CBRN preparedness using discrete event simulation

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Abstract

Preparing for the aftermath of a Chemical, Biological, Radiological or Nuclear (CBRN) incident is particularly challenging. The number of unknown variables specific to an incident leads to a combinatorial explosion; hence live training can only cover a small subset of possible events. To exacerbate the problem, the job of responding promptly and effectively to a CBRN attack, as well as ensuring a quick recovery from any incident, falls to multiple agencies at the local level who are guided by national policy and/or international guidelines.

In a military context the ability to retain or regenerate operational capability following a CBRN incident is a priority. The physiological effects of wearing personal protective equipment (PPE) are significant. Additionally, the need to remove contaminated equipment from active service is a major risk against delivering the required military outputs.

BAE Systems CORDA has developed a CBRN decontamination tool called CRISTAL[1] to provide insight into the impact of implementing different decontamination strategies. It is a fast-running, discrete event simulation which uses stochastic modelling techniques to guide the decision-maker on the impact of using different resource mixes and approaches in a CBRN scenario.

CRISTAL has been used in demonstrations and exercises across Europe as part of the EDEN project, and has proved itself effective at providing users with evidence-based information on which to base decisions. This paper will describe the tool and present some illustrative analysis to show how it may be used.

Introduction

Strategic context

The aspiration of terrorist groups to acquire an offensive Chemical, Biological, Radiological or Nuclear (CBRN) capability is well established. It has been regarded for many years as one of the highest-priority risks to the security of the United Kingdom [1] [2].

The Tokyo attacks of 1995 provided a vivid demonstration of the threat posed by CBRN terrorism to the major cities of industrialised nations. Members of a terrorist cult released sarin gas inside three subway trains at rush hour, injuring more than five thousand people and killing twelve [3].

In the intervening decades, Islamist groups including al-Qaeda have made explicit their intention to develop a CBRN capability. While Western governments have always taken this threat seriously [2] [4], some analysts questioned both the level of al-Qaeda's dedication to this aim [5] and their ability to achieve it [6] [7].

[1] CORDA's cbRn Incident Simulation Tool for AnaLysis

The threat has arguably grown more credible with the emergence of Islamic State, which has successfully carried out chemical attacks in Syria/Iraq and aspires to do the same in Europe [8] [9]. Islamic State's control of a large amount of territory, its funding and its access to CBRN expertise and raw materials all compound the seriousness of the threat it poses [8].

The risk of a CBRN incident is not confined to deliberate hostile action. Incidents leading to the accidental release of radioactive or other hazardous materials also represent an important risk to the safety of the UK populace. However, such accidents are most likely to occur at industrial sites where extensive risk management strategies are already in place, or within the national transport infrastructure. In either case, the risk to the public and the difficulties faced by responders are very much lessened relative to a CBRN terrorist attack targeted directly at a population centre [10].

Government response

Western governments are tasked with meeting these challenges. Since 2003, the UK Government has maintained a coordinated counter-terrorism strategy called CONTEST [11] [12]. This strategy covers a range of measures designed to: *prevent* disaffected individuals from becoming terrorists; *pursue* those who are planning terrorist attacks; *protect* the citizens and infrastructure of the UK from such attacks; and *prepare* the emergency services and others to respond effectively.

It is on this final point of *preparedness* that this paper focusses. CBRN preparedness is complex: it typically involves the use of specialist equipment and resources, and it must be able to deal with potentially very large numbers of casualties. An additional layer of complexity comes from the diverse array of Government bodies with responsibilities for CBRN response.

In the UK, public sector organisations with an operational role in responding to a CBRN incident include police services, fire and rescue services, ambulance services, the National Health Service, local authorities, Public Health England, Government Decontamination Service, Environment Agency, Health & Safety Executive, Food Standards Agency and the armed forces. Within central Government, planning and policymaking for CBRN preparedness involves the Home Office, Cabinet Office, Department of Health, Department of the Environment Food & Rural Affairs, Department of Communities & Local Government, and the Ministry of Defence, as well as the devolved administrations [13] [14].

In working to ensure that its response plans are as effective as possible, a coordinated approach is required, which draws upon capabilities across government, industry and academia. The challenge in achieving this coordination across such a disparate customer and stakeholder community has been noted by several observers [15] [16] [17]: it can instead lead to a fragmented approach to research and analysis.

Notwithstanding these challenges, the UK Government clearly recognises the need to invest time and effort into determining optimal response plans for different types of CBRN incidents [18] [19], and to communicate these plans effectively to first responders [13] [20] [21].

For classification purposes this paper concentrates on the response to a CBRN incident in a civilian environment. CRISTAL itself is equally applicable to military scenarios across all domains.

