The Institution of Engineering and Technology

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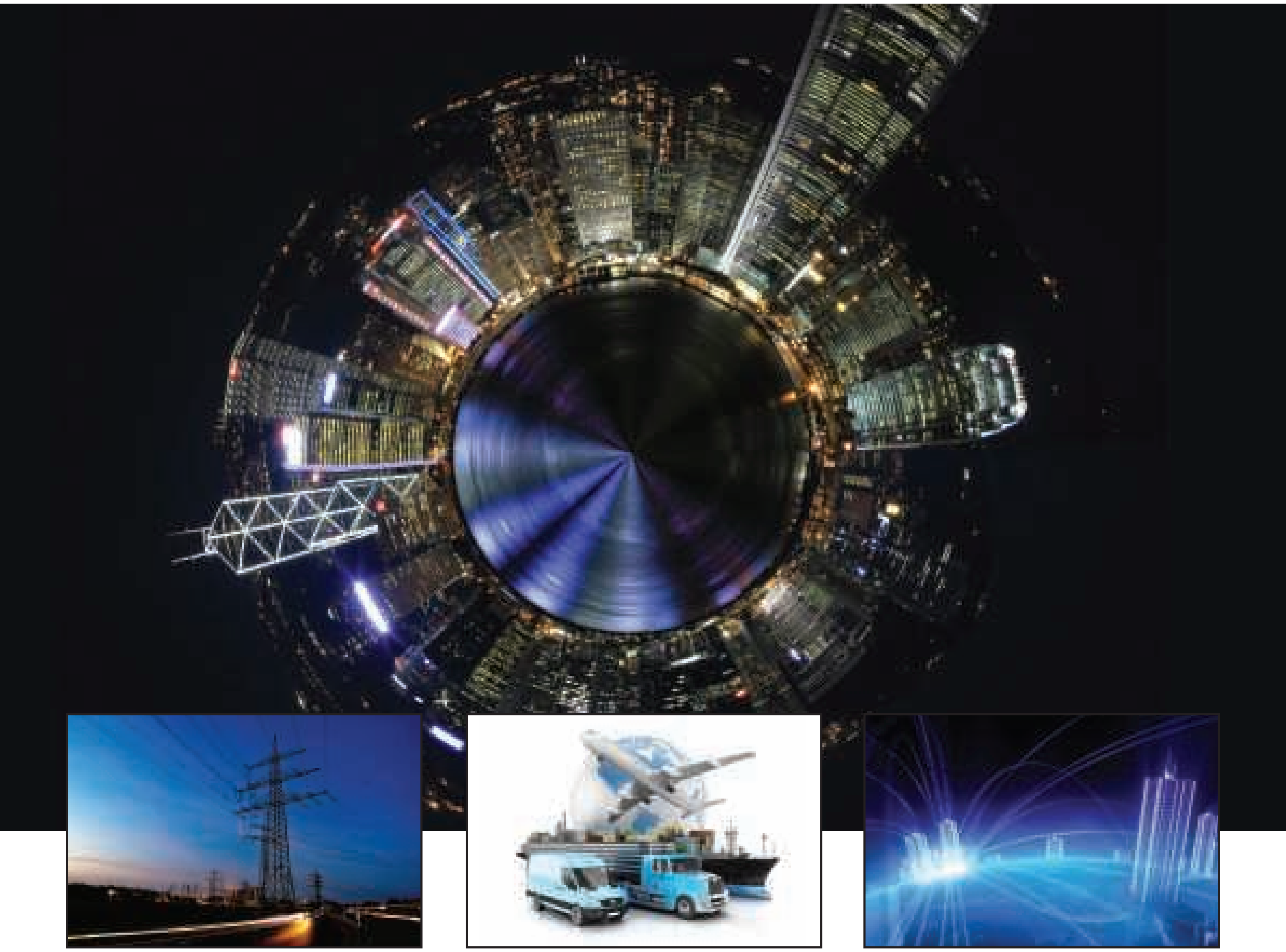
Infrastructure Risk and Resilience: Managing Complexity and Uncertainty in Developing Cities

INSIDE THIS SPECIAL INTEREST PUBLICATION

Selected papers highlighting current thinking regarding the resilience of cities, including Crisis Management and Disaster Recovery and strategies to mitigate risk and increase resilience of cities and their supporting infrastructure



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Preface

This Special Interest Publication of papers highlights current thinking on the resilience of Future Cities and follows a similar publication regarding the resilience of Transport Networks in 2013. The importance of Resilience in Cities of the future is supported by estimates that towards the middle of this Century the world' urban population will increase beyond 6 billion, and account for approximately 70% of the total population. Further predictions are that approximately 600 cities will have approximately 20% of this population and generate 60% of Global GDP.

To be successful these cities will need to, provide safety, security and a good quality of life, whilst being environmentally sustainable, and above all support economic competitiveness. This will require secure and reliable physical – cyber infrastructure systems providing energy, water, transport, logistics, telecommunications, waste-management, healthcare, food and shelter. The scale, complexity, and the increasing dependency between cyber and physical systems means that there are increasing vulnerabilities potentially affecting the availability, safety, security, reliability and resilience of the required infrastructure. Major challenges exist in assessing, understanding and managing these complex systems, or as they are increasingly described 'systems of systems'.

The IET continues its interest in the engineering and management techniques relating to the protection of infrastructure assets, and in collaborating with other bodies such as The Knowledge Transfer Network, The Institute of Risk Management, and the Register of Security Engineers and Specialists in order to develop and communicate the body of knowledge in this area. In support of these goals this publication has brought together papers to provide a source of reference covering physical and cyber technology, as well as softer social and safety management aspects of modelling, that may be used in assessing and managing safety, security and resilience of cities.

