Modelling the Human and Economic Costs of Major Industrial Accidents

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Major industrial accidents pose an ever-present risk to the society and economy of the UK. The Health and Safety Executive (HSE) regulates sites with major accident hazard potential in order to reduce the risk of accidents and mitigate the impacts should they occur. The addition of enhanced spatial information into impact assessments has the potential to make these assessments more focussed and localised. Cost estimates for major accident consequences have previously relied on actual accidents, such as the incident at Buncefield in 2005, which was costed at around £900m (2008 prices). This paper presents the first attempt in Europe to model the costs of potential major accidents and produces estimates for GB via a collaborative effort between HSE and Cardiff Business School. This work will assist in continuing to ensure that the level of regulation remains proportionate for the level of risk.

An innovative catastrophe modelling approach to estimate the costs of major accidents is presented. Emphasis has been placed on the novel application and re-use of available data sources and techniques. Monetised impacts comprise key direct and indirect effects including casualty impacts, disruption and temporary relocation of businesses, building damage, and evacuation and emergency service requirements. Property level data from the National Receptor Dataset, Valuation Office Agency and National Population Database were combined in a Geographical Information System (GIS) to create original property and population impact layers. Populations more vulnerable to harm were identified, such as those in hospitals, care homes and childcare facilities. Impacts were estimated through spatial intersection of site-specific hazard zones and the impact datasets, and costed based on methods developed from those in the COCO-2 model for nuclear accidents.

Results were aggregated by region and site type to provide data protection and confidence in general results and handling of inherent sensitivities associated with individual sites. Regionally, sites in London contribute the largest costs per site, with a cost that is nearly double the average (mean) cost of sites in other regions. Overpressure sites modelled based on a vapour cloud explosion contribute the highest mean cost by main type of hazard. Large-scale petrol storage sites represent the highest mean cost by substance and storage type.

This approach can be generalised to assess the impacts of other UK and global scale risks including natural disasters, infrastructure failure and terror attacks. Automation enables the model to be updated, enables multi-temporal analysis, while the generic conceptual model provides a standard footing with potential application outside the UK. Future directions of research include refinement of metrics, breakdown of site and hazard types, and inclusion of environmental impacts. Cluster analysis could provide useful information for sector and regional regulatory management, and new insights into how the impact of accidents or regulatory pressures might be locally communicated.

Key words: COMAH, major hazard sites, economic impact assessment, catastrophe modelling, GIS, hazards

Background

Accidents at major hazard sites are seldom, but when they do occur, consequences can be significant. The incident at Buncefield in 2005 is a recent example of a particularly impactful and costful major accident in the UK; there were no fatalities but there were injuries as well as damage to buildings, and impacts on business and the environment. A review by the Major Incident Investigation Board (MIIB) found that the overall costs were estimated at £894m at 2008 prices (MIIB, 2008). This estimate was derived from a range of impacts listed in Table 1. The largest cost was the cost to business, which was estimated at £625m. This equates to 70% of the total estimated cost of the incident.

Table 1 Components of the overall cost of the Buncefield incident.

Localised Impacts	Wider Impacts
Costs to business Unemployment Housing market Emergency response Environmental cost Personal injury	National supply-chain implications Effects on the aviation industry Site rebuilding costs Costs to the Government of the investigation response

The MIIB (2008) made a series of recommendations for improving the land use planning system following Buncefield. Among these was a recommendation for a review considering the full range of costs and benefits of land use planning, including costs to the relevant industry sectors, local businesses and regional economies to support the economic case for a revised land use planning system.

The Seveso Directives (Council of the European Union, 1996) aim to prevent major accidents involving dangerous substances, and to limit their consequences on people and the environment. The Directives are currently in their third iteration, with the most recent Seveso III Directive replacing the previous incarnation on 1st June 2015 (HSE, 2016a). The latest iteration addresses issues including European Commission (EC) reclassification of hazardous substances meaning changes to site classification for some major hazard sites (HSE, 2016b). Further amendments to the Directives include a more comprehensive requirement to release basic information about hazardous sites to the general public. In Great Britain, HSE work in partnership with the Environment Agency (EA), Scottish Environmental Protection Agency and Natural Resources Wales to implement the Seveso III Directive legislation via the enforcement of COMAH (Control of Major Accident Hazards) regulations as part of the COMAH Competent Authority, who oversee and coordinate major hazard regulation.