Role of simulation modelling

Work to optimise response plans can make effective use of simulation modelling and synthetic environments. These techniques provide a safe and cost-effective means of assessing a large number of CBRN scenarios and exploring different potential responses.

Examples of these techniques can be found in [22] and [23], where the authors present simulation models designed to aid the design of mass decontamination facilities and antibiotic distribution centres, respectively. However, UK Government research in this area tends to draw more heavily on trials and experimentation, conducted either in the laboratory or real-world operational environments. It has been noted that simulation modelling capabilities could be exploited by government bodies to a greater extent to inform preparedness in this domain [24] [25]. Simulation modelling used as a supplement to live trials can be especially informative [26].

This paper presents a discrete event simulation model called CRISTAL, initially developed by BAE Systems CORDA for the Ministry of Defence to consider CBRN response in the specific context of military operations. It has since been developed further in order to inform CBRN response planning more widely, and to aid civilian decision makers with responsibility for operational response, planning or policymaking.

CRISTAL enables the user to determine the best resource mix, in terms of different types of equipment and personnel, to enable a given CBRN incident to be resolved as efficiently or effectively as possible. It can identify the best response plan within existing resource constraints, or inform procurement decisions by establishing the optimum resource mix to achieve a target outcome in different scenarios.

Though designed principally to aid preparation and decision making during the planning phase, CRISTAL has demonstrated utility to inform operational decision-making as an incident unfolds. The model was used during a live CBRN exercise held in Rome as part of the EDEN project[2], where CRISTAL was used to predict in real-time the outcomes of on-site decontamination processes. This provided medical staff at off-site treatment centres with a forecast of patient numbers and arrival times.

The following sections of this paper present two case studies to demonstrate the utility of the model.

Managing decontamination scenarios using CRISTAL

CRISTAL methodology

The decontamination problem has been characterised as one of queueing for a constrained volume of resources. Due to these queues and the stochastic nature of the time and consumables required to decontaminate an asset, it was decided that a discrete event simulation was the most appropriate method of modelling this process. The tool has been implemented in SIMUL8. A number of factors contributed to this decision. These included the availability of a free, read-only application, the ease of implementing rule-based logic and the availability of in-built diagnostic and batch running functionalities. For ease of accessibility to the end user community, model inputs and outputs are contained within Excel workbooks.

The degree to which an asset[3] has been affected by a contaminate has been parameterised by its contamination level (CL) within the model. In general, CRISTAL seeks to reduce the CL to zero (i.e. so that it is clean) in the quickest way possible using the fewest steps[4]. This process is shown in Figure 1. Each decontamination event requires decontamination equipment and may need manpower, protective equipment and/or consumables (such as oil or water). Events are constrained by the maximum amount of time manpower can work (due to regulations or the maximum exposure times of their protective equipment) and the user-specified priority of the asset (i.e. contaminated people are almost universally seen as a higher priority than contaminated equipment).

[2] https://eden-security-fp7.eu/
[3] An asset is the item to be decontaminated, be it personnel, personal effects, terrain or equipment
[4] The exception is if a triage activity is included, which doesn't reduce the Contamination Level but has the potential to reduce overall queuing times

