Simulation and analysis to support decision making in the treatment and handling of radioactive waste

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Abstract

This paper describes three practical applications of System Dynamics methods for the consideration of issues associated with managing low level radioactive waste in the United Kingdom. These projects were undertaken for the Low Level Waste Repository Ltd, who manage and operate the national low level waste repository on behalf of the Nuclear Decommissioning Authority. These projects included creation of a causal loop diagram of the national low level waste system; quantification of the national system to enable analysis of treatment and disposal strategies and a more detailed analysis of a particular type of low level waste. This paper describes how the models were used and the benefits associated with the System Dynamics approach.

Key Words: System dynamics, Radioactive waste, Nuclear, Strategic analysis

1 Introduction

This paper describes three practical applications of System Dynamics methods for the consideration of issues associated with managing low level radioactive waste in the United Kingdom (UK). These projects were undertaken for the Low Level Waste Repository Ltd (LLWR), who manage and operate the national low level waste repository on behalf of the Nuclear Decommissioning Authority (NDA).

These three practical applications considered the management of low level waste and ranged from national level to modelling a specific type of low level waste, as follows:

- Creation of a shared representation of the UK Low Level Waste (LLW) system using Causal Loop Diagram notation;
- Quantification of the UK LLW model to enable analysis of treatment and disposal strategies;
- Quantification of Multi Element Bottles (MEB) treatment and disposal to support business case analysis.

This paper is structured as follows:

Section 2 provides brief background information about how radioactive waste is generated, treated and disposed of in the UK, with particular reference to Low Level Waste. **Section 3** gives a brief description of System Dynamics, describing instances where it has previously been used to model the radioactive waste disposal and treatment system. It also describes the particular reasons why LLWR required the use of System Dynamics. **Section 4** describes the first case study in the paper, whereby the UK LLW system was mapped using causal loop diagram notation. The second and third case studies describe quantitative models that were developed for LLWR, and **Section 5** describes the approach adopted to model development. **Section 6** describes the second case study, the development of a simulation model that enables the analysis of treatment and disposal strategies over a time horizon that stretched to 2130. **Section 7** describes the third case study which is a simulation model used to quantify the business case for a particular type of low level waste. Finally, **Section 8** concludes the paper with a description of the benefits of the System Dynamics approach and potential future applications at LLWR.

2 Introduction

This section provides brief background information about how radioactive waste is generated, treated and disposed of in the UK, with particular reference to Low Level Waste.

2.1 What is radioactive waste?

Nuclear material has wide application in the UK, from generating power through to carrying out medical treatments. Materials that have no further use, and are contaminated or activated by radioactivity above certain levels, are known as radioactive wastes. Radioactive wastes are produced as a by-product from many important industrial, medical, research and defence activities. Great attempts are made to reduce the amount of radioactive waste produced but some waste production is unavoidable and must be managed appropriately. (Nuclear Decommissioning Authority, 2015).

The vast majority of radioactive waste produced in the UK is solid and made from a variety of materials. A smaller proportion is in the form of liquids or sludges, and these are usually solidified by drying or incorporating into a solid matrix (usually cement or glass) to improve stability and containment. Finally, a relatively small proportion of the UK's radioactive waste is in gaseous form, such as radon.

In the UK, radioactive wastes are classified into four categories according to the type and quantity of radioactivity contained and the amount of heat this radioactivity produces. These classifications are as follows:

High level wastes (HLW) are those wastes where the temperature may rise significantly as a result of their radioactivity, and arises as a liquid from the reprocessing of spent nuclear fuel.

Intermediate level wastes (ILW) are those exceeding the upper boundaries for Low Level Waste (LLW) that do not generate sufficient heat for this to be a factor in the design of waste storage or disposal facilities. The major components of ILW are metal items such as nuclear reactor components, graphite from nuclear reactor cores and sludges from the treatment of radioactive liquid effluents.

Low level wastes (LLW) are those which contain relatively low levels of radioactivity. More specifically, wastes where the radioactive content does not exceed 4 GBq (gigabecquerels) per tonne of alpha, or 12 GBq per tonne of beta/gamma activity. Most LLW comes from the operation and decommissioning of nuclear facilities, and mainly consists of scrap metal items, paper and plastics. Some smaller amounts of LLW also come from hospitals and universities.

