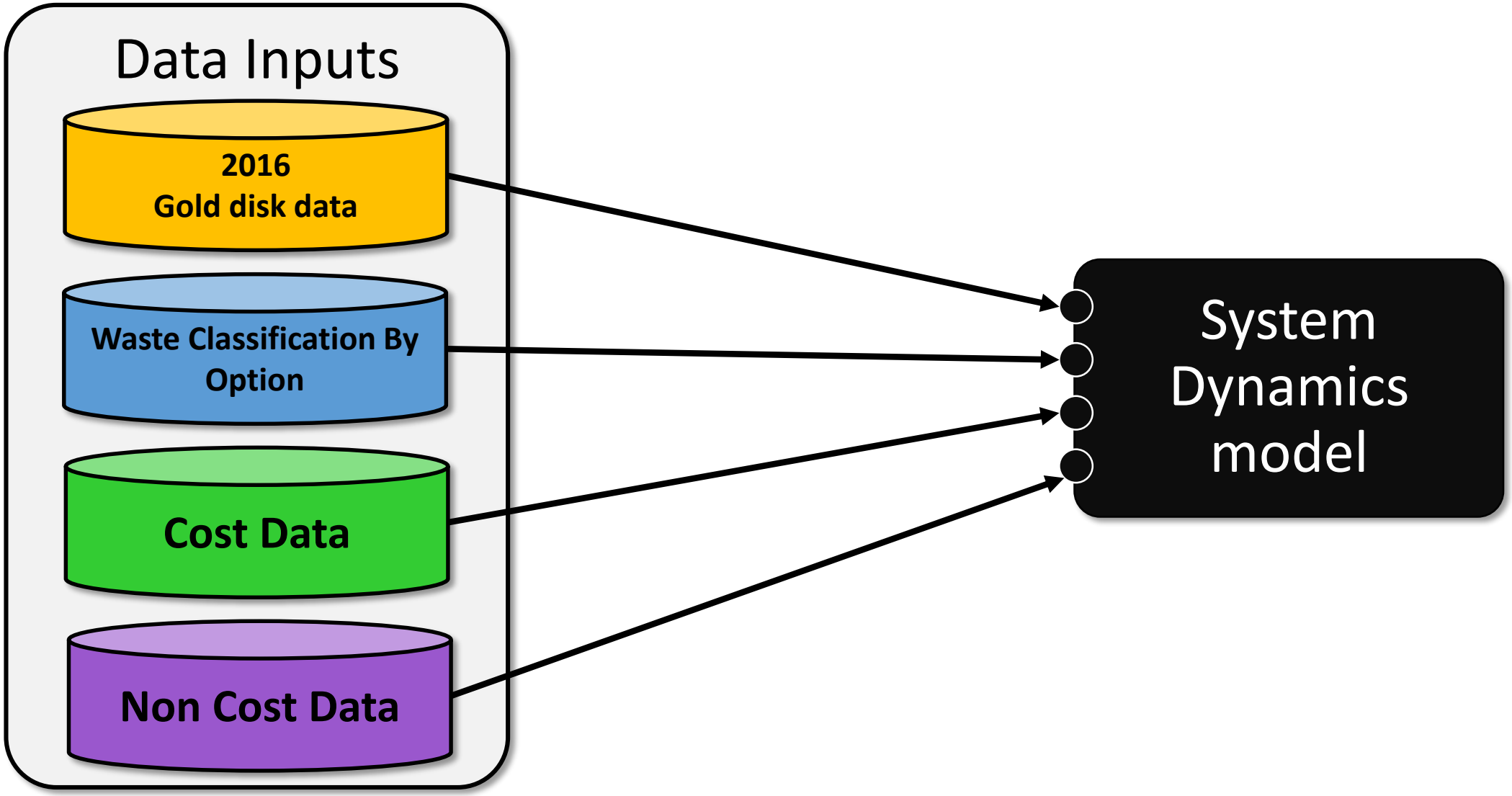


Model Architecture



Model Data


Data Inputs
2016
Gold disk data
Waste Classification By Option
Cost Data
Non Cost Data
System Dynamics model