HSE has a responsibility as a regulator for 'major hazard sites'. As part of this role, HSE limits the impacts on the general public through its role as a statutory consultee in the land use planning process, providing advice to Local Planning Authorities with regard to developments in the vicinity of major hazard sites and pipelines. Major hazard sites are operations that manufacture, store or use hazardous substances in quantities that have the potential to cause major harm to employees, the public or the environment. In Great Britain, there are 1,700 major hazard sites, of which, approximately 1,000 are subject to COMAH regulations. These sites vary in the composition, volume and storage methods of substances that can be held on site. This presents a range of potential hazards and associated risks, and creates a challenge for optimisation of regulatory activities.

Current risk analysis for major hazard sites deals with consequences of land use planning in zones of potential exposure to hazardous sites. These typically focus on quantitative risk assessments based on exposed populations and planning guidelines, however these are generally designed for small scale or single site analysis (Pasman, 2014). Alternative approaches have expanded the estimation of risk to a wide range of impacts including projected fatalities, social, economic and environmental losses (Cavanagh, 2012). The outputs of such models create highly detailed information on risks and impacts, but due to the complexity and granularity of the input data, these may be inappropriate to scale up to a national level.

HSE has an interest in the economic consequences of accidents across Great Britain to ensure that it can provide robust regulation and that the resources given to controlling risks are proportionate to the likely impacts. The MIIB investigation into the accident at Buncefield has provided evidence that demonstrates the range and scale of costs that can occur as a result of an accident at a major hazard site. The MIIB review also revealed that the impacts are much broader than the consequences associated with the direct harm to people. The Costs to Britain research (HSE, 2013) found that the non-financial costs of accidents to workers, such as impact on quality and loss of life, can be the greatest cost. Attempting to quantify the impact of these accidents on people's health and well-being ensures that a more complete economic cost is assessed, and helps HSE's regulation be more proportionate. Consequently, the aim of the research documented in this paper is to estimate the potential costs of accidents at major hazard sites in Great Britain, focusing on the impacts of an accident, and taking into consideration a broad spectrum of loss types. The research applies a catastrophe modelling approach to assess the potential economic losses of a major accident. The model developed in this research contains three distinct components: the hazard, the vulnerability of potentially impacted receptors, and the related economic losses. Offshore, nuclear and pipelines are also subject to major hazard regulations but are currently outside of the scope of this project.

Methods

The catastrophe modelling approach

Catastrophe modelling is a method of assessing potential economic loss as a result of a catastrophic event (Woo, 2011). It is a commonly used tool in the insurance industry where it is used to evaluate and quantify the risk from hazards to receptors such as people, buildings and infrastructure. Catastrophe modelling provides a framework that can be used to assess natural hazards such as floods, landslides and wildfire, as well as societal hazards like major accidents, terrorism or pandemic flu. Although the nature and consequences of these hazards can be varied, the underlying concepts can be standardised within the model. Catastrophe modelling applies three common components, covering three distinct areas of science:

- The hazard component models the catastrophe event, outputting information describing the hazard scale and magnitude. The hazard component is commonly represented as a footprint, or as areas defined by differing risk levels.
- The vulnerability component makes an assessment of the exposure to the hazard, based on what might be at risk. Key to this component is information describing the receptors that might be impacted by the hazard, including information about their vulnerability to that hazard.
- The economic loss component assigns costs to the impacts that are a consequence of the interactions between the hazard and vulnerability components. This could be realised as the cost of damage to buildings, costs of business disruption or by valuations associated with morbidity or mortality.

The hazard component

The hazard component of the model estimates how receptors might be impacted by an accident at a major hazard site. Due to the national scale of the research and the unique characteristics of individual major hazard sites, the main source of hazard footprint information for this work was the HSE consultation zone maps, which are produced for all sites that require hazardous substances consent under Planning Legislation (HSE, 2016c; HMSO, 2009). These maps are used to inform HSE's Land Use Planning (LUP) advice in the vicinity of major hazard sites. They give an indication of how the hazard, or risk, posed by the site decreases with distance from the site. A consultation zone map for a fictitious site is shown in

Figure 1. Most consultation zone maps have three zones representing criterion levels of risk or consequence, known as the inner, middle and outer zones.