Very low level waste (VLLW) is a sub-category of LLW with specific activity limits. VLLW includes small volumes of waste, principally from hospitals and universities, that can be safely disposed of with household, commercial or industrial waste (either directly or after incineration), and larger volumes of waste from nuclear sites that can be disposed to appropriately permitted landfill facilities. It is expected that the major components of VLLW from nuclear sites will be building rubble, soil and steel items arising from the future dismantling and demolition of nuclear reactors and other nuclear facilities.

The diagram below illustrates the relative difference in the nuclear waste inventories for the different categories of radioactive waste. This is the latest inventory data, collected in 2013, showing the different types of waste that will be produced, from all sources including future arisings:

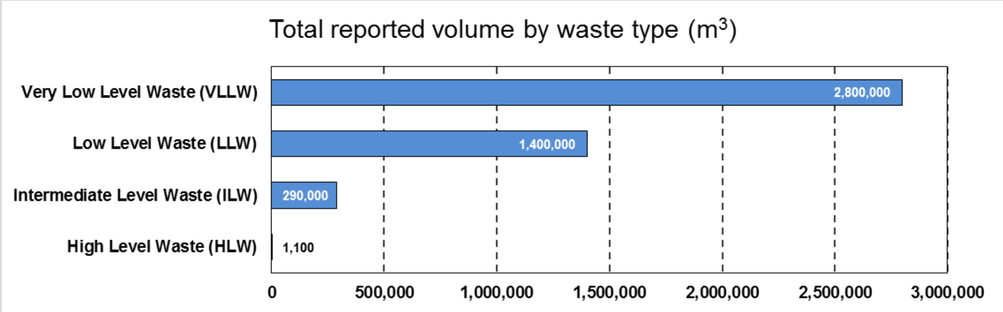


Figure 1: Adapted from NDA (2015)

Although the greatest volume of radioactive waste is VLLW, the vast majority of the radioactivity (over 90%) is contained in the relatively small volume of HLW.

In the UK, the vast majority of radioactive waste (over 90%) is produced by activities that are part of the nuclear fuel cycle. Much smaller amounts of waste are produced by defence, research, medical and industrial activities.

2.2 Low Level Waste (LLW)

Please note that for the remainder of this paper all references to LLW are inclusive of VLLW. Over 80% of LLW is generated from nuclear power stations (>80% as of 2011 (LLWR, 2011)). Figure 2 below shows the volume of LLW by different producers and the different materials that make up the LLW.

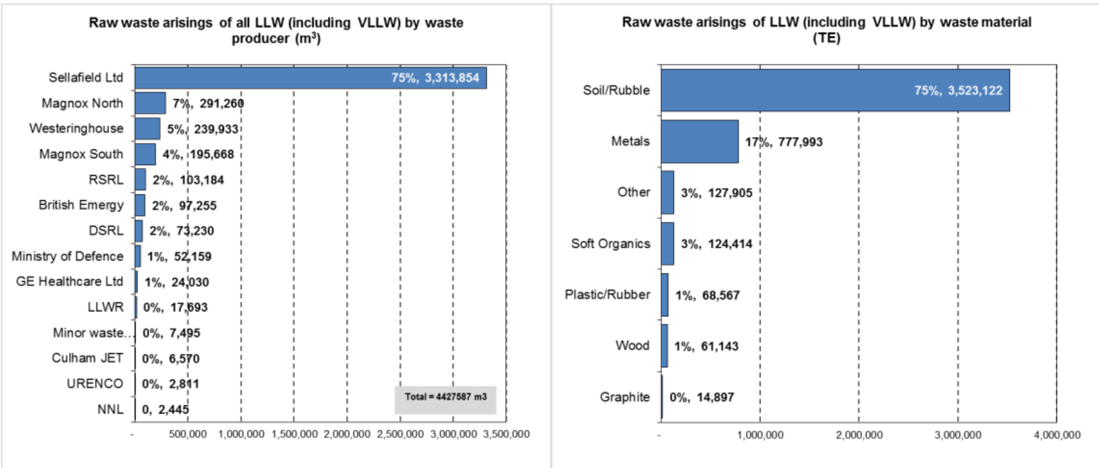


Figure 2: Adapted from LLWR (2011)

Although LLW represents less than 0.1% of total UK radioactive waste by radioactivity, it makes up more than 90% of the UK's radioactive waste legacy by volume. Therefore, serious consideration is required with regards to identifying both economically viable and space efficient methods of treating, storing and eventually disposing of LLW.