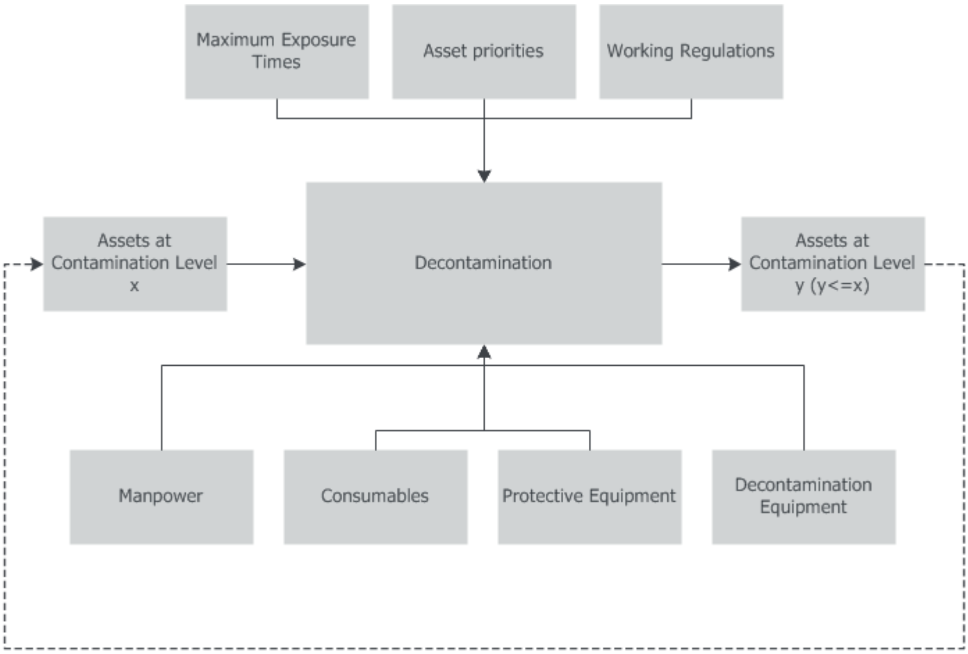


Figure 1: The decontamination method modelled within SIMUL8

Within SIMUL8, asset characteristics have been attached to simulation objects to enable the simulation to make rule-based decisions. A preference was given to modelling with work items; even manpower and equipment that could be represented by resources were represented as work items as this gave a greater amount of flexibility with regards to the collection of results and enabled greater freedom in respect of prioritisation and re-roling. As shown in
Figure 2, the decontamination of assets was represented using activities; tanks were utilised to allow consumable levels to be monitored. SIMUL8's inbuilt programming language, Visual Logic, was used to determine the 'best' course of action to take based on the priority of the decontamination to be undertaken and the availability of manpower, decontamination equipment and consumables. This visual logic also allowed for re-prioritising: stopping an activity mid-way through if a higher priority asset comes along.

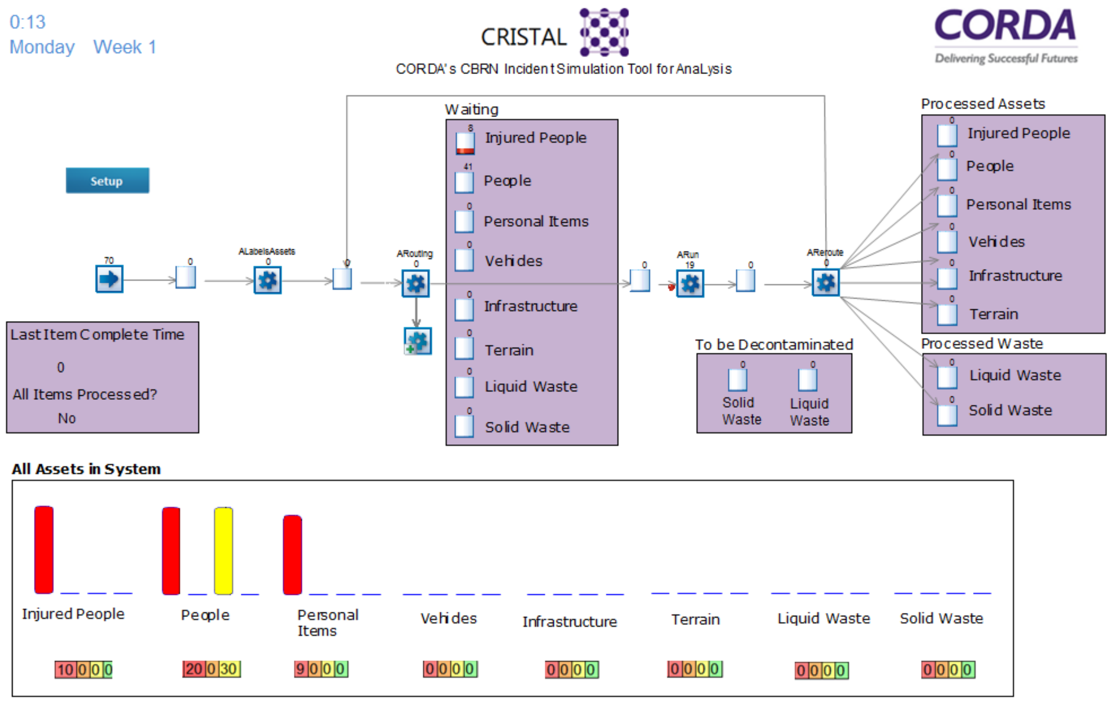


Figure 2: The SIMUL8 model

CRISTAL also contains optimisation routines to enable the best mix of resources to be derived for a given scenario. This was achieved using SIMUL8's inbuilt Scenario Manager, which flexes the number of these inputs between the range specified by the user.

CRISTAL in Europe

Under the EDEN programme, CRISTAL has been demonstrated to users from across the Europe. In each case the scenario and the information required has been different, testing the flexibility of the tool. A sample of the previous applications of CRISTAL includes:

- Simulation of the decontamination of a public space following release of a chemical agent
- Simulation of the decontamination of a public space following the detonation of an improvised radiological dispersion device (RDD)
- Simulation of the decontamination and treatment of affected workers at a nuclear power plant following a terrorist incident
- Simulation of the decontamination of the population of a small town following a large scale radiological release

In each case, CRISTAL has proved its value in the 'prepare' stages of an operation to inform the user how long it will take to complete decontamination given the resources at their disposal. In the latter two cases, CRISTAL was also used in real time, taking the best available information and providing rapid answers to decision makers in a virtual control room.