Dr James P Kimmance FIET

Chair Technical Editorial Panel

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IRM overview and introduction for developing cities publication

Introduction

IRM is the leading professional body for risk management. We are an independent, not-for-profit organisation that champions excellence in managing risk to improve organisational performance.

We do this by providing internationally recognised qualifications and training, publishing research and guidance and raising professional standards across the world. Our members work in all industries, in all risk disciplines and across the public, private and not-for-profit sectors.

Overview

The Institute of Risk Management (IRM) is delighted to be working again with the IET on the publication of this timely document on Managing Complexity and Uncertainty in Developing Cities.

We are told that by 2050 three quarters of the world's population will live in cities, which means that existing cities will need to be expanded and new ones built, often in challenging circumstances. All cities will need to get much 'smarter' in order to tackle issues of congestion and pollution and to support economic growth and the aspirations of their inhabitants. Cities are an efficient form of land use to support the population and also foster creativity and innovation but we also need to be alert to the risks of failing to provide the critical infrastructure and connectivity as well as the operational risks of development.

The papers in this publication look at some cutting edge tools and techniques that are emerging to address these urban challenges, ranging from energy supplies to crowd control. They draw on experience found in other fields to apply to this challenge. We were particularly pleased to see rigorous application of risk assessment and other risk management techniques being brought to bear on some tough problems.

Qualified professionals from all disciplines, supported by their professional institutes like IET and IRM should be working together on big challenges like the development of cities. The project to produce this document has brought together professionals and academics from various disciplines to learn from each other and contribute towards the knowledge resources available for all. IRM and its members have been very pleased to take part.

Carolyn Williams

Technical Director

The Institute of Risk Management

For more information, visit www.theirm.org.uk

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The KTN - Connecting people who accelerate innovation

The Knowledge Transfer Network (KTN) is the UK's innovation network. It brings together businesses, entrepreneurs, academics and funders to develop new products, processes and services. It does this by initiating, facilitating and building Strategic, Creative, Cross-sector, Business and Investment Collaborations.

To do this the KTN works closely with businesses, entrepreneurs and research institutes to ensure that we provide ongoing and independent insight and information to government and policy makers. This directly informs strategy and investment programmes, with more effective results for the UK's long-term competitiveness.

As a result, the KTN is able to connect businesses, value chains, entrepreneurs, innovators and investors – helping them to identify and develop the ideas, expertise and technologies, wherever they reside, which have the potential to be world-beating products, processes and services.

For Big Business, the KTN facilitates access to the entrepreneurs, start-ups, academics and small businesses developing the new technologies and platforms with the potential to transform industry.

UK Academia has expertise and ideas so the KTN helps academic researchers to connect to markets and convert their knowledge into viable products, processes and services with economic, social and environmental value.

The KTN is not a funding body and has no regulatory powers. But we are able to achieve all of the above because of the breadth and depth of knowledge to which The KTN has access. The KTN covers industries ranging from bio-technology to designer fashion, and is made up of staff with deep sectoral knowledge – both as researchers and within a commercial environment.

Although working closely with businesses, the KTN is not an industry group, government body or lobbying organisation beholden to any particular interests. As such it is a trusted intermediary, committed to innovation, and working with everyone, big or small, commercial or public, wanting to achieve this.

The KTN has strong, well-established relationships with commercial and academic innovators, as well as major support and investment agencies – both nationally and at the European level. Through these it is able to make things happen, initiating the projects and investment programmes where they are most needed.

Typical areas of activity include Big Data, Cyber Security, the Built Environment, for which there are several programmes around Risk and Recovery for infra-structure and energy, and Transport.

Stephen Lowe
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For more information visit-
https://connect.innovateuk.org/web/modernbuiltktn

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Energy security challenges in developing African mega cities: the Lagos experience

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Abstract: As demand for energy continues to rise, especially in rapidly industrializing and developing cities as Lagos, energy security concerns become ever more important. To maintain high levels of economic performance and provide solid economic growth, energy must be readily available, affordable, and able to provide a reliable source of power without vulnerability to long or short-term disruptions. Interruption of energy supplies can cause major financial losses and create havoc in economic centers, as well as potential damage to the health and well being of the population. Hence, this study analyzes the various energy security drivers and determinants of electricity supply in Nigeria and their impact to Lagos using a combination of exploratory and empirical research methods. Results shows that projected lost GDP growth in Nigeria attributed to power supply constraints will reach $130 billion by 2020. Lagos will account for more than 40% of that. This paper highlights the key drivers governing the secure supply of energy - from a developing economy perspective - and their impact in developing and ensuring a secured energy future.

Keywords: Energy security, Energy demand, Energy barriers, Energy economics, Energy market

1 Introduction

Lagos is located in the south-west coast of Nigeria with an estimated population of 20 million people. Lagos is home to almost 50% of Nigeria's skilled workers [1] and has a large concentration of multinational companies. It is one of Africa's biggest consumer markets and boasts of a higher standard of living than anywhere else in the country. However, rapid population growth and urbanization have introduced significant challenges for its water, sanitation and waste management infrastructures, as well as energy supply, traffic management, and so on. Despite these, officials of the Lagos state government are keen to transform this mega city into a first class business hub by investing heavily in a mass transit plan and establishing a dedicated environmental authority [2]. The Lagos state government established the ministry of energy and mineral resources with the sole aim of developing and implementing a comprehensive energy policy for Lagos State that will support the states' socio-political development plans (which include job creation and revenue generation).