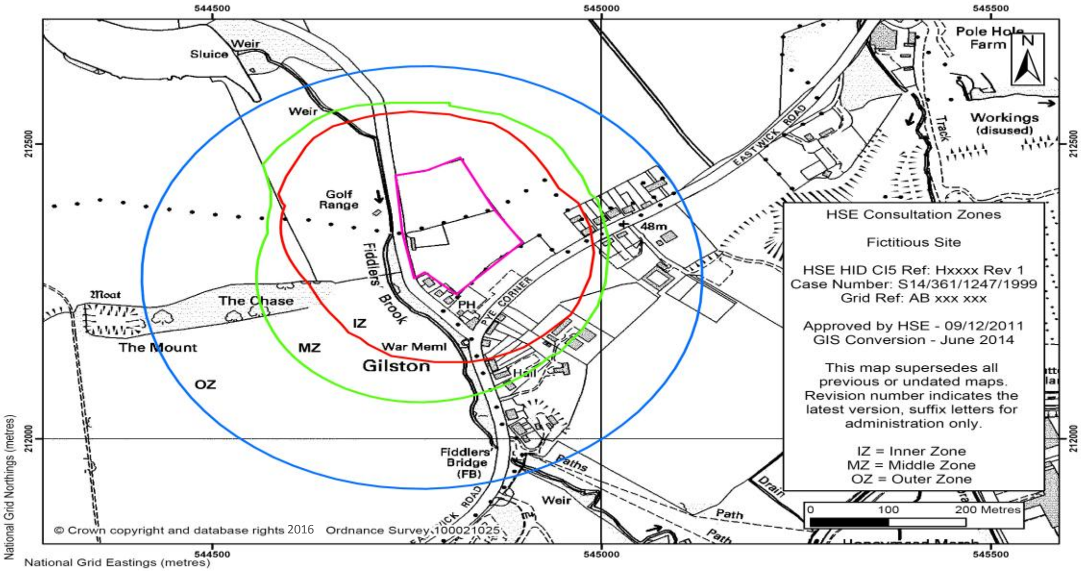

Figure 1 Example of consultation zone map.

The consultation zone maps are determined by detailed risk or hazard assessment calculations, which take account of the substances that the company is entitled to handle or store on site. The risk or hazard assessment considers what release scenarios could occur (such as, for example, the catastrophic failure of a storage tank or a leak from pipework), and the hazards that these scenarios would pose. For a toxic substance such as chlorine, the primary hazard is a toxic cloud formed from material released from pipework or a storage tank, which disperses with the wind away from the site (HSE, 2016d). For bulk storage of liquefied petroleum gas (LPG), the primary hazard is a BLEVE (Boiling Liquid Expanding Vapour Explosion), which could occur if a fire impinges on a LPG storage vessel, causing it to rupture.

The consultation zone maps provide information about regions within which a person might be exposed to a specific dangerous dose of a substance, but they do not directly provide information about the proportion of people likely to be killed or injured, or the severity of the damage to buildings. It was therefore necessary to convert the consultation zone maps into a relevant format using established methods and calculations found within the literature. This process included classification of each major hazard site according to the substances that are handled or stored on site and the type of storage. Examples of site classifications include chlorine (bulk storage), liquefied petroleum gas (cylinder storage) and natural gas (high pressure storage). The site classifications have been grouped according to how the consultation zone map for that classification is derived. The majority of sites fall into three main categories:

- Sites handling or storing toxic or very toxic substances, which have risk-based zones
- Sites with hazard-based zones set by overpressure criteria
- Sites with hazard-based zones set by thermal dose criteria

Site classifications which do not fit into any of the above categories, such as liquid oxygen storage or cylinder storage of liquefied petroleum gas (LPG), have been considered separately. Substances which are classified only because they are dangerous to the environment have been neglected in the analysis, since environmental impacts are beyond the scope of this project.

The Vulnerability Component

There are two main requirements for an effective vulnerability component. First is an understanding of *what* is at-risk from the hazard, referred to here as exposure. Second is information on *how* the exposed receptors might be affected by the hazard described in Section 2.2. In the model, exposure is defined as the activity occurring on and off site that might be affected by an accident at a major hazard site. This activity can be categorised into sources of loss and associated metrics (Table 2), which are a selection of the impacts identified by the MIIB for Buncefield (Table 1), and those used in the COCO-2 model for nuclear accidents (Higgins, 2008). The data used to model these losses can be split logically into three outline categories: Buildings, Population and Business.

Table 2 Sources of loss and model metrics.

Sources of loss	Required metric
Harm to people	Numbers and types of people at risk
Evacuation	Numbers of people affected
Damage to buildings (residential and non-residential)	Numbers and types of property at risk, including valuation information
Loss of business	Scale and types of business affected, including (rental) valuation information
Relocation of business	Types of business and potential relocation costs
Emergency Services	Percentage cost based on other factors

Buildings

The approach taken for modelling buildings within consultation zones was to estimate the value for each building based on its size and type, using geographically appropriate economic multipliers. The National Receptors Dataset (NRD) was the key dataset used. The NRD is a collection of property-based risk receptors produced by the EA (2016). The NRD property dataset details location and attribute information for every building in England and Wales that has a corresponding record in Ordnance Survey (OS) AddressLayer2 data, or has a footprint (ground floor area) greater than 25 m^2 based on the OS MasterMap data product. Key attributes for this research include building classification, floor area and dwelling type. The NRD property points data were filtered for residential locations based on building classification to identify ‘detached’, ‘semi-detached’, ‘terraced’ and ‘flat/maisonette’. Non-residential locations were considered to be any NRD feature not classified as a dwelling and with a floor area greater than 0 m^2. For major hazard sites based in Scotland, OS AddressBase Premium and OS Mastermap were used to create an equivalent property point dataset.