2.2.1 Managing the treatment and disposal of LLW in the UK

The Low Level Waste Repository Ltd (LLWR) manages and operates the national low level waste repository on behalf of the Nuclear Decommissioning Authority (NDA). The main focus for the LLWR is to provide a safe, cost effective and sustained low level waste management service. The low level waste repository itself is the biggest site for disposal of LLW in the UK. The site is located south of Sellafield, in Cumbria, UK. Disposals at this site are currently made in a specially engineered facility consisting of concrete-lined disposal 'vaults'. LLW arriving at the repository is grouted with cement in metal containers to form a robust solid. These containers are then placed within an engineered vault which when full is covered with an engineered cap and closed.

It is desirable to prolong the lifespan of the UK's existing low level waste repository. In order to achieve this, consignors (the term used for those producing radioactive waste), in-line with the Nuclear Decommissioning Authority (NDA) strategy (NDA, 2010), will make all reasonable efforts to prevent, minimise, reuse and/or recycle LLW generated. The LLWR will then work to deal with residual waste in the most effective way possible. Amongst the options LLWR has available are:

- Encouraging better segregation of waste;
- Making greater use of waste treatment facilities;
- Introducing improved waste containers.

To deliver their objectives, and in parallel with the successful, initial roll-out of new initiatives for waste segregation and treatment, the LLWR are looking for ways to improve the container fleet used for transporting, storing and, ultimately, disposing of low level waste.

3 System Dynamics (SD) and its application to the Low Level Waste system

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. System Dynamics was first developed in the 1960's by Jay Forrester (Forester, 1961) with many more important texts produced in the subsequent years (for example see Sterman, 2000; Warren 2007 and Morecroft 2007). The System Dynamics approach has been successfully used across many different sectors.

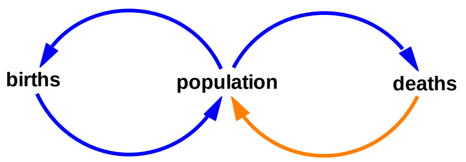
The System Dynamics approach is composed of two key components; the first is mapping the system to better understand it, and the second is using computer simulation to calculate system behaviour over time.

3.1 Mapping the system to understand behaviour

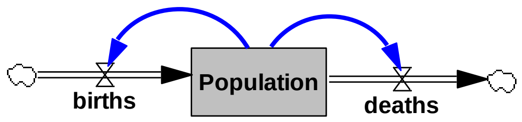
The first stage of a System Dynamics based project involves mapping the cause and effect relationships that drive system behaviour. System Dynamics uses specific diagramming notation such as stock and flow diagrams or causal loop diagrams to map the system, as illustrated in the Figure below:

Both diagrams below represent the same system using different diagrams. The ***population*** is increased by ***births*** and reduced by ***deaths***. The more people in the ***population***, the more ***births*** and ***deaths*** there will be.

Causal Loop Diagram



Stock and Flow Diagram



A **Causal Loop Diagram** is used to capture major feedback mechanisms. The diagram includes variables and arrows (causal links) linking these variables together. The blue arrows show a postive influence and red arrows show a negative influence.

A **Stock and Flow Diagram** captures the main stocks in the system, and the flows that act to increase and decrease the size of the stocks. The stocks are represented as rectangles.

Figure 3: Brief description of Causal Loop Diagrams and Stock and Flow Diagrams

The diagrams are created with the system stakeholders, who best understand how the system of interest works. The completed diagrams represents a shared understanding of the system, which can then be used in many ways, for example to investigate potential points where interventions could be made.