Case study scenarios

Results are presented below for two fictional exemplar scenarios. These have been selected to demonstrate the tool's flexibility in being able to represent one method of mass decontamination following a radiological release (Example 1) and one method of decontaminating a building following a chemical release (Example 2).

Example 1. Radiological release

This scenario assumes a large scale release of radionuclides has occurred. The radioactive material has been dispersed across a wide area affecting a number of towns and villages. Alerts have been issued warning people to stay indoors until the highest concentration zone of radioactive material has passed. Not all the population received the notification meaning some people are more contaminated than others. It is assumed that a total of 1000 people have been contaminated to varying degrees, categorised as 'moderate contamination' (920 people) and 'severe contamination' (80 people). The authorities can access 40 showers, eight field washing facilities and 40 fire fighters to run the facility and could also operate a triage system to separate people of different contamination levels.

Baseline scenario

The baseline (see Figure 3) assumes that all people must be processed in showers. Each of 40 shower units has one firefighter supervising.

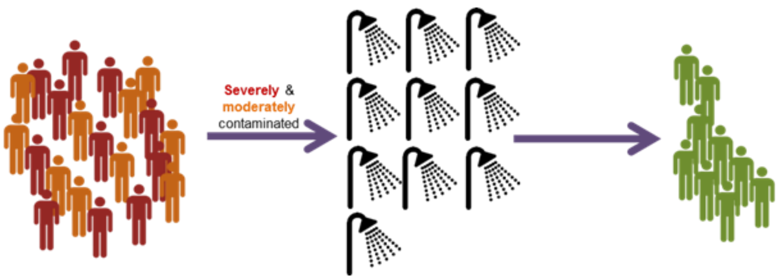


Figure 3: Baseline scenario including 1000 people of mixed contamination level and 40 showers

Table 1 below shows the time taken to decontaminate all people in the scenario, sampling shower times from a triangular distribution with bounds between 10 minutes and 15 minutes. In failing to discriminate and prioritise between people of different levels of contamination, it is possible that those most in need of treatment will not be processed for nearly six hours. Whilst this time may be acceptable for moderately contaminated people, the impact of the wait on the more severely contaminated population could be severe.

Start Time		10:00
Finish Time		15:53
Time Queuing (mins)	Minimum	37.2
	Mean	185.2
	Maximum	339.0
Total Time Taken (mins)	Minimum	47.9
	Mean	197.5
	Maximum	353.7

Table 1: Final decontamination time for the treatment of 1000 contaminated people using showers only

Interrogation of the outputs show that the major bottleneck in the system is the shower system, with a prolonged period of maximum utilisation.

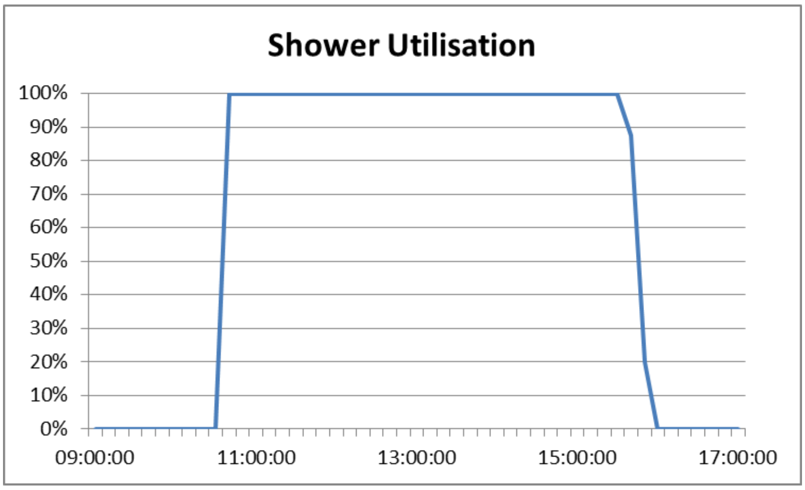


Figure 4: Utilisation of the shower system in the radiological release scenario

There are a number of options to reduce the total time required. The crudest of these is simply to introduce more showers, with their associated manpower. In reality an upper bound to equipment and manpower numbers will be reached, at which point a change in process should be investigated. The benefits associated with a change can be assessed by CRISTAL.