System Dynamics Model Overview

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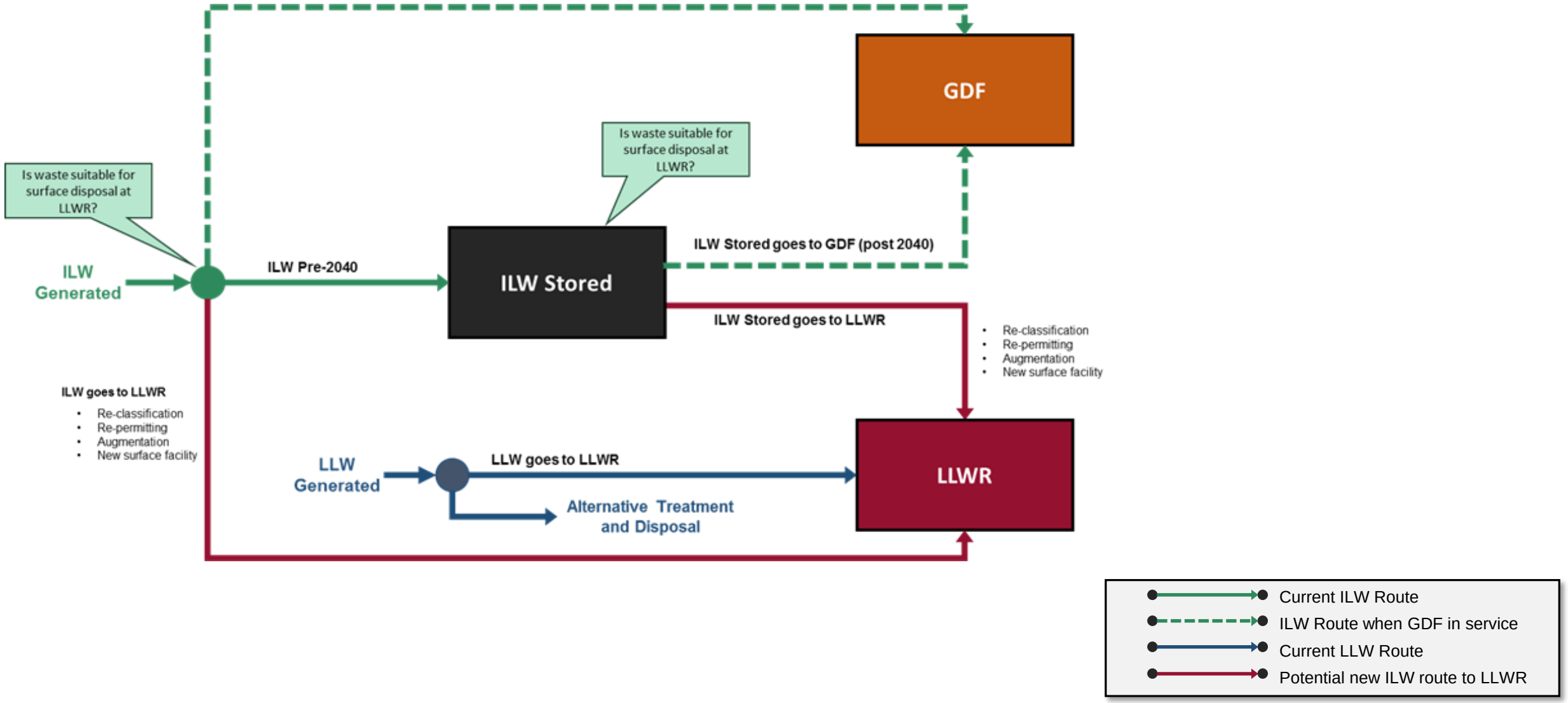
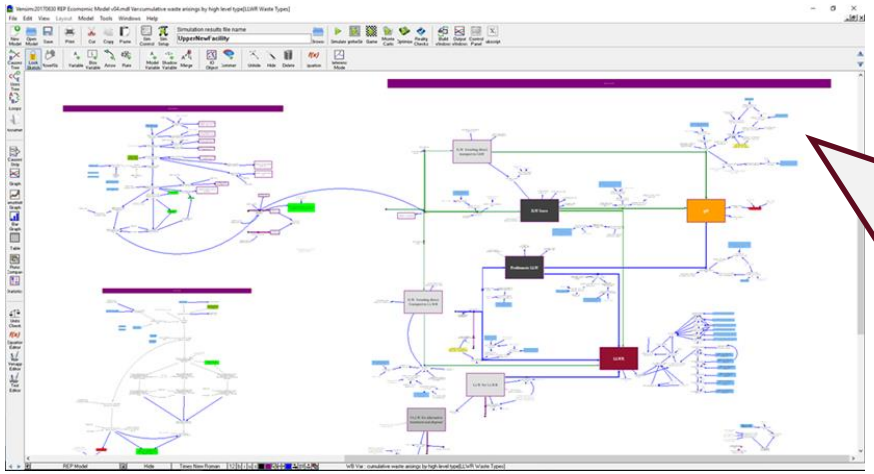