3.2 Simulating the system to quantify behaviour

Once an agreed diagrammatic representation of the system has been created, specialist software can be used to quantify the relationships. The completed simulation model can be used to rapidly test system interventions in a risk free environment.

The simulation model provides a means to calculate change over time depending on the underlying assumptions and proposed interventions. System Dynamics models simulate rapidly and can use management information data sources. The models can be developed to produce outputs using desired performance measures, and can be validated against historic performance. A number of authors have produced guidance on producing robust SD models, for example see Sterman (2000), Keating (1999), Randers (1980) and Cave (2014).

3.3 Application of SD to managing the treatment and disposal of radioactive waste

There has been other work that has described the application of System Dynamics to the generation, treatment and disposal of radioactive waste. Jacobson et al (2008), Yacout et al (2005) Pierpoint (2011), Van Den Durpel, L (2008), Van Den Durpel et al (2006) and Van Den Durpel et al (2005) all describe models used to represent various components of the nuclear fuel cycle, including waste generation and management.

Love et al (2011) describe a qualitative analysis using causal loop diagrams and stock and flow diagrams of the issues associated with radioactive by-products of nuclear weapons development and government-sponsored research.

As can be seen, previous models are primarily focussed on waste generated through the use of nuclear fuel, rather than from all sources; and they also do not deal with the specifics of waste transportation and disposal at waste repositories.

3.3.1 Application of System Dynamics to the UK low level waste system

The process of handling LLW in the UK, from creation, through transportation, to treatment, storage and disposal is a complex system which the LLWR needs to both understand and manage. Two key challenges for the LLWR are:

1. The range of containers used for the transportation and storage/disposal of the LLW;
2. The potential waste treatment methods and their impact on resources e.g. costs, containers, and resulting storage volume requirements.

As described in section 2.2.1 above, volume minimisation is a critical consideration in order to maximise the lifespan of the existing national storage and disposal capacity.

In addition, this is a problem with a long time horizon, where the period of interest extends to over 100 years.

LLWR collaborated with specialist practitioners in System Dynamics to explore whether System Dynamics could be used to model this system, and subsequently be used to ensure robust critical management and investment decisions. This exploration was composed of three projects:

1. Creation of a shared representation of the UK LLW system using Causal Loop Diagrams notation;
2. Quantification of the UK LLW model to enable analysis of treatment and disposal strategies;
3. Quantification of MEB treatment and disposal to support business case analysis.

These three projects are described briefly below.

4 Case study 1: Creation of a shared representation of the UK LLW system using Causal Loop Diagram notation

The first project involved the generation of a high level understanding of the national LLW system, in the form of a high level causal loop diagram. This was achieved through facilitated workshops and interviews with leading engineers, designers, consignor support, finance, commercial and environmental subject matter experts. Gathering together this mix of stakeholders, who are split across two different sites and so have limited interaction, also ensured consensus and joint ownership of the resulting high level system representation.

A sample high level Causal Loop Diagram, that formed the basis for subsequent quantitative modelling, is outlined in Figure 4 (start and end points of the waste path are highlighted in green and red respectively).