For residential buildings, property values were based on postcode average price-paid data from the Land Registry (May 2012 – April 2013). Valuation of English and Welsh non-residential property points was based on Valuation Office Agency (VOA) data classifications which are created regionally at Middle Super Output Level by building classification (data.gov.uk, 2016). Due to a lack of data containing categorised value per m^2 in Scotland at a comparable local scale, valuation of Scottish non-residential buildings was based on England and Wales averages.

Population

The approach adopted for modelling human populations was to estimate the numbers of people who might be located within consultation zones at the time of an accident, considering how they might be defined and how they might be affected. The National Population Database (NPD) was the key dataset used. The NPD was originally developed by HSL for HSE (HSE, 2005 and 2008) to assist with individual and societal risk work around major hazard sites, but has since been used in a wider context including impact analysis for natural hazards (Cole, 2013). It provides estimates of population density and distribution for the whole of Great Britain, using a local scale representation that locates people within individual buildings. The NPD is set up as a series of GIS layers, which represent five different population themes: Residential, Sensitive (including schools, hospitals, care homes, childcare facilities and prisons), Workplace, Transport and Leisure. The NPD population statistics were created using information from datasets sourced from wider UK government departments including Office of National Statistics (ONS) census information, and registers from government departments (e.g. Care Quality Commission, Department for Transport, Department for Education). The point location data in the NPD is derived from Ordnance Survey (OS) address and postcode data (HSE, 2008). The data layers within these themes can be combined to represent various spatial and temporal population scenarios.

For this work, two basic scenarios were used: day time and night time. These scenarios were compiled from different NPD population layers (Table 3). The scenarios allow for the selection of the worst-case. For the purposes of estimating evacuation, separate counts for resident and non-resident populations were also required. The *residential*, *care home* and *prison* populations were used to define the resident population, with the remaining layers used for the non-resident.

Table 3 NPD Population layers used to define the time scenarios.

Day Time Scenario	Night Time Scenario
Residential day time population	Residential night time population
Workplace population	Care home population
School population	Hospital population
Care home population	Prison population
Hospital population	
Prison population	

Business

For estimation of economic losses associated with business, the workplace layer of the NPD was used. It is based on the Inter-Departmental Business Register (IDBR), a comprehensive listing of businesses in the UK with attribute data including the number of employees (full-time and part-time), and a 2007 Standard Industrial Classification code describing the type of business (ONS, 2016a). Due to commercial sensitivity, workplace locations were modelled using postcodes rather than individual addresses. Consequently, a dasymetric approach (i.e. reallocation of attributes collated at larger scales to smaller scale geographies based on reasonable assumptions) was applied to redistribute workplace populations to suitable non-residential buildings locations within each postcode (Maantay, 2007). Where no suitable workplace property points were identified within a workplace postcode area, the postcode centroid (centre point) was used as the workplace location (9% of cases). The workplace population used was an estimate of the Full-Time Equivalent (FTE) employment. FTE employment was estimated for each business based on the number of employees and information on the number of part-time workers; an average 50% working-time arrangement for part-time workers was assumed.

Economic loss

The economic loss component followed a reduced adaptation of the COCO-2 model, which was created to assess the potential economic costs likely to arise off-site following an accident at a nuclear reactor site (Higgins, 2008). Adjustments have been made due to differing hazard consequences and differing scales of analysis, and to focus on the main components of impact. For this analysis, economic losses were subdivided into five components which capture the major costs envisaged to arise from major hazard site accidents.

Casualty impact costs

In order to accurately inform decisions on the appropriate level of risk reduction and hazard mitigation cost, estimates are required on the monetary value of intangible losses such as injuries and deaths. This research applied a 'Willingness to Pay' (WTP) approach, where estimates are made of the amount that individuals are prepared to pay to reduce risks to their lives, in order to attach a value on a 'statistical' life. For each hazard site, the number of fatalities, major and minor injuries were estimated based on day and night population data (Section 2.3.2). An economic value for each of these injuries and fatalities was derived from figures published by HSE in the "Costs to Britain of workplace injuries and work related ill health" 2013 update publication (HSE, 2016e).