Variant scenario

As people are contaminated to varying degrees, it is possible that not all are contaminated enough to need full wet decontamination. Those individuals who are only mildly contaminated could be processed by quicker field decontamination stations. These enable the washing of hands and face. By introducing a triage system, it is possible to divert the least contaminated people to these field decontamination stations, allowing the severely contaminated to be processed through the shower units without the additional queue caused by moderately contaminated people. When showers are not in use treating severely contaminated people, they may be used to treat moderately contaminated people.

CRISTAL has been used to analyse the benefits of triage. Assuming resource constraints, the number of showers has been reduced from 40 to 28. The process now includes eight triage stations and eight wash stations, all manned by the pool of 40 fire fighters.

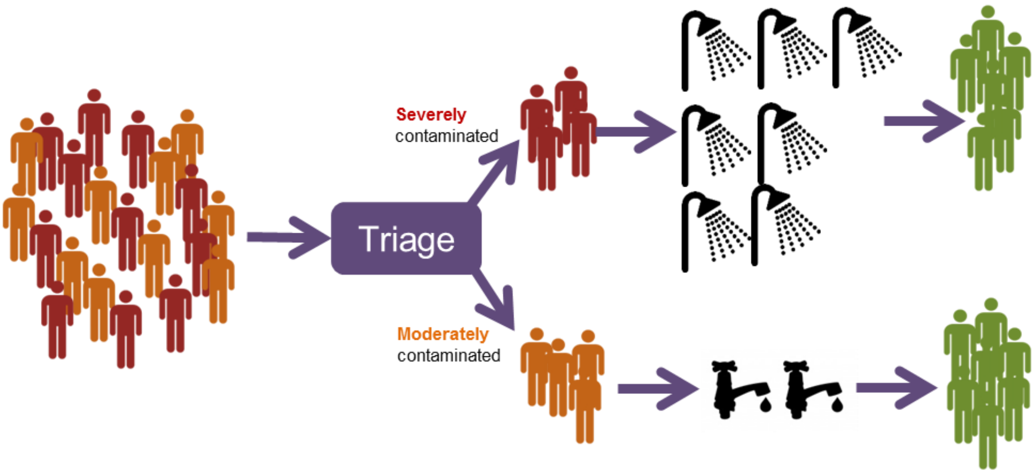


Figure 5: Variant scenario including 1000 people of mixed contamination level treated either by showers or field wash stations

Table 2 shows the time taken broken down by contamination level.

		Severely contaminated	Moderately contaminated
Start time		10:00	10:00
Finish time		15:35	15:43
Time queuing (mins)	Minimum	37.1	32.5
	Mean	185.3	174.6
	Maximum	322.4	328.4
Total time taken (mins)	Minimum	49.7	39.2
	Mean	198.5	185.7
	Maximum	335.2	343.2

Table 2. Final decontamination time for the treatment of 1000 contaminated people using a combination of showers and field wash stations

The benefit obtained by adopting a triage process amounts to an 18 minute reduction in the time taken to decontaminate the cohort of most severely contaminated people. Whilst the reduction in time to treat the moderately contaminated cohort is less dramatic, the re-direction of resources still results is a small decrease in time to complete the process. Constrained manpower means that a maximum of 40 pieces of equipment can be operated concurrently, from a pool of 44, resulting in the variation of equipment utilisation seen in Figure 6. It is striking how such a significant effect can be achieved through such a simple procedural change.

Investigation of the outputs reveals where queues are building up in the process, and hence where additional gains could be made by employing additional equipment and people.

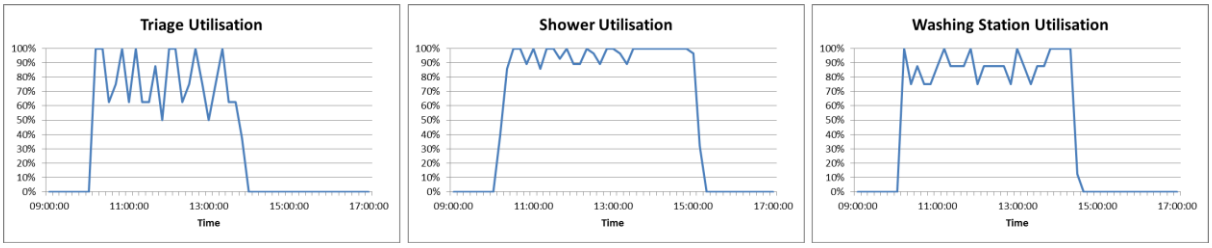


Figure 6: Decontamination equipment utilisation

Taken as a set these graphs provide useful information on the dynamics of the decontamination process. Once set up the triage stations are working at a significant throughput, such that the subsequent showers and wash stations are working at near maximum capacity, constrained by available manpower. It can be inferred that queues are built up prior to the wet decontamination stations (both showers and wash stations) by observing the period of maximum utilisation towards the end of the process, when manpower is freed from triage. When looking to increase the overall decontamination tempo, it is clear that a planner should prioritise accessing more manpower, followed by showers and washing equipment.