2 Energy demand & supply analysis

Within the past decade, energy demand in its various forms (electricity, oil, gas, etc) has grown rapidly due to increased economic activities and population growth, with Lagos accounting for over 50% of the incremental energy demand in Nigeria [3]. The US Energy Information Administration (EIA) in 2011, estimated the total primary energy consumption in Nigeria to be about 4.3 quadrillion British thermal unit (Btu), with traditional biomass and waste (consisting of wood, and other crop residues accounting for 83% of the energy use [4]. Figure 1 shows the proportion of traditional biomass and waste in relation with oil, natural gas and hydropower.

This section presents a historical overview of the development of the various energy resources in Nigeria and their connection to the Energy Security challenge in Lagos

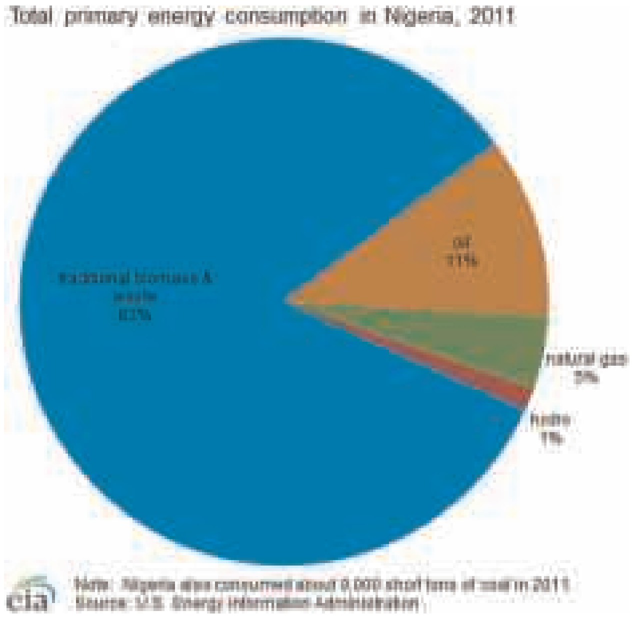

Figure 1 *Total primary energy consumption in Nigeria in 2011*

2.1 The Nigerian electricity supply market

Electricity generation in Nigeria started in 1896. In 1929, the Nigerian Electricity Supply Company (the first Nigerian utility company) was established. In the 1950's, the Electricity Corporation of Nigeria was established to control all diesel and coal fired power plants. In the 1960's, the Niger Dams Authority was established to develop hydroelectric power plants [5]. In 1972, the National Electric Power Authority was formed from the merger of the Electricity Corporation of Nigeria and the Niger Dams Authority. From the late 1990's, Nigerians started feeling the pinch of insufficient electricity supply. It became obvious that the publicly owned and managed electricity systems were not meeting Nigeria's electricity needs. In 2001, the government established a National Electric Power Policy which paved the way for the electrical power reforms.

At the dawn of the new civilian administration in 1999, after a long era of military rule, the following were challenges at the time [6]

- The Nigerian Electricity Supply market had reached its lowest electricity generation point in 100 years of her history
- Only 19 electricity generating plants were operational out of 79, with a daily electricity generation average of 1750MW
- Between 1989 and 1999, there was no investment in new electricity generation infrastructure
- The newest electricity generation plant was built in 1990
- The last electricity transmission line was built in 1987
- It was estimated that about 90 million people had no access to grid electricity
- There was no reliable information on the actual industry losses due to insufficient electricity supply. However, it is believed that industry losses is in excess of 50%

Installed (public) electricity generation capacity stands at 5900MW while current actual electricity generation stands at 3000–4000MW. Generation capacity required to meet the current electricity demand stands at 16,000MW [7]. Considering a population of 177.2 million (2014 estimate), this invariably means that 75% of the Nigerian population have no access to electricity [8]. Lost GDP growth attributed to power supply constraints will reach $130billion by 2020 [9]. The Nigerian government, in her on-going power reforms, have projected a target electricity generation capacity of 40,000MW by 2020. About $10billion annual investment will be required to reach the target in the coming years. Considering the huge investment required to meeting the ever-growing energy demand, one of the biggest opportunities lies in the effective utilization of available energy. Table 1 shows Nigeria's position on the world stage in terms of electricity generation capacity and the corresponding per capita electrical energy.

A recent Energy Audit conducted by the Lagos State Government in 2012 estimates the total electricity demand requirement for Lagos as 10,251MW [3]. Table 2 highlights the distribution of the energy demand from residential, commercial and industrial users in Lagos with an estimated projection of what the electricity demand in Lagos will look like by 2015.

Table 1 Nigeria on the world stage. Source CIA World Fact book

Country*	Generation Capacity (GW)	Watts per capita
S. Africa	40.498	826
Egypt	20.46	259
Nigeria	5.96	40 (25 available)
Ghana	1.49	62
USA	977.06	3,180
Germany	120.83	1,468
UK	80.42	1,316
Brazil	96.64	486
China	623.56	466
India	143.77	124
Indonesia	24.62	102

Table 2 Current electricity demand in Lagos with a 2015 projection

Sector	Energy Needs; 2012 (MW)	Energy Needs; 2015 (MW)
Residential	7,241	7,913
Industrial	2,350	2,464
Commercial	660	682
Total	**10,251**	**11,059**

This study shows that residential use of electrical energy in Lagos accounts for over 70% of the incremental energy demand. This is true as it correlates with the rapid population growth rate in Lagos (over 10%) as compared to other major cities in Nigeria

2.2 The Nigerian oil & gas market

Nigeria, the largest oil producer in Africa, started her oil & gas operations in 1956 with the first commercial discovery by Shell D'Arcy. However, since November 1938, a concession was signed with the same company to explore for possible petroleum resources within Nigeria's borders. After the discovery, Shell played a dominant role in the Nigerian oil industry for many years until 1971 when Nigeria joined the Organization of Petroleum Exporting Countries (OPEC), after which the country began to take a firmer control of her oil and gas resources [10]. Nigeria holds the largest natural gas reserves on the African continent, and was the fourth world leading exporter of liquefied natural gas in 2012 [4].