Business disruption costs

The approach taken to estimating the cost of business disruption was to examine potential direct losses of industry value added (which measures the contribution to the economy by industry), and then to augment this with an estimate for indirect costs by using Input-Output modelling. For this analysis, an estimate of Gross Value Added (GVA) and linked employment information was an effective method for highlighting the economic activity in each zone. GVA measures the contribution to the economy of each individual producer, industry or sector in the United Kingdom. The potential GVA loss in directly impacted industries was calculated by multiplying the FTE employment numbers, by industry, by average GVA per FTE worker in the corresponding industry in the UK (based on data from the ONS Annual Business Survey (ABS) (ONS, 2016b)). The impact model assumes GVA to be lost for the period a business is closed and that this will occur if the workforce is required to shelter, evacuate or relocate. It is assumed that businesses are not bankrupted or that the workforce are made redundant but, instead, that a business is disrupted and takes time to recover. The affected business may resume business or relocate.

The potential GVA loss in indirect effects were more challenging to value, but have been based on the disruption to the supply and sale of goods and services using input-output tables. Input-Output modelling considers the economy to be a system of interdependent activities used as inputs and outputs by different industries within the system. Input-output tables have been calculated by ONS, which contain economic multipliers by industrial sector.

Building damage costs

The approach to estimating the capital loss of buildings damaged or destroyed as a result of a major hazard site accident was to take a proportion of the property value dependent on the damage estimated for each individual building. For non-residential buildings the property value was estimated from the ratio of the rental value to the rental yield for each type of property classification. To convert pounds per square metre VOA rental value, into 'pounds per square metre' capital value, a 'property yield' was required. A property yield provides a hypothetical yield for a freehold interest in a property, fully leased at current market rent; it is published by a number of organisations including CBRE, a well-known property brokerage and research firm. This provides the present value of a rental income in perpetuity and therefore the capital value of the property as:

$$\text{Capital Value (£)} = \left(\frac{1}{\text{\% Yield}}\right) \times \text{Rental (£)} \qquad \text{Equation } \{1\}$$

Business temporary relocation costs

Relocation costs were derived from the VOA rateable value data attached to the NRD. A proportion of the annual rateable value was taken depending on how long the temporary relocation site is required (based on building damage).

Evacuation costs

In estimating the evacuation costs arising from an event the major elements of costs accruing to households were combined with an estimation of the costs to the emergency services and public authorities. Household costs were split into 'immediate evacuation costs' and 'long-term accommodation costs'.

Immediate evacuation costs were composed of the cost of travelling to an evacuation area, the cost of the time taken to evacuate, and the impact of evacuation (loss of working and leisure time, accommodation and food). Data drawn from the Automobile Association, The Department for Transport, ONS and Trivago were used to calculate these costs. Longer term accommodation costs were calculated by determining the number of buildings destroyed or damaged by the hazard and including rebuild times and average rental values from LSL Property Services (2013). Emergency services and other public costs were derived by assigning a conservatively valued 2.0% of the total economic cost of the major hazard site event to the costs involved. This approach is based on a literature review and a review of historical events.

Results

The results presented here focus on the reporting of aggregate statistics against some of the different site classifications. Costs have been rounded to two significant figures for all the results listed. For this reason, totals will not sum. Table 4 includes the mean and median costs for all sites, broken into the different components of loss. The median cost components are taken from different sites so are independent. Figure 2 illustrates the contribution of the different components of loss. The biggest contributor across all of the sites is the non-financial human costs (HSE, 2016e), making up 62.4% of the total cost.

Table 4 Average costs per site for all sites.

	Mean per site	**Median per site**
Site count	1,725	
Population Impact		
Non-financial human costs	£68,000,000	£14,000,000
Financial costs	£29,000,000	£6,000,000
Total population impact	**£97,000,000**	**£20,000,000**
Evacuation	£170,000	£6,300
Building damage	£4,700,000	£1,300,000
Business disruption	£5,100,000	£520,000
Business temporary relocation	£340,000	£96,000
Emergency services	£2,100,000	£520,000
Total cost (average)	**£110,000,000**	**£26,000,000**

Note: The median cost components and the median total cost are all independent so will not sum.