System Dynamics Model Detail



- Separate Stock and Flow diagrams covering waste generation, waste storage, transport constraints and associated cost estimates.
- Model segmented by:
  - Waste Stream (>1000)
  - Waste Type (HLW, ILW, LLW, VLLW)
  - Site (Sellafield, Harwell, Winfrith, Elsewhere)
  - Scenario Estimates (Minimum, Most Likely, Maximum).
- Model calculates costs and waste disposal and storage profiles over time.
- Each simulation takes seconds to run and is simulated in batches.

System Dynamics Model Sample Outputs

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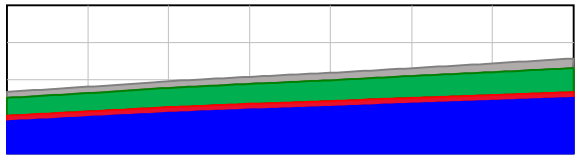
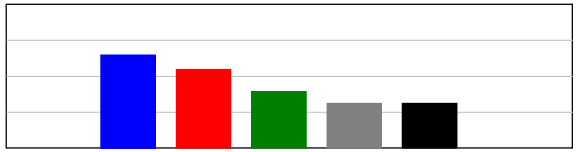
System Dynamics model

Sample Outputs

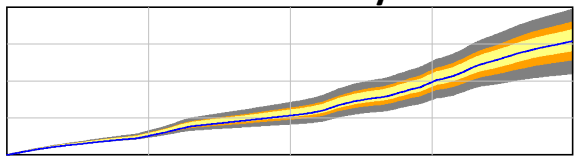
Time Series



Bar charts



Uncertainty



Tabular

Disposal option		3A - Re-classification		3B - Re-permitting		3C, D, E - Augmentation of existing vaults		4 - New Surface Facility	
Time of Arising		Pre-2050	At 2140	Pre-2050	At 2140	Pre-2050	At 2140	Pre-2050	At 2140
Cumulative Lower Benefit (£M)	Storage								
	Packaging								
	Disposal								
	Total								
Cumulative Upper Benefit (£M)	Storage								
	Packaging								
	Disposal								
	Total								

3. Model Impact

Model Impact

- **The model was used to determine the cost and benefits for the third term contract option Business Case.**

- The model provided a “whole system view” of the Business Case and the different underlying datasets and assumptions.

- The rapid simulation runtime allowed multiple options to be explored and the impact of varying the underlying assumptions to be tested.

- As each of the variables were available for analysis it was possible to present the model results in different ways.