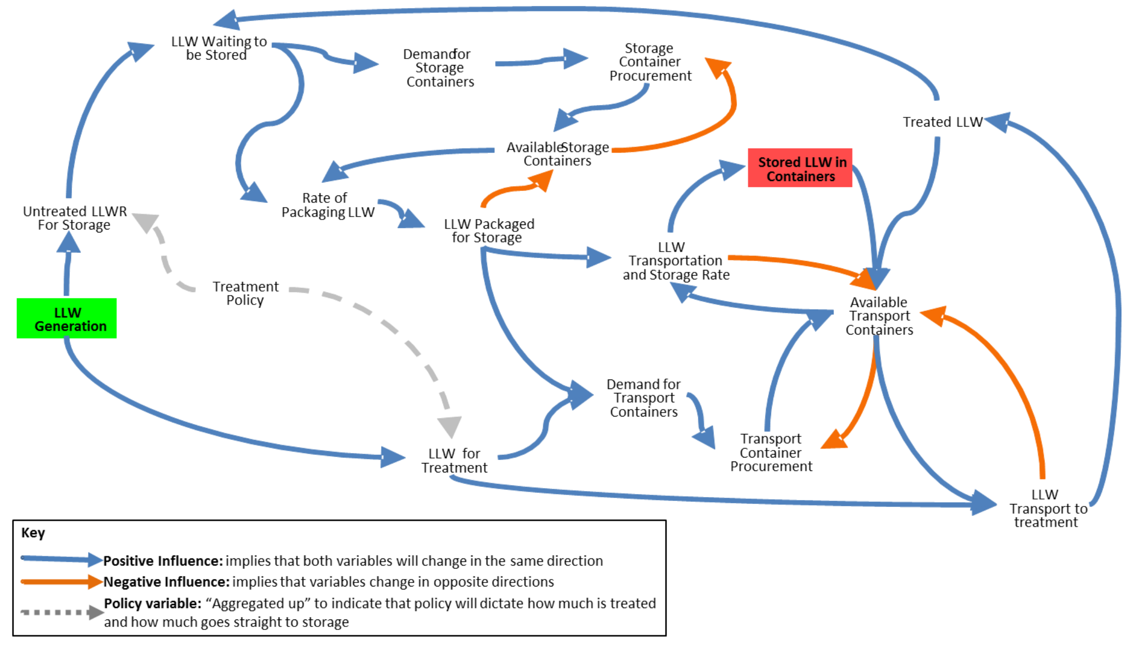


Figure 4: Sample High-Level Causal Loop Diagram of the UK's Low Level Waste System

The diagram illustrates some of the complexity of the system, which is compounded through a wide range of other factors that vary over time and are not fully within the control of the LLWR. These factors include:

- Uncertainty over consigner LLW site generation volumes;
- Varying consignor site methods of operation, e.g. container selection, LLW segregation;
- Availability of treatment technologies for LLW;
- Adherence to transport regulations for LLW;
- Adherence to environmental regulations for LLW.

The influence of these factors were understood and incorporated to ensure that the model reflected the reality of the UK LLW system. The process of developing this diagram also helped to coalesce the understanding of people from across the LLW system.

5 Approach to quantitative model development

Case studies 2 (Section 6) and 3 (Section 7) required the development of quantitative models for specific strategic questions. As such, a typical approach for model development as shown in Figure 5:

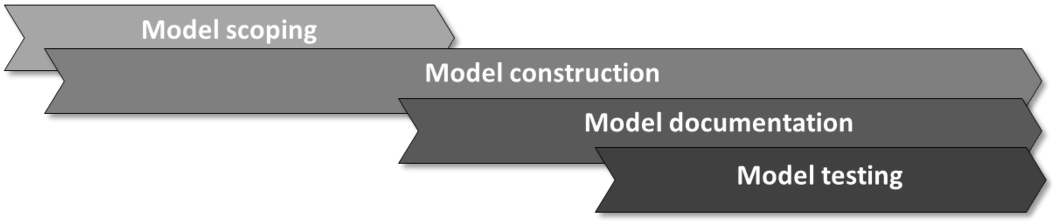


Figure 5: High level proves for developing a System Dynamics model (adapted from Cave (2014))

During the model scoping stage a formal model definition was created which defined the scope and purpose of the model. The model scope document also captured all the assumptions that would be made in the model. Model construction included data acquisition and calibration. The models were then formally documented and tested. Stakeholders were involved throughout the process, for example to get agreement on the model representation and to "sanity check" model results.

6 Case study 2: Quantification of the UK LLW model to enable analysis of treatment and disposal strategies

6.1 Problem definition

At the heart of the approach to handling low level waste is the fleet of containers used to meet the requirements of safely transporting, storing and disposing of the waste. Two primary metrics are used to measure achievements in extending vault lifetimes at the national LLW Repository:

1. The achievement of higher waste packaging ratios (e.g. the volume of waste divided by the internal container volume), and
2. Vault stacking efficiencies for containers, i.e. reduce the "dead" space between containers. This is important because even if the waste is efficient packed within the container itself, the overall packing ratio could still be low if the container stacking efficiency is low.