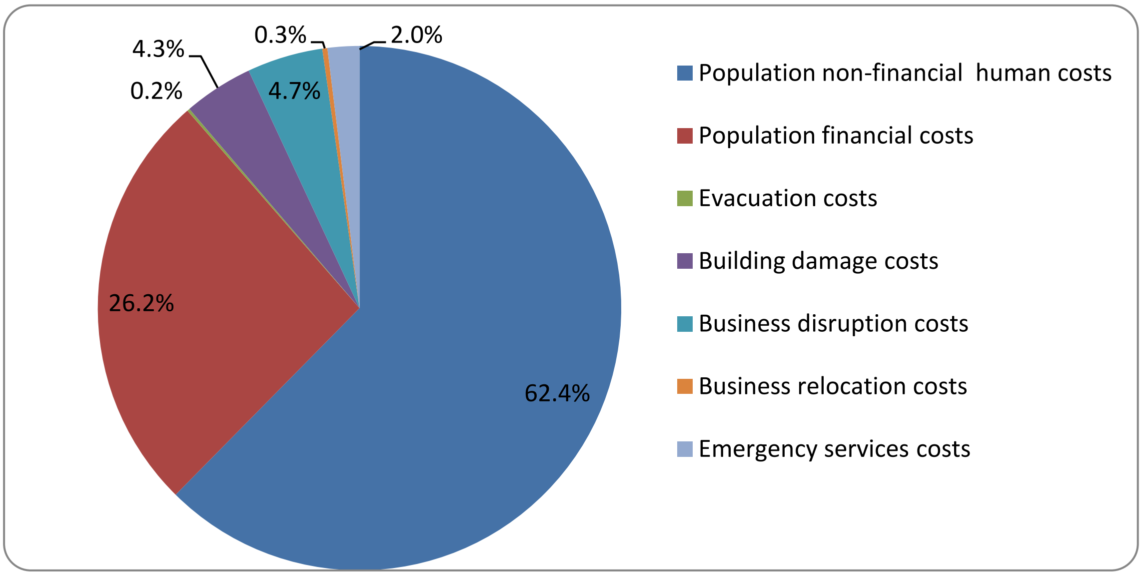

Figure 2 Breakdown of average (mean) costs for all sites.

Table 5 provides a geographical breakdown of the mean costs by Government Office Region. The London Government Office Region has the greatest average cost – at £200m per site. This is £40m greater than the South East, which has the second highest cost. Sites in the East Midlands and Eastern regions have the lowest average costs.

Table 5 Average (mean) costs per site by Government Office Region.

	Government Office Region					
	East Midlands	**Eastern**	**London**	**North East**	**North West**	**Scotland**
Site count	123	182	63	113	245	248
Population Impact						
Non-financial human costs	£50,000,000	£52,000,000	£120,000,000	£59,000,000	£75,000,000	£64,000,000
Financial costs	£21,000,000	£22,000,000	£51,000,000	£25,000,000	£31,000,000	£27,000,000
Total population impact	**£71,000,000**	**£74,000,000**	**£170,000,000**	**£83,000,000**	**£110,000,000**	**£91,000,000**
Evacuation	£160,000	£140,000	£460,000	£170,000	£120,000	£150,000
Building damage	£3,500,000	£4,700,000	£12,000,000	£3,300,000	£2,700,000	£6,200,000
Business disruption	£4,300,000	£4,700,000	£7,300,000	£3,800,000	£3,700,000	£7,800,000
Business temporary relocation	£270,000	£380,000	£330,000	£310,000	£210,000	£610,000
Emergency services	£1,600,000	£1,700,000	£3,900,000	£1,800,000	£2,300,000	£2,100,000
Total cost (mean average)	**£81,000,000**	**£85,000,000**	**£200,000,000**	**£92,000,000**	**£120,000,000**	**£110,000,000**
	Government Office Region					
	South East	**South West**	**Wales**	**West Midlands**	**Yorks & Humber**	
Site count	181	153	98	118	201	
Population Impact						
Non-financial human costs	£100,000,000	£61,000,000	£63,000,000	£65,000,000	£59,000,000	
Financial costs	£42,000,000	£26,000,000	£26,000,000	£27,000,000	£25,000,000	
Total population impact	**£140,000,000**	**£87,000,000**	**£89,000,000**	**£93,000,000**	**£83,000,000**	
Evacuation	£250,000	£320,000	£100,000	£120,000	£86,000	
Building damage	£7,500,000	£5,500,000	£2,500,000	£4,100,000	£2,900,000	
Business disruption	£6,100,000	£6,200,000	£3,600,000	£4,500,000	£3,600,000	
Business temporary relocation	£370,000	£320,000	£210,000	£340,000	£280,000	
Emergency services	£3,200,000	£2,000,000	£1,900,000	£2,000,000	£1,800,000	
Total cost (mean average)	**£160,000,000**	**£100,000,000**	**£97,000,000**	**£100,000,000**	**£92,000,000**	

Table 6 and Table 7 detail the average cost by the model type and site classification respectively. The model type with the highest average (mean) cost is Overpressure (Vapour Cloud Explosion (VCE)). The majority of the sites included in this classification are large-scale petrol storage sites (Buncefield-type), which have the greatest estimate of cost of all the site classifications in Table 8.