Nigeria has the second largest amount of proven oil reserves in Africa after Libya. In 2005, crude oil production in Nigeria reached its peak of 2.44 million barrels per day, but began to decline significantly as violence from militant groups surged within the Niger Delta region, forcing many companies to withdraw staff and shut in production. Oil production recovered somewhat after 2009-2010 but still remains lower than its peak because of ongoing supply disruptions [4]. Figure 2 shows Nigeria's oil production and consumption from 2003 – 2012.

Nigeria has a crude oil distillation capacity of 445,000 barrels per day. Despite having a refinery nameplate capacity that exceeds domestic demand, the country still has to import petroleum products since the refinery utilization rates are low.

Nigeria has the largest proven reserves of natural gas in Africa, and the ninth largest proven reserves in the world. Nigeria produced 1.2 Tcf of dry natural gas in 2012, ranking it as the world's 25th largest natural gas producer. Natural gas production is restricted by the lack of infrastructure to monetize natural gas that is currently being flared. Figure 3 gives a picture of dry natural gas production in Nigeria from 2003 to 2012.

The oil and gas industry, primarily located within the Niger Delta region, have been a source of conflict with local groups seeking a share of the wealth via attack of the oil infrastructure, forcing companies to declare force majeure on oil shipment. Loss of production and pollution caused primarily by oil theft (bunkering), leading to pipeline damage that is often severe, is forcing some companies to shut in production.

3 Energy security drivers

This section highlights the major energy drivers that need to be considered to guaranty a secured energy future for Lagos.