Base Business Case options for analysis

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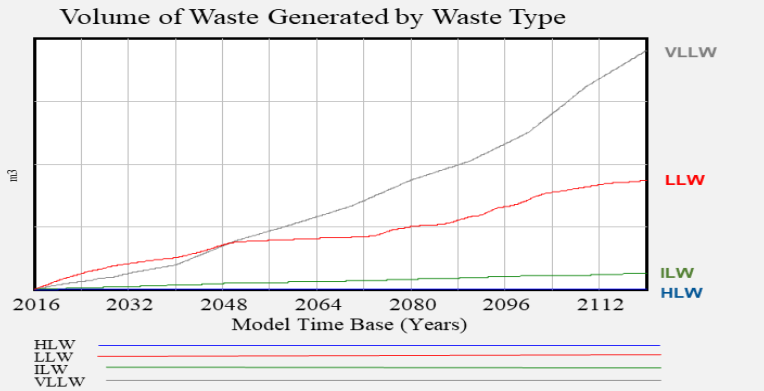
As Is: "Business as Usual" – ILW disposed of in line with current strategy;

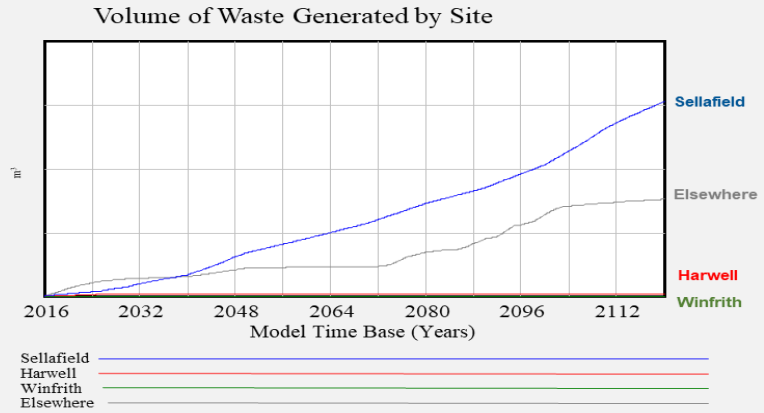
Potential Future Options (Not current UK Policy)

1. **Re-classification:** The focus would be would be working with consigners upstream to help characterise and segregate suitable wastes to allow disposal of those fractions of ILW waste streams which can be re-classified as LLW in the current vault system.
2. **Disposal by Safety Case and Re-Permitting:** Modify the current LLWR Environmental Safety Case to allow disposal of suitable ILW waste streams in the current vault system by removing the constraints of the current LLW definition limits (4&12 GB/te).
3. **Vault Augmentation:** Modify the current vault system (emplacement strategies, additional shielding, semi-remote handling etc.) to allow a larger range of Higher Activity waste stream to be disposed (i.e. those requiring shielding).
4. **New Surface Facility:** Disposal of Higher Activity waste streams following build of a new, purpose built surface facility similar to Centre de L'Aube which includes shielding, roof and remote handling.