Table 6 Average (mean) costs per site by model type

	Model				
	Overpressure (Ammonium Nitrate)	**Risk (Toxic)**	**Overpressure (VCE)**	**Overpressure (Condensed Phase Explosion)**	**Flammable (Fireball/ BLEVE)**
Site count	173	341	43	22	684
Population Impact					
Non-financial human costs	£59,000,000	£100,000,000	£260,000,000	£130,000,000	£67,000,000
Financial costs	£25,000,000	£44,000,000	£110,000,000	£55,000,000	£28,000,000
Total population impact	**£84,000,000**	**£150,000,000**	**£360,000,000**	**£190,000,000**	**£95,000,000**
Evacuation	£700,000	£40,000	£710,000	£720,000	£120,000
Building damage	£9,500,000	£0	£25,000,000	£14,000,000	£3,300,000
Business disruption	£8,200,000	£0	£34,000,000	£18,000,000	£4,300,000
Business temporary relocation	£610,000	£0	£2,000,000	£1,000,000	£200,000
Emergency services	£2,100,000	£3,000,000	£8,500,000	£4,400,000	£2,100,000
Total cost (mean average)	**£100,000,000**	**£150,000,000**	**£430,000,000**	**£220,000,000**	**£100,000,000**

	Model				
	Flammable (Jet fire/ Pool fire)	**Flammable (Flash fire)**	**Flammable (Oxygen)**	**Flammable (LPG Cylinder)**	**Mixed Substance and Refinery**
Site count	287	21	15	111	28
Population Impact					
Non-financial human costs	£13,000,000	£56,000,000	£11,000,000	£11,000	£250,000,000
Financial costs	£5,500,000	£24,000,000	£4,800,000	£4,500	£100,000,000
Total population impact	**£19,000,000**	**£80,000,000**	**£16,000,000**	**£15,000**	**£350,000,000**
Evacuation	£74,000	£130,000	£12,000	£41,000	£270,000
Building damage	£5,200,000	£560,000	£0	£5,500,000	£25,000,000
Business disruption	£4,500,000	£520,000	£0	£7,500,000	£17,000,000
Business temporary relocation	£500,000	£49,000	£0	£370,000	£1,800,000
Emergency services	£580,000	£1,600,000	£330,000	£270,000	£7,900,000
Total cost (mean average)	**£30,000,000**	**£82,000,000**	**£17,000,000**	**£14,000,000**	**£400,000,000**

Table 7 Average (mean) costs by site type

Site type	Count	Total cost		Site type	Count	Total cost
Ammonium Nitrate	170	£100,000,000		LPG Cylinder Storage	110	£12,000,000
B1 - very toxic	65	£120,000,000		LVT	19	£38,000,000
B1 & B2	59	£180,000,000		Mixed Substance	106	£190,000,000
B2 - Toxic	80	£93,000,000		Natural Gas - High Pressure	74	£33,000,000
B3	14	£290,000,000		Natural Gas - Low Pressure	238	£130,000,000
Chlorine	74	£280,000,000		Oxygen	15	£17,000,000
EO/PO	8	£59,000,000		RFLs	19	£91,000,000
Large-scale petrol storage (Buncefield-type)	38	£480,000,000		Various Flammables	204	£29,000,000
LPG Bulk Storage	428	£86,000,000		Various Toxic	4	£34,000,000

Note - *Site types* using letter classifications are based on the substance classifications at the time of commencement of the study (2012)

Table 8 details the mean costs by COMAH status. As expected the greatest average costs are associated with the top tier sites, followed by lower tier, and sub-COMAH.

Table 8 Average (mean) costs per site by COMAH Status

	COMAH Top Tier	COMAH Lower Tier	Sub-COMAH
Site count	332	655	652
Population Impact			
Non-financial human costs	£130,000,000	£60,000,000	£42,000,000
Financial costs	£55,000,000	£25,000,000	£18,000,000
Total Population Impact	**£190,000,000**	**£86,000,000**	**£60,000,000**
Evacuation	£220,000	£140,000	£160,000
Building damage	£8,400,000	£3,500,000	£3,600,000
Business disruption	£7,600,000	£4,700,000	£3,900,000
Business temporary relocation	£690,000	£270,000	£220,000
Emergency services	£4,100,000	£1,900,000	£1,400,000
Total cost (mean average)	**£210,000,000**	**£96,000,000**	**£69,000,000**
COMAH statuses were sourced for 1,639 (95%) of the 1,725 major hazard sites. The remaining 5% of sites are excluded from the table.			