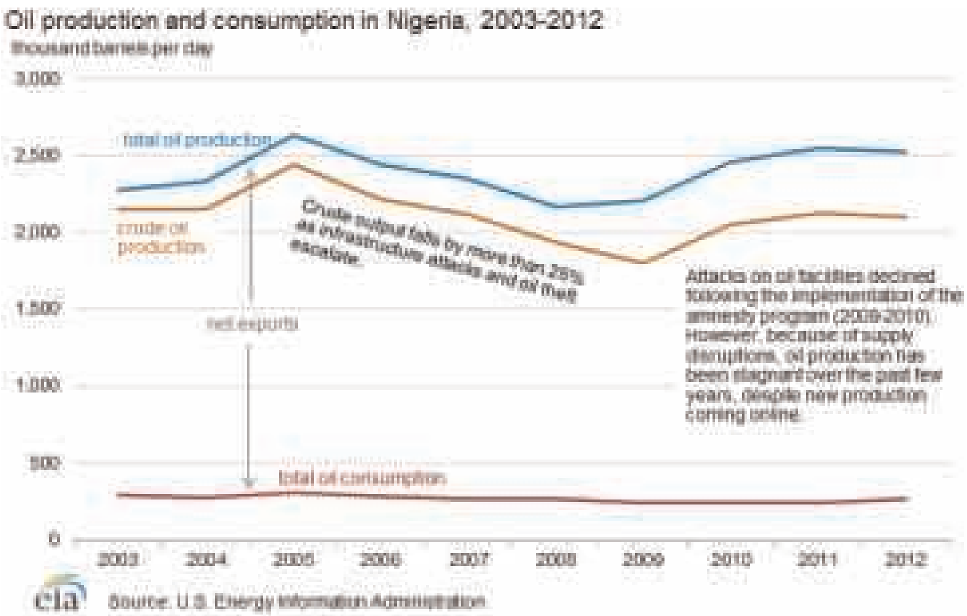

Figure 2 *Nigeria's oil production & consumption. 2003 – 2012*

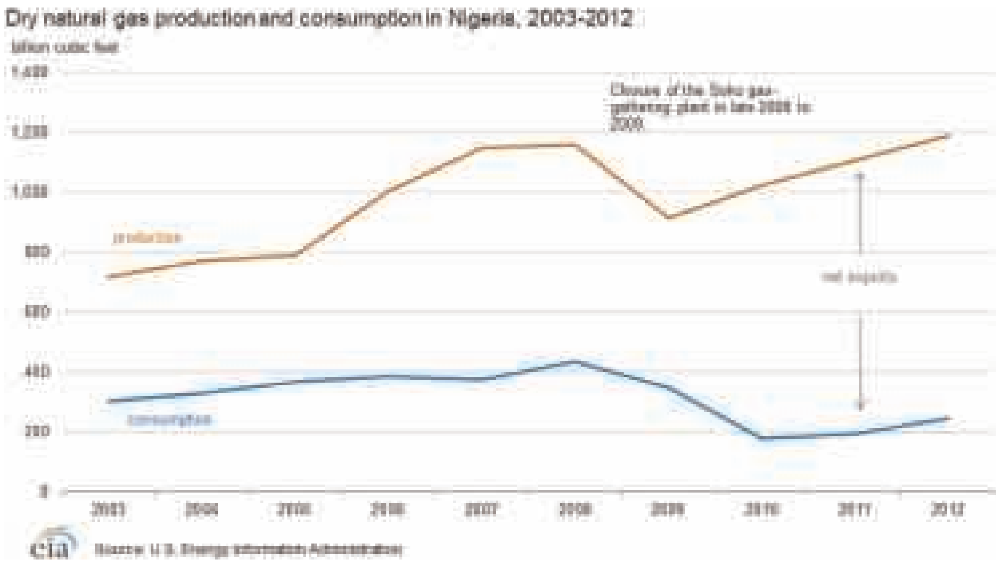

Figure 3 *Dry natural gas production in Nigeria. 2003 – 2012*

3.1 Energy affordability

A very important aspect of energy security is energy affordability. A lot of literatures exist that describes and analyzes energy security in strictly economic terms. However, this is understandable since rapid price increases and economic losses are yardsticks for measuring the impact of disruption of energy systems. There is a clear difference between energy affordability and energy security. Energy affordability measures the cost of energy in relation to economic parameters such as income per capita, GDP, etc. It is also influenced by changes (increase or decrease) outside energy systems such as a rise in income levels. Primarily, it is in a situation of economic equilibrium that affordability addresses the relative cost of energy. In contrast, energy security focuses on price disruptions – outside economic equilibrium – induced by changes in energy systems rather than general economic development such as supply disruptions [11].

Central to the issue of household energy affordability is the relationship between energy cost and income. While the majority of existing literature on energy affordability discusses energy required to maintain a suitable indoor environment in terms of heating energy, it is also noteworthy that in some areas energy may also be required to cool homes as is the case in Nigeria. Synott, in a publication, noted that discussions of fuel poverty need to take into account *the impact of both hot and cold on the health of householders, particularly vulnerable households* and *the proportion of income spent on fuel bills (and the proportion which would need to be spent to adequately heat and cool the dwelling) for low income households* [12]. However, it is good to note that:

- Household energy expenditure has a positive correlation with household income.

- Energy cost make up a smaller proportion of the total household expenditure as income increases.

- There are significant variations in low-income households' expenditure on energy (as a proportion of the total) indicating some households spend very little on energy in absolute terms.

The cost of power generation, transmission, and distribution is a major determinant for the provision of affordable energy. Supply interruptions have, over the years, impacted negatively on prices and have created economic difficulties for the country due to exposure and over-reliance on very few energy sources. From experience, inflation and recession has been triggered by sustained rise and short term spike in prices of oil, gas and electricity.

3.2 Energy for transport

Transportation is an essential element which is crucial for every aspect of modern society. Transportation has helped and shaped the way we address varying issues such as; food production, personal mobility, availability of goods and services, trade, military security, and so on. Over 20% of energy use in many developed countries accounts for transport. In as much as there is a rapid growth in energy use in developing countries (including India and China), energy use in developing countries for transportation is less than 15%. In least developed countries, transport account for less that 10% of their energy use. There is a competition for the same energy resources used for both modern transport systems and other applications such as construction, agriculture, and other machinery. Thus, security of fuels for construction, agricultural production, and other related sectors is also applicable in the discussion of energy security for transportation [9].

Transportation is one of the most vulnerable sectors among all vital services in the country. Its vulnerability is a result of the over-reliance on imported refined petroleum products used as transport fuel. Increasing demand of energy systems for transportation purposes also increases its vulnerability. The rapid growth of energy use in transportation signals a pressure on transport.

In Lagos, there has been massive investment in transportation infrastructures, particularly within the past five years. The Bus Rapid Transit (BRT) scheme, the building of a new rail infrastructure for rail transportation, and the development of the Lagos waterway transport systems are vivid examples. This sudden rise in provision of transport infrastructure has a definite impact on energy demand and the energy security mix.

3.3 Energy for industry

Energy use in industrial applications is mainly in the form of heat and electricity. This varies between countries. In most developed countries, energy use in the industrial sector accounts for about 15% of total energy use. The industrial sector accounts for over 25% of energy use in about 60 countries with a population of 4.5 billion people. In about 12 countries (including Brazil, China, and Ukraine) with a population of about 1.7 billion, the energy use in the industrial sector accounts for over 40% [13]. Emerging and developing economies are dominated by a few industries relying on distinct energy systems which are critical for energy security in those societies.

In Nigeria, there is a big contrast to this as the biggest manufacturing challenge is inadequate infrastructure, and specifically inadequate electricity supply. The manufacturing industry in Nigeria today generates about 72% of its own electricity needs [14]. The cost of manufacturing goods has increased tremendously due to large operating cost of generators for electricity generation.

Demand-side vulnerabilities should also be noted. Growth in industrial use of energy cannot be considered pressing or permanent as is the case of residential and transport sectors. Industrial growth of energy use may be reversed. Industrial energy intensity is an important factor that can make the industrial sector relatively vulnerable to price volatility and other energy supply disruptions.

3.4 Energy for residential and commercial centres

The residential and commercial sector depends largely on supply of electricity for lighting, cooking, heating, and other applications. Energy use in this sector for heating is of particular importance since it is a matter of national priority in the temperate region.

In many developing countries, this sector significantly relies on traditional biomass. Energy statistics generally designates this source as combustible and renewable without any distinction between traditional (e.g. firewood) or modern (e.g. straw boilers, modern heaters) uses of biomass. Reliance on traditional biomass in this sector is a serious national energy security issue due to its side effects on environment, health, and development. Low access to electricity has been identified as one of the primarily reasons for the massive use of traditional biomass. For modern nation states, this is untenable. In Nigeria, energy systems are under pressure to find new sources of energy in replacement of traditional biomass which invariably can lead to a case of worsening national energy vulnerability.

Energy use pattern in this sector differs between industrialized and developing countries. Countries with lower income typically have high proportion of residential and commercial energy use. This typically explains why Lagos has about 70% of her total electricity demand from residential use.