Another practical consideration for planners is the volume of consumables required and waste generated. For example, wet decontamination relies on the availability of a large quantity of water and a method to dispose of the waste. Depending on circumstances these criteria may not be met. CRISTAL calculates the consumable demand and waste generated to enable planners to assess the viability and efficacy of alternative decontamination methods. In this case, it may be that dry decontamination should be considered.

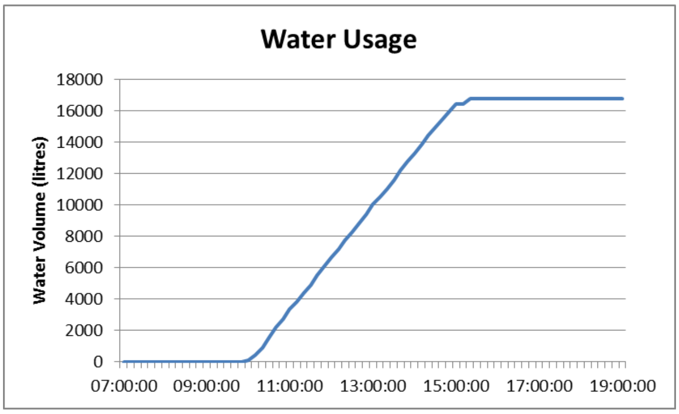


Figure 7: Water required for wet decontamination

Example 2. Chemical incident within a building

A chemical agent has been released within a building which consists of a common area with one separate office (see Figure 8). The agent, which is harmful by contact and inhalation, has been adsorbed onto all surfaces within the building, including floors, ceilings, windows and the office fixtures and fittings. Resources have been made available to decontaminate the building, consisting of BX24 solution, soap, 5 people and the equipment needed to clear and clean the area. The contractors responsible for undertaking the decontamination need to find the fastest way of completing the task and how much waste liquid will be generated.

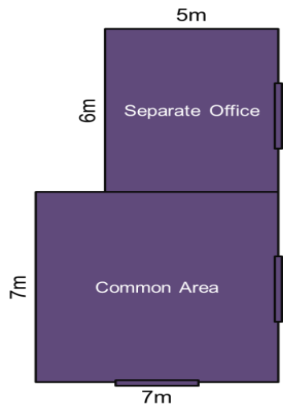


Figure 8: Office layout

The process being modelled is shown in Figure 9. In this example it is assumed that distinct processes are used to decontaminate fixtures and fittings, floors, walls, ceilings and windows but that a common pool of people can undertake any of the activities.

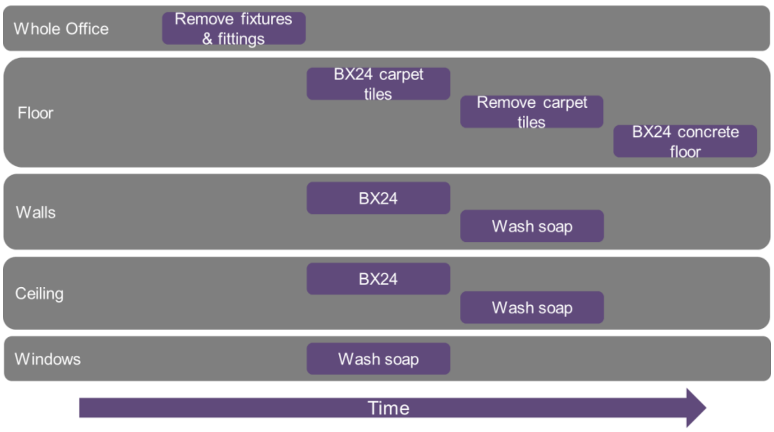


Figure 9: Building decontamination process

Table 3 shows the times taken to decontaminate each element of the office space assuming 100% effectiveness of the process, i.e. only one pass is needed. Interrogation of the utilisation graphs reveals why certain elements take as long as reported.