Discussion

The development and implementation of this model has demonstrated the possibilities for large-scale analysis of the potential costs of accidents at major hazard sites. The aim when creating the model was to make best use of the methodologies available, building on existing datasets and approaches. The work has demonstrated that GIS is well suited to conduct large-scale analysis of major hazard sites. It has also highlighted the value in this application of the data available within government or on open data licences, such as the NPD, NRD, and VOA data. The use of land use planning zones as a representation of the hazard, with the associated vulnerability multipliers has limitations for some sites and methodologies, but is a pragmatic choice, which aligns with HSE's current regulatory system. The model uses a 'catastrophe-modelling' approach and three basic components of hazard, vulnerability and economic losses to provide final cost estimates. This has proved to be an effective and transparent method of structuring the work; the clear distinction of components has also enabled project partners to apply their respective scientific expertise with minimal restraint.

The results follow findings from the HSE's Cost to Britain research (HSE, 2013). Table 4 and Figure 2 highlight the economic importance of non-financial human costs and that the direct impacts to human populations could contribute over 88% of the total cost of an accident. These results highlight the importance of the exposure and vulnerability components in assessing the potential impact. Regionally, the highest mean costs are found in London, due to the high density of population and infrastructure around the sites. The breakdown of costs by site type in Tables 6 and 7 quantitatively demonstrates that large scale petrol storage sites are estimated to produce the highest costs. This emphasises the importance of continuing to improve our understanding of the Buncefield incident through investigative reports (MIIB, 2008) and via scientific study (Atkinson, 2015). Due to the rarity of actual accidents being modelled, it is difficult to test the effectiveness of the model. However, the economic costs of the Buncefield incident (£980m) (MIIB, 2008) correspond approximately with the 80th percentile results for large-scale petrol storage sites. Further statistical analysis of the data could yield further insights and could clarify the sensitivities in the methodologies.

The economic multipliers used to estimate the population impact, GVA (business disruption), and evacuation have been implemented based on lookup tables within a database. Updating these with up-to-date, more accurate, or projected figures is possible without the need for re-running any of the spatial analysis, and is a straightforward task meaning that some economic costs can be refined as necessary. Economic updates against the other criteria (building damage and business relocation) are more complex but could be implemented via annual multipliers applied across the whole results set. The non-economic multipliers for population impact (loss of life and injury probabilities), building damage (percentage) and evacuation time also use lookup tables and can be kept up-to-date with relative ease.

The input data for the model is held in a GIS database which includes spatial referencing. This means that further information could be added based on a site's location (e.g. urban/rural contexts or alternative administration boundaries). However, due to the comprehensive nature of the attributes associated with each building, update of this information could be a complex procedure. Although the model estimated costs for individual sites, they are most effective when considered as an aggregate because the methodologies used are much less certain at the local level. Examples of cost estimates for case study sites are not presented in this paper due to the sensitivity associated with accidents of this nature, such as loss of life, business, or site reputation. However, analysis of individual sites based on a standardised automated model could produce valuable and novel insights to augment existing regulation and analysis of major hazard sites within HSE. Additionally, further analysis of the spatial clustering of major hazard sites could provide useful inputs for regional characterisation, information for regional regulatory management, and new insights into how the impact of accidents or regulatory pressures might be locally communicated.

The highly automated and standardised site-based approach allows for updated or supplementary site information to be added into the GIS database, if further breakdowns of statistics were required. This might include information on site ownership, responsible authority, or size. Alternatively, the model allows refinement or addition of updated/new sources of loss and vulnerability. The flexibility that has been built into the model provides clear scope for a number of future applications:

1. Economic assessment of major hazard sites across Europe to target regulatory efforts and further refine legislation within the Seveso Directives. This would provide a uniform, scientifically robust approach to economic assessment, which in turn would facilitate easier comparison between nations. This is however dependent on data quality and data availability across Europe.
2. The cost of environmental impacts is a recognised requirement within the Seveso Directives (HSE, 2016b); however this was outside the original scope of the research. Future integration of environmental sources of loss would provide a richer breakdown of costs and better acknowledge the impacts to the wider environment. This may require the assistance of additional partners, with the required data archives and expertise.
3. By refining the hazard criteria, economic assessment could be applied to other incidents including malicious attack or natural hazards. This may require some modification of vulnerability and impact criteria, but would offer a standardisation across hazards, which may be a useful input into scenario planning work across Europe including National Risk Registers or emergency planning.

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