3.5 Energy for water

There seem to be some relatively very uniform water cycle among developed countries which does not necessarily seem the same among developing countries. This starts from the water source where water is extracted and conveyed, then moved directly to an end use (such as irrigation) or to a treatment plant from where it will be distributed to final consumers. After the water is used by end users, the waste water is collected through a waste water collection system to a treatment plant after which it is discharged to the environment. In some cases, the treated waste water could be used again before finally discharging to the environment. The entire value chain of water extraction, conveyance, treatment, distribution, and discharge all require energy. Figure 4 shows a typical water flowchart, highlighting the various aspects requiring energy for water extraction, conveyance, distribution, and treatment.

A very important factor for consideration in the water-energy mix concerns energy required for treating and supplying water. This involves electricity requirements for pumps used in the extraction (from ground and surface sources), collection, transportation, and distribution of water. The amount of energy required depends on the distance to (or depth of) the water source. The conversion of various water types – saline, fresh, brackish, and waste water – into water that is fit for specific use requires electricity, heat, and other processes involved in desalination of water which can be very expensive and energy intensive. There are other energy requirements associated with end-use application of water - mostly in households - for water heating, cloth washing, etc.

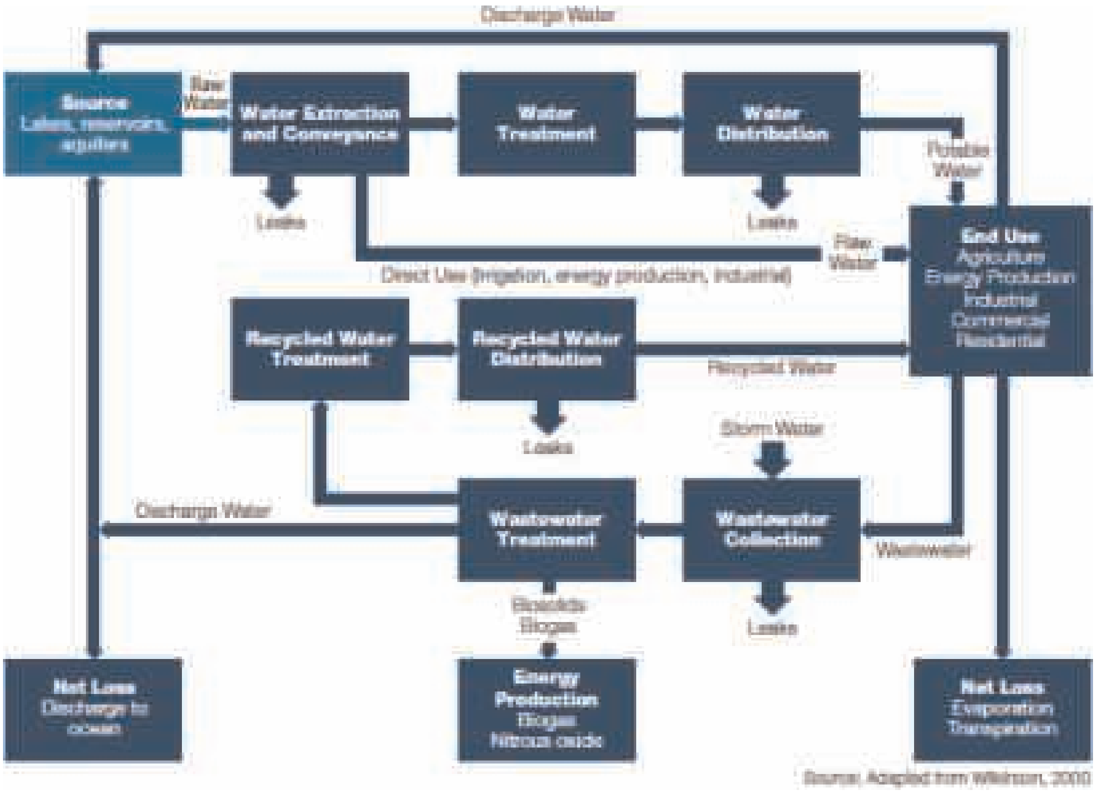

Figure 4 *Water flowchart*

Growing population, improved standards of living, and scarcer freshwater supplies in the proximity of population centres will contribute to the rising demand for energy for the water sector in Lagos, looking ahead. The implication is that water might need to be pumped from greater depth, undergo additional treatment, and transported over long distances. A shift from the traditional surface/flood irrigation method to pumped method puts further pressure on energy requirement for water. Although this method is more water efficient.

A major factor to be considered is the urgent need to identify and optimize the existing policies, perceptions, and practices associated with lowering energy consumption in the entire water value chain (extraction, conveyance, treatment, distribution, use, and recovery of water and waste water.

3.6 Water for energy

The extraction, mining, exploration, and production of nearly all forms of energy require water. In connection with primary fuels, water is used for resource extraction, fuel processing and refining, transport, and irrigation of biofuels feedstock crops. In electrical power generation, water is used for cooling and other related processes in thermal power plants, as well as in hydropower facilities where movement of water is harnessed for electricity generation [15].

Water required for the extraction, processing, and transportation of fossil fuel varies. Minimal water is used for drilling and processing of conventional natural gas as compared with other fossil fuels or biofuels. The development and extraction of shale gas uses a technique that pumps fluids (water and sand, with chemical additives that aid the process) into shale formations at high pressure to crack the rock and release gas. In Nigeria, the availability of huge natural gas reserves will limit activities in the extraction and production of shale gas for some time. However, with existing concerns over the already contaminated water bodies in the Niger Delta region owing to oil exploration activities, there is likely to be a huge public outcry over water contamination risks associated with shale gas production.