LLWR wished to better understand and quantify the transition from the current (or "legacy") fleet of containers to a new (or "aspirational") fleet of containers by 2130 via an interim (or "transitional") fleet. The aspirational and transitional fleets will incorporate new containers and methods for waste segregation and treatment. However, the transitional state must consider a number of waste segregation and treatment approaches being introduced whilst also having both the legacy and new container types in circulation.

This project recognised that new containers can be produced that fulfil different functions within the waste handling cycle to generate efficiencies. By separating the transport function from the storage/disposal function transport containers can be introduced to specifically ferry dedicated storage containers to the repository. In addition, as a consequence of being tailored to vault storage, new dedicated storage containers will be capable of achieving far higher vault stacking efficiencies than the existing dual-purpose fleet.

With regard to achieving better waste packaging ratios, when separating LLW into individual waste streams, e.g. soft organics, metals, rubble, on consignor sites, then new storage only container types will provide a more optimal arrangement. A package designed specifically for a segregated waste stream will achieve a higher waste packaging ratio through having a leaner design and making better use of the container overall volume envelope.

The model was required to represent the operational container fleets over the 2130 time horizon and allow cost and volume efficiency analysis. The diagram below illustrates the fleet flexibilities and attributes that were to be explored:

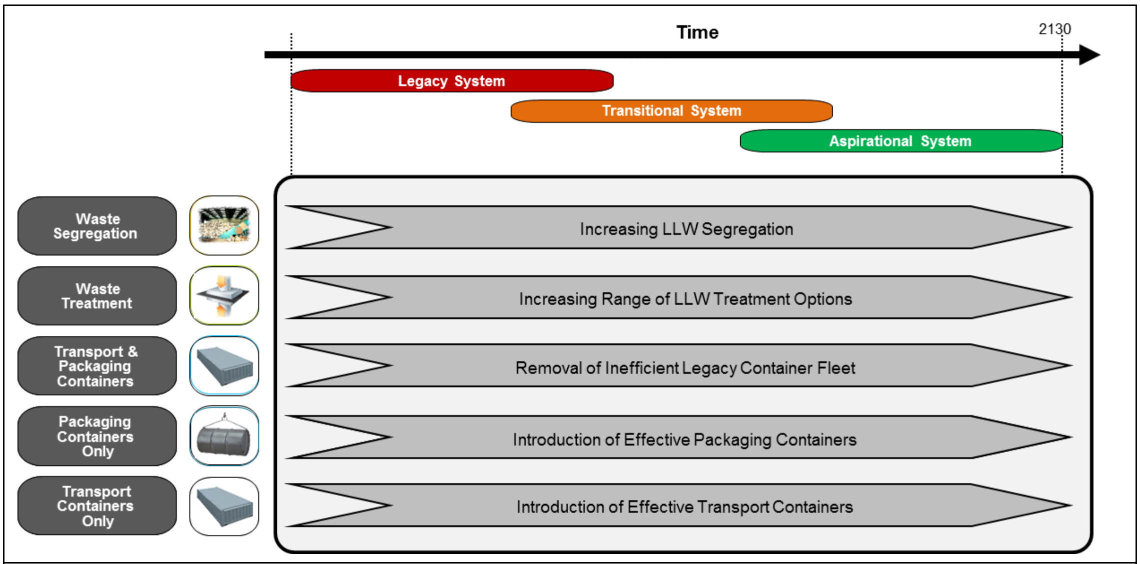


Figure 6: Improving the Low Level Waste System over time

6.2 Model description

A besoke model was developed using the System Dynamics software package Powersim. The model used the Causal Loop diagram presented in Figure 4 as a starting point for a more detailed Stock and Flow representation of the LLW system.

Each of the consignor sites produces waste generation forecasts through to 2130, which is gathered by the LLWR and approved for use by the NDA. These waste generation forecasts were integrated into the model to generate the projected LLW treatment and disposal demand.