Example Analysis 1

Waste Generation over time



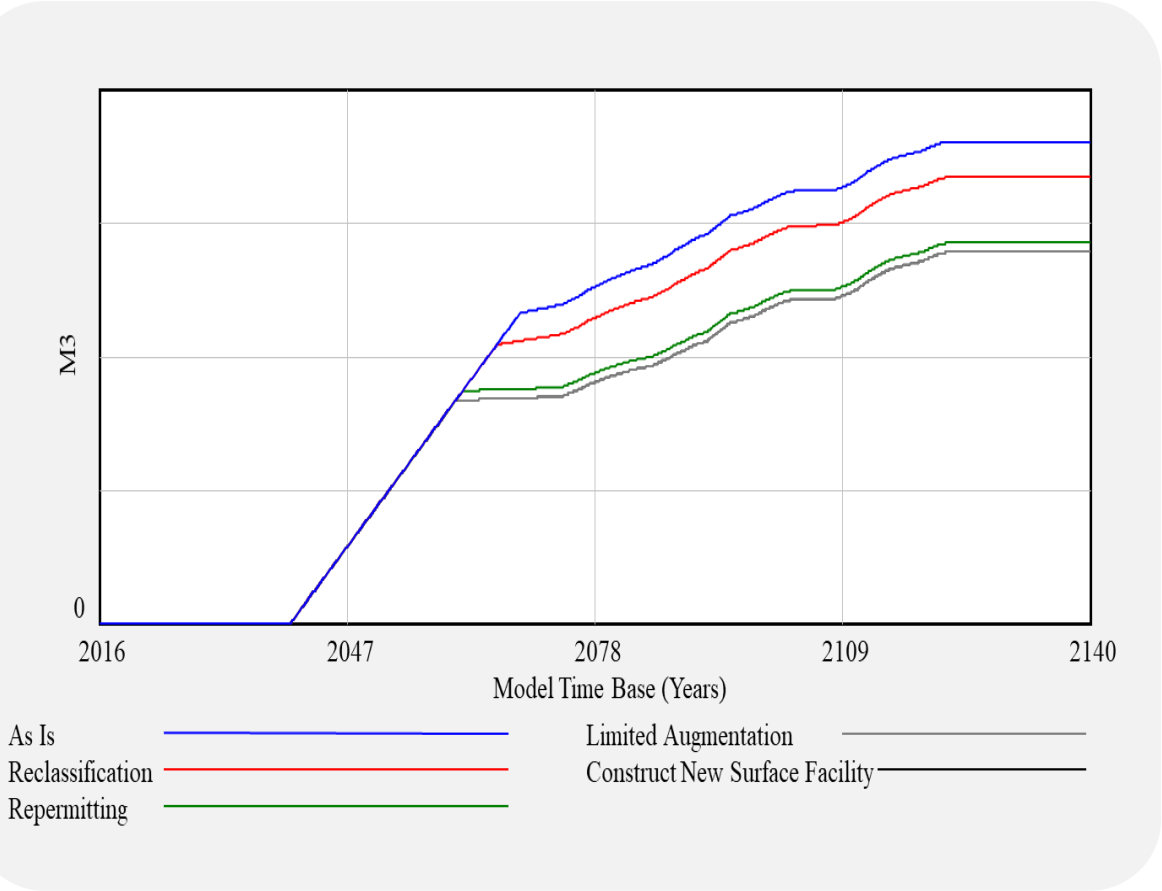


- The model enables large sets of data to be processed and presented in a easy to understand format.
- Profiles the waste generation over time which can be broken down by waste type, site and waste stream.
- Monte-Carlo analysis can be used to determine the uncertainty associated with the projections of waste generation.

NOTE: Model results are currently embargoed due to commercial sensitivities.