In coal production, water is used mainly for mining activities such as dust suppression and coal cutting. The amount of water required is dependent on the characteristics of the coal mine such as the transportation and processing requirements, as well as whether it is underground or surface mine. Increasing the grade and quality of coal requires coal washing which invariably involves additional water. Some quality concern issues associated with coal production include the runoff water from coal mine operations that can pollute surface and ground water.

In oil extraction and production, the recovery technology applied, as well as the geology of the oil field, and its production history are major determinants of the amount of water required. The refining of crude oil into end-use products requires chemical processes and further water for cooling with water amount varying widely according to the process configuration, and technologies employed.

In thermal electrical power plants (which includes nuclear and fossil fuel based power plants) water is used primarily for cooling. Thermal power plants are the energy sector's most intensive users of water per unit of energy produced. Cooling systems employed, access to alternative heat sinks and power plant efficiency are major determinants of water needs for thermal power plants. For a given type of thermal power generation plant, the choice of cooling has the greatest impact on water requirements.

In renewable electrical energy generation, water requirements range from negligible levels to that comparable with thermal power plants using wet tower cooling. Cleaning and washing of the panels are typical applications where water is used in non-thermal renewables such as solar photovoltaic (PV) and wind technologies. Renewables is seen in Lagos as the main energy source for the near future, not only because of the lower water use at the electricity generation site, but also because renewable technologies have little or no water use associated with the production of fuel inputs and minimal impact on water quality compared to alternatives that discharge large volumes of heated cooling water or contaminants into the environment.

3.7 Energy generation diversification

There is a need to have a well balanced energy system in Lagos, made up of a variety of generation technologies with suitable capacities that enables the advantage of each technology to be maximized. This helps in ensuring a continuity of supply to the customers at fairly reasonable and stable prices. Studies by the EIA shows that wind energy can better be harnessed in places of higher altitude and geographies closer to the (north and south) poles. The same study shows that solar energy can be better harnessed around the equator, which is where Nigeria (and Lagos) falls. Some generation technologies that could be harnessed include

- Small wind generation plants on high rise buildings and sky scrapers to generate power for elevators and office lighting systems

- Harnessing solar generation technology as backup power source in the dry season for powering some important public infrastructures such as primary health centres, street lighting, and emergency care units, among others.

Policy formulation and incentives to help encourage the private use of some of these new technologies on a smaller scale can help reduce, more rapidly, the residential energy demand in the state. These new generation technologies, deployed on a smaller scale can take care of some domestic energy needs like lighting, electronics and refrigeration systems.

4 The future of energy security in Lagos

In the global energy security scheme, the role of oil will likely be more important in the short and medium term. The dynamics in global oil and gas production is likely to have a consequent shift away from these sources. This is already being vigorously pursued by many countries.

The increasing role of electricity in energy systems is another imminent development affecting energy security. The continuing spread of information and communications technology, other consumer technologies requiring electricity, increasing use of electricity by the rising middle class in emerging economies like Nigeria, and the advent of plug-in electric propulsion vehicles will make electricity play a very important role in the energy security mix.

Reliability issues regarding production and distribution of electricity will come to the forefront of energy security concerns in the future as a result of increasing reliance on electricity. Electricity systems complexity in Nigeria in the near future is likely to increase to include the following:

- New technologies for electricity storage.

- Devices for smart grids including active load.

- Transferring with minimal losses (over long distances) large quantities of electricity using super grids. This can be achieved through the use of high voltage DC lines when localized distribution systems are not sufficient or feasible.

- Increasing reliability of distributed generation and power generation with the use of hybrid systems. This will be in the form of modular small scale systems with improved energy storage capacity.

Some of the aforementioned approaches may help reduce the inherent risk of cascading failures in modern complex centralized grids. The combination of information technologies with electricity, together with a combination of other approaches is likely to increase reliability. As the role of electricity in energy systems increases, institutional structures and capacities will form part of the increasing factors affecting energy security, much more than traditional issues of access to natural resources.

4.1 Proposed policy priorities

This section highlights some proposed energy policy priorities that Lagos can adopt to ensure a secured energy future.

4.1.1 Energy efficiency standard: There is an urgent need to set some standards regarding energy efficiency which must be adhered to by both utility and non-utility administrators. Specific long term energy savings target must be set which must be met by utility and non-utility administrators through programs focused on customer energy efficiency. There is also a need for a workable federal energy efficiency standard to help compliment the efforts at the state level in order to reach the desired targets [16].

4.1.2 Air emission regulations: There is an urgent need for clear regulations on emissions. The impact of pollution as a result of emissions from the burning and usage of our energy resources has very serious health implications. Coal fired power plants must have facilities for carbon capture to limit the impact on the environment. There should be limits set on vehicles emissions, among others.

4.1.3 Climate change policy: Studies show that energy efficiency measures are the surest, fastest, and most cost effective route to addressing issues of climate change. Reducing energy usage and widening the use of affordable renewable energy resource are other very important means. Energy efficiency standards for utility, standards for vehicles and appliances, land use planning, and energy codes for buildings, should be a part of the climate change policy/bill both at state and federal levels.

4.1.4 Utility policy/regulation: With the deregulation of the electrical generation sector in Nigeria, there is need for effective implementation of regulations to ensure energy security. Some aspects of utility regulations are very critical in ensuring and enabling utility energy efficiency programs. Regulation also ensures there is investor confidence that they can recover their cost of investment, as well as ensuring they can surmount the barriers to investment in energy efficiency. Regulators and policy makers can help give clear directions to utilities on the importance of energy efficiency.