The model also allowed different variations on the container fleet, with associated treatment and disposal characteristics to be flexed. The attributes of the assets that could be defined in the model are shown in the Table below:

Table 1: Quantifying the SD Model – Asset Properties		
Asset introduction & lifetime • In service date • Out of service decision date • Asset life duration (months) • Initial stock (No) • Target fleet size (no) • Maximum procurement batch size (No) • Minimum procurement batch size • Implementation cost (£) • Cost per unit	**Asset specification** • Internal container volume (m^3) • External container volume (m^3) • Packing efficiency for non-segregated material waste (%) • Packing efficiency for segregated material waster by type (%) • Stacking efficiency (%)	**Asset maintenance** • Failure/irreplaceable damage rate (%/year) • Preventative maintenance cost (£) • Preventative maintenance duration (months) • Preventative maintenance frequency (events/year) • Overhaul cost (£) • Overhaul duration (months) • Overhaul frequency

The Table shows that along with introduction and packing/volume attributes maintenance of the assets could also be defined.

The model allowed the following key outcomes to be calculated over time:

- **Waste Volumes:** Monthly and cumulative forecast volume for waste generated at Consignor Sites, waste not yet removed from Consignor Sites, volume of waste currently going through treatment, overall volume required at LLWR (including containers and stacking of those containers) and volume of actual waste stored at LLWR.
- **Key LLWR Ratios**: Monthly and cumulative forecast of the storage efficiency for waste at LLWR, i.e. the proportion of actual waste by volume as compared to the total volume required for containers and the stacking of those containers.
- **Key Asset Quantities & Usage**: Monthly forecast of the number of key assets in circulation and the utilisation rates of those assets.
- **Key Financials**: Monthly and cumulative forecast of the Capital and Operational Expenditure required to introduce and maintain assets in the system (with values either Constant, Discounted or Escalated to support NDA requirements).

Finally, the model had a user friendly interface that allowed all inputs to be altered, the model simulated and the results reviewed. A sample screenshot is shown below:

Figure 7: Screenshot from the LLWR SD Model (redacted data used)

6.3 Model usage

This approach to representing the complete LLW system was novel to the civil nuclear industry, and integrated System Dynamics principles with LLWR's vision for the future of LLW handling in the UK. The resulting model was used to ensure a robust business case for LLWR's future waste treatment and container strategy. The model also enabled the exploration of different initiatives, such as different treatment strategies and container fleets and the resulting impact on costs and LLWR performance ratios.

7 Quantification of MEB treatment and disposal to support business case analysis

Case study 2 (See Section 6) provides an example of how System Dynamics was used to represent the full LLW system at a national level. The third and final case study demonstrates how System Dynamics was used to represent the system for a particular LLW waste, but at a much greater level of granularity.

7.1 Problem definition

In 2011 LLWR was developing a multi-million pound business proposal to treat and dispose of Multi Element Bottles (MEB) from Sellafield. MEBs are containers used to hold irradiated Light Water Reactor (LWR) fuel in cooling ponds prior to reprocessing. MEBs can be considered to consist of three primary components, the carcass mass, a lead mass and an internal basket mass. These three components require different treatment and handling. LLWR required a model to validate their proposed method of handling the MEBs, and also enable different handling strategies to be explored and costed.

7.2 Model description

The model was based on the various MEB treatment and disposal options that were developed based on discussions with LLWR experts. The model was required to represent each of these option, shown in Figure 8, and enable the different strategies to be evaluated. The model was required to represent the MEB treatment and disposal options out to 2030.