Example Analysis 2

How different waste disposal options vary based on diversion from the GDF

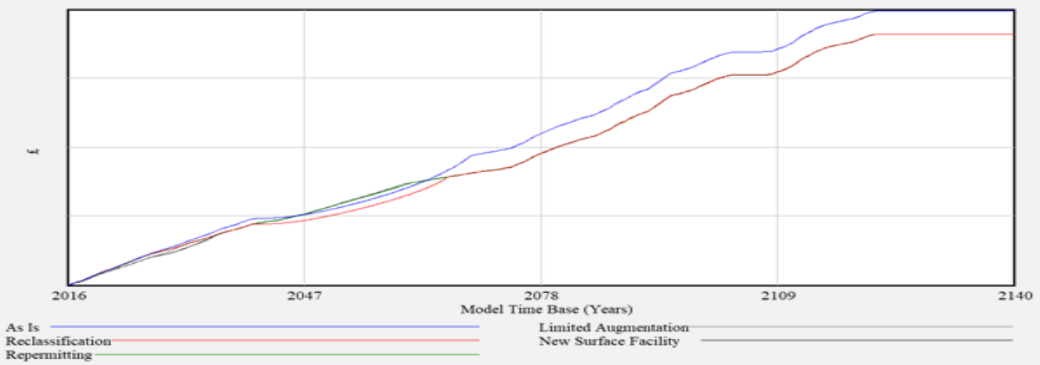


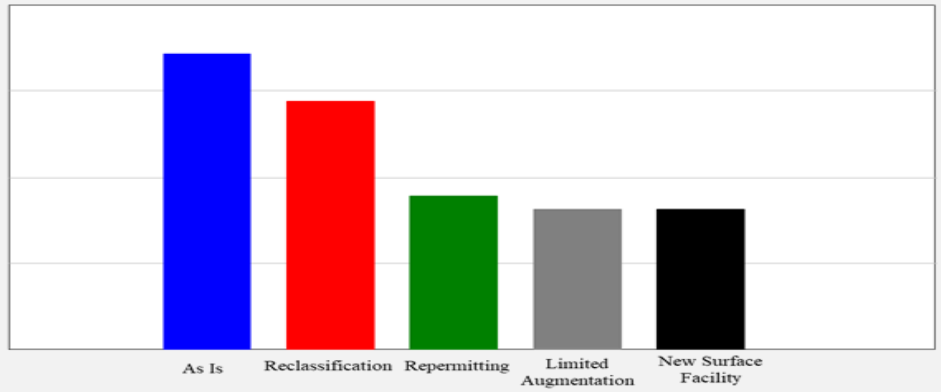
- The model enables profiles of waste over time to be determined at different stages of the waste management process.
- Diversion from final disposal at GDF means that there is a lower requirement for on-site storage
- This reduces volumes of waste requiring packaging, transportation and disposal when the GDF becomes available, and reduces risks associated with GDF availability.

NOTE: Model results are currently embargoed due to commercial sensitivities .

Example Analysis 3

How different options vary based on Whole Life Cost





- **Different options will have different associated costs**

- **For example**
  - Packaging Costs: Potential opportunity to package some ILW in an alternative, cheaper container.
  - Disposal Fees: the fee to dispose waste at the GDF is currently unknown, it is estimated to be up to 160% greater than the LLWR disposal fee therefore cost savings can be realised for every m^3 of waste diverted from the GDF to the LLWR.

NOTE: Model results are currently embargoed due to commercial sensitivities .

4. Conclusions

4. Conclusions

- The model was effective in supporting Business Case development as it allowed rapid analysis of the “As-Is” option.
- Lots of work is continuing to underpin our findings around the alternative options.
- Although UK policy does not currently support the approach of diversion of ILW to LLWR, this work provides insights into the benefits of taking it forward.
- The NDA are deciding if and how to take this (and other options) forward.
- The model can be reused to undertake this analysis, and will be improved for example to include addition consigner sites, additional disposal facilities and more detailed waste segmentation.

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Appendix A: What is System Dynamics

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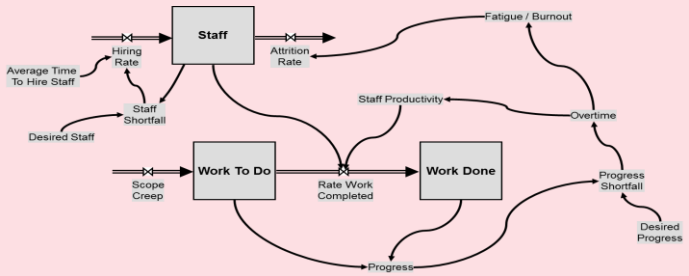
System Dynamics is a modelling approach that enables complex systems to be better understood, and their behaviour over time to be projected using computer simulation

Qualitative

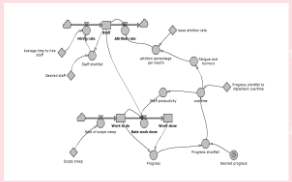
Graphical description of the cause and effect relations that define system behaviour

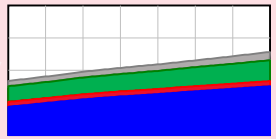


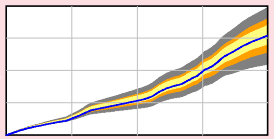
- **Holistic view** of how the system of interest operates
- Generated through **facilitated workshops and interviews**
- **Graphical representation** brings together the knowledge held by all stakeholders
- Identifies **ownership**, **bottlenecks**, **intervention points**
- Standard diagramming conventions called **Stock Flow Diagrams** or **Causal Loop Diagrams**

Quantitative

Computer simulation to calculate the behaviour of the system over time







- **Time based simulation**
- **Quantifies** the potentially complex **feedback mechanisms** that drive behaviour
- Enables **alternative scenarios** to be quantified and so make informed strategic decisions
- “Drill-in” to key performance drivers and detail to **mitigate risk** and understand implications of alternative interventions
- Stakeholder can be provided with **management simulation tools** that they can use to test out their own interventions