Asset type	Start time	Finish time
Walls	10:00:00	16:00:03
Ceilings	10:00:00	18:32:34
Windows	10:00:00	10:22:58
Floor	10:00:00	14:18:49

Table 3: Time taken to decontaminate office broken into its constituent parts

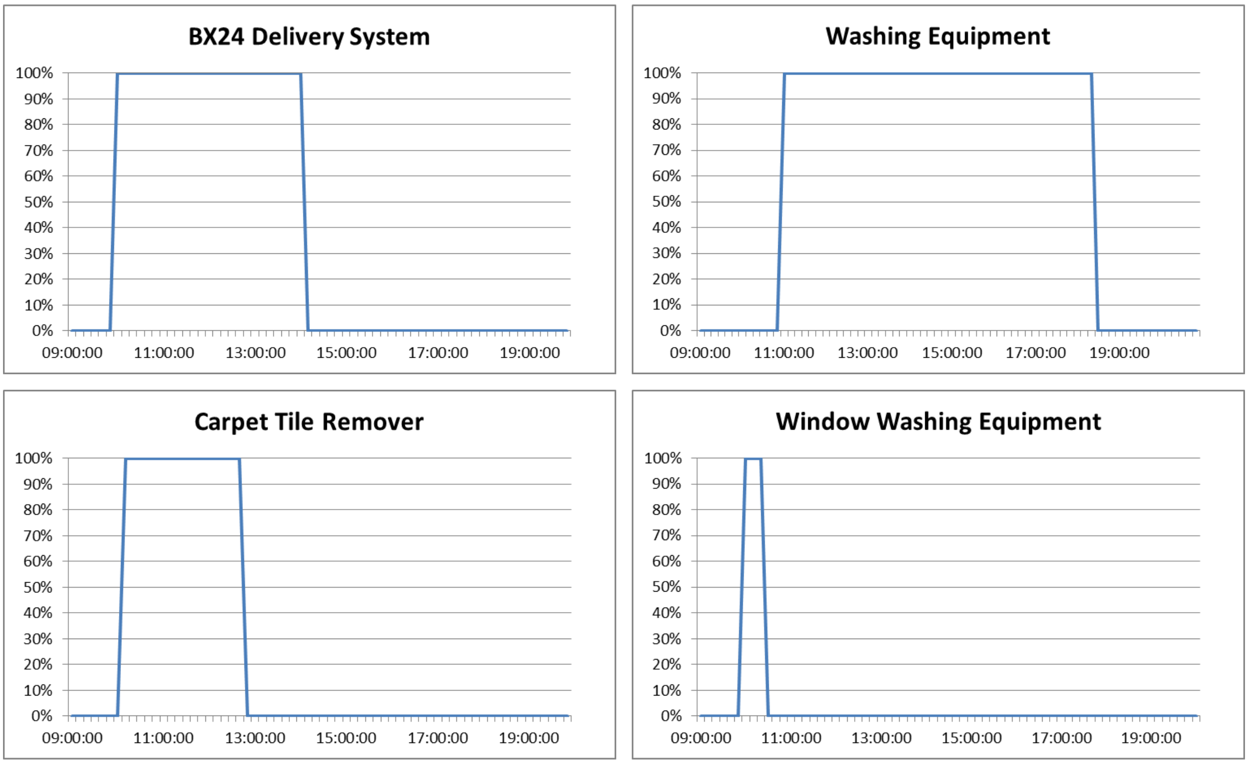


Figure 10: Utilisation of decontamination equipment

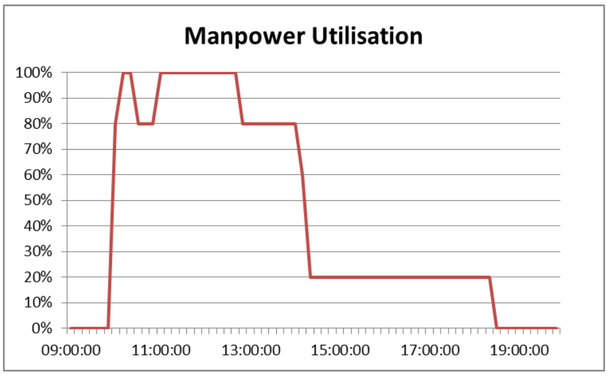
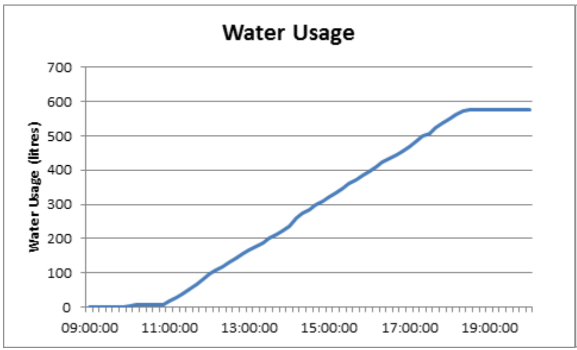


Figure 11: Total manpower utilisation

It can be seen that the major constraint in the system is the number of washing equipment available. As long as there is only one of these equipment packages available, processes have to wait until the single piece of equipment becomes free. Investigations have shown that incremental increases in the number of washing equipment available do not add significant benefit. Rather, the whole portfolio (carpet removal equipment, washing equipment, BX24 delivery equipment and manpower) needs to be increased so that all processes in both offices can run concurrently if time is critical.