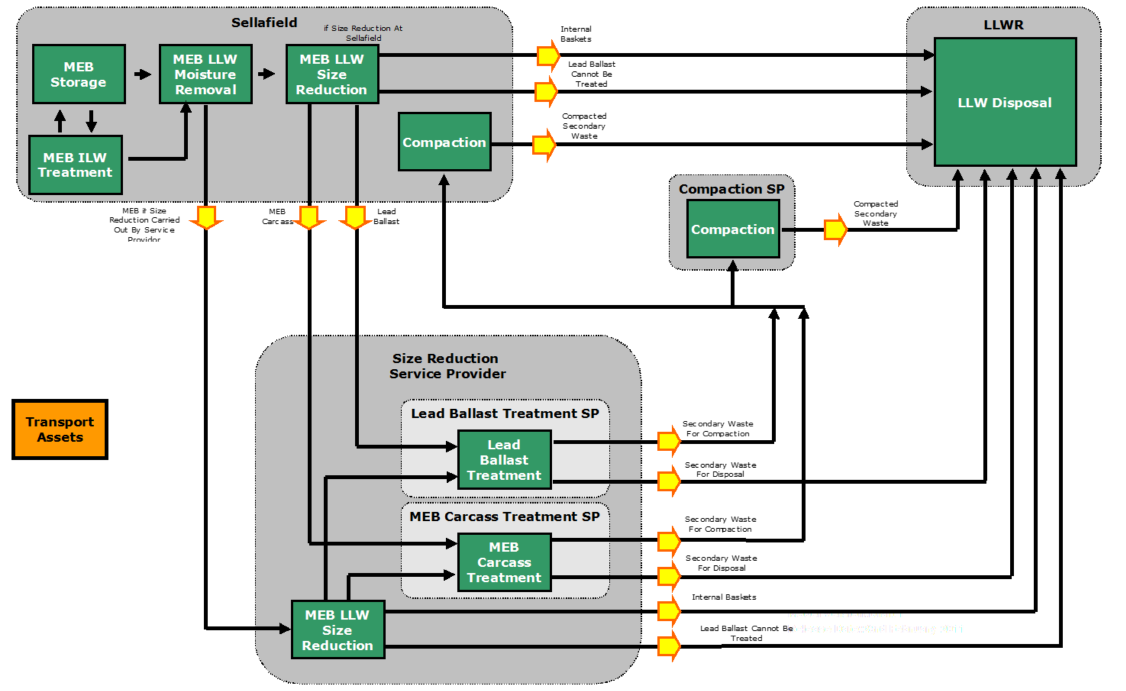


Figure 8: Processes represented in the MEB model

A bespoke model was developed using the System Dynamics software package Powersim. The model represented two types of MEB, which had different quantities of each of the three components. The model enabled the rate at which the MEBs were removed from the Sellafield pond and their subsequent treatment and disposal rates to be assessed. These treatment and disposal rates were dependent upon the actual treatment processes that were selected, and the available container fleet. The container fleet could be fully specified, and their attributes (as per Table 1, see case study 2 above) defined in the model user interface.

As with case study 2 (Described in Section 6), cost and volume were key model outputs. An additional output required for this model was the maximum radioactivity dosage received by the staff employed to carry out the processes. This was used to determine the number of staff required such that maximum radiation doses per annum were not exceeded.

This model also had a user friendly interface that allowed all inputs to be altered, the model simulated and the results reviewed.

7.3 Model usage

The model was successfully used to validate the LLWR business proposal, with a particular benefit of the model being that it offered a very visual representation of the planned treatment and disposal strategy.

LLWR's business proposal was successful, and by 2013 an MEB recycling route had been developed and was processing a significant number of MEBs per annum (LLWR, 2013). As of January 2015 the 500th MEB had been recovered from the Sellafield pond (WCS, 2015).

8 Conclusions

Both qualitative and quantitative methods have been applied to support real world strategic issues associated with the treatment and disposal of low level radioactive waste. Models that describe the specifics of radioactive waste transportation, disposal and treatment have not previously been described in the literature.

The qualitative models ensured an agreed, stakeholder owned, understanding of the system under study.

The quantitative models allowed robust investment decisions based on sound, objective data for the procurement of critical LLW assets and infrastructure. In addition, the quantitative models allowed rapid analysis of strategic options, where key performance metrics such as storage space requirements, costs, and staff radioactivity dosages could be readily viewed and assessed through user friendly interfaces.

Of particular note was that the System Dynamics models enabled this complex system, which has a large combination of possible treatment, container options and transportation options to be represented in a more efficient manner than an Excel model would. The System Dynamics models also enabled the model structure to be more easily validated as all the cause and effect relationships were visible in the stock and flow diagrams.

9 Abbreviations

HLW	High level waste
ILW	Intermediate level waste
LLW	Low level waste
LLWR	Low Level Waste Repository Ltd
LWR	Light Water Reactor
MEB	Multi element bottles
NDA	Nuclear Decommissioning Authority
SD	System Dynamics
UK	United kingdom
VLLW	Very low level waste

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