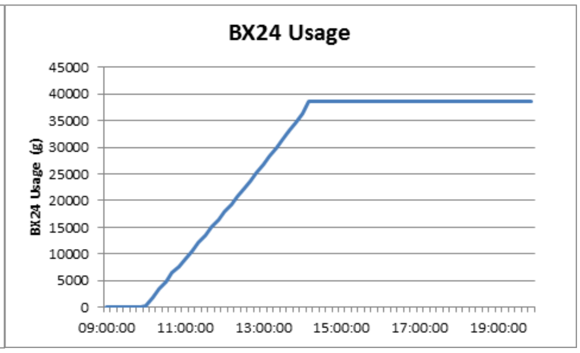


Figure 12: Water and BX24 usage required for building decontamination

A final analysis is presented in which the efficacy of each decontamination activity is reduced to 75%, i.e. there is a 25% probability that an activity needs to be repeated. This example is representative of a common situation in which final checks of a treated area reveal contaminant to still be present.

Debate continues around what is meant by 'clean' and at which level of residual contaminant it is safe to re-introduce people. CRISTAL can inform the decision-maker on the time impact of decontaminating to different levels using the method in this analysis.

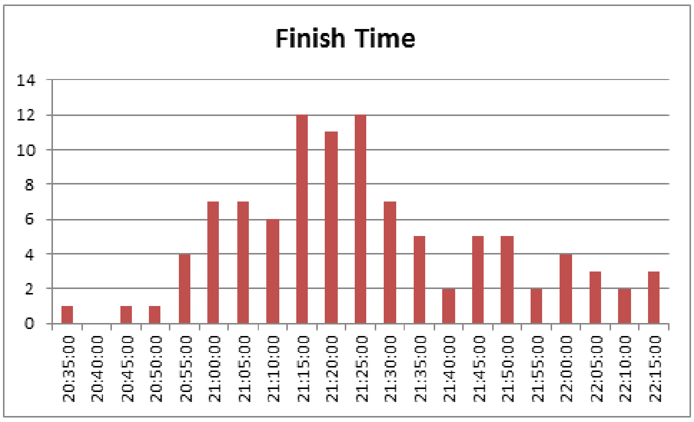


Figure 13: Graphical representation of the distribution of times to complete decontamination of the office space given a 'need to repeat' probability of 25%

	Time to complete
Min	20:35:00
Max	22:15:00
-95%	21:19:27
Mean	21:23:44
+95%	21:28:02

Table 4: Distribution of times to complete decontamination of the office space given a 'need to repeat' probability of 25%

Figure 13 shows the distribution of the total times taken to decontaminate the office over 200 trials. The example demonstrates how long it could take, as compared to the baseline assumption of 100% efficacy, to decontaminate the offices. In the baseline the office was decontaminated by 18:33. Including a 'need to repeat' probability of 25% increases the mean end time to 21:24, a significant increase. This is due to the number of activities which could need to be repeated (and re-repeated) and the competition for resources this introduces into the system.

In order to reduce the likely maximum time the user has two non-exclusive options: reduce the time for each process by employing more equipment and manpower or reduce the likelihood of having to re-treat an area by using more effective decontaminant. We note that the shape of the distribution will vary for different surface types and contaminant, and these may limit the ways they can be treated.

Conclusions

The nature of a CBRN incident makes preparation challenging. The number of variables involved means that live exercises can only cover a subset of possible incidents and offer a limited opportunity to try different ways of managing the response. Whilst simulation cannot replace live exercises it can be used as a cost-effective complementary technique to narrow down the options to be tested at an exercise, and can guide the decision maker on what the most effective course of action will be given an incident.

In addition, CRISTAL can provide the evidence that decision makers need in order to develop robust policy in the CBRN area. The tool enables the user to readily investigate the impact of different options and through sensitivity analysis the user may develop a matched portfolio of resources and procedures which can best meet current and future demands.

The specific circumstances of a CBRN incident (e.g. weather) have a significant impact on the outcome. CRISTAL can incorporate uncertainty to provide a level of confidence for a decontamination strategy enabling the decision maker to rank options, even in the absence of precise information.

Previous uses have relied on subject matter experts to provide example data. However there is scope to include CRISTAL within an integrated modelling suite, drawing on detailed dispersion and population models to provide the number of affected items at each contamination level. We are also investigating how the tool can include a dynamic calculation of dose, translated to contamination level, to better represent reality.

We have demonstrated the benefits of using discrete event simulation to analyse a resource-constrained queuing problem. Numerous similar problems exist across business and defence which would benefit from a similar approach.

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