4.1.5 Standards for appliances: There is an urgent need to set some minimum efficiency standards for domestic appliances. As highlighted in section 2, the residential; use of energy accounts for about 70% of electrical energy demand in Lagos. Setting energy efficiency standards for appliances will help change consumer attitudes in ensuring the prohibition of energy-consuming appliances, as well as prohibiting the production, sale, and importation of such appliances.

4.1.6 Building codes: There is need for the implementation of building construction standards that helps in ensuring energy efficiency in buildings. Ensuring the implementation of energy efficiency standards in buildings is one of the sure ways to help consumers save money and energy, reduce air pollution, as well as ensuring affordable housing.

5 Conclusions

In Nigeria, and particularly in Lagos, one of the most prominent concerns in relation with energy is adequate protection of vital energy systems from disruption. Energy systems disruption may result from short term shocks such as technical failures, natural events, deliberate sabotage, or malfunctioning markets. Some more permanent threats which are slowly unfolding include: ageing of infrastructure, unsustainable demand growth, and resource scarcity. Disruptions in these forms may affect other broader security issues ranging from the viability of national economies and stability of political systems, to the danger of armed conflicts. This invariably means that the driving force in the transformation of energy systems will likely remain as policies developed in the quest for higher energy security.

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Safe transport in an emotionally smart city

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Abstract: Emotional stress is a major cause of accidents and difficulties in rescue operations. Navigating the transportation infrastructure invoke stress through high tension situations like traffic congestion, peak running times and learning new routes. This is especially so with the global push towards urbanisation, resulting in high population density cities. As such, the stress on public infrastructure concomitantly increases, which directly leads to higher anxiety for users. This new era of urbanisation requires technology advancements to understand, monitor and control stress at a city level and hence reduce the risk of accidents in public transportation systems.

In this article, we propose a conceptual path that connects neuroscience with technological innovation to manage the complexity of stress and risk in transport functions of tomorrow's cities.

Individual and collective emotional resilience are components of the resilience of the city fundamental to prevent and recover from accidents and environmental disasters.

We will discuss how emotions can lead to stress that limits the attention and decision-making abilities of employees in public transport as well as the citizens using the system.

We will also discuss the possibilities of using technology to understand emotions using portable instruments connected with processing hubs creating a real time network that continuously monitors and manages emotional stress throughout the system with a feedback loop to key stakeholders.

Affective biometrics and urban sensing are really new fields of research. Although the results of practical applications are yet to be available, we offer the opportunity to better understand how human factors can impact cities' resilience.

Keywords: Emotions, Stress, Facial coding, Public transport, Cloud computing

1 Introduction

Cities are continually growing, most notably in less developed countries. Soon more than 70% of the world's population will live in urban areas.

With an increase in population, the stress on the transit system continually increases. This stress applies to both the citizens and the employees within the system.

Recent technological developments allow interesting solutions by integrating the measurement of emotions with real-time communication and machine learning algorithms to build predictive models that help prevent and manage situations of emotional overload (stress).

There are many aspects that link emotions to both individual and collective resilience, recover after a disaster [1].

2 Stress causes accidents

Hans Selye first coined the term "stress" back in 1936. He defined it as the "non-specific response of the body to any demand for change."

Stress may be the immediate cause of accidents due to the difficulties of attention, concentration and impairment for rapid decision making [2] [3].

More than 10 million days were lost to stress in the UK in 2012. Assuming a 'sick' day cost of £618, workplace stress totalled £6,427,200,000 [4].

1. Although the importance of individual differences cannot be ignored, scientific evidence suggests that certain working conditions cause more stress in any work environment, among these there are unpleasant or dangerous physical conditions such as crowding, noise, air pollution, structure of tasks and long work hours.

In the transport system of a city, stress concerns both workers and users. Bus driving, for example, is one of the most hazardous occupations for health. Research has shown that bus drivers have higher rates of cardiovascular, gastrointestinal, and musculoskeletal disorders than their counterparts in other occupations [5]. The emotional stress undergone by public transport operators will have consequences for safety, employee absence and labour turnover [4] [5].

Research has shown that stress is a large contributor to accidents and therefore reducing stress levels may prevent some accidents.

3 Emotions cause stress

Emotions are a cause of physiological arousal: heart rate, blood pressure, muscle tension, the (de) focusing of attention are all physiological parameters associated with the emotions that we experience, a constant emotional overload will cause stress. While fear and anger may seem as most important to our survival skills, our positive and more complex socially-oriented emotion experiences are also invaluable to our survival. If we do not understand the emotions of others, we cannot keep peace, share food, build alliances and friendships to share what the group can jointly create.

From these findings, if this emotional arousal occurs on many occasions during the day, even in the absence of real hazards, the physiological changes become dangerous to health, we call this condition stress.

There is significant research found in literature on the relationship between positive emotions and resilience. Studies show that maintaining positive emotions whilst facing adversity promote flexibility in thinking and problem solving. Positive emotions serve an important function in their ability to help an individual recover from stressful experiences [6]. Emotion-focused interventions are among the most commonly used strategies for stress reduction [7].

4 Measuring emotions

So if stress is the issue in causing accidents and emotions are the primary contributors to stress, then we must capture and measure individual emotions throughout a smart city of tomorrow.

Here we discuss emotion measurement techniques at a very high level and which would align best with capturing emotions in smart city transport environments.

To capture emotions in smart city environments, we look at the methods with the following criteria:
1. Easy to install - fits within current/near future city designs and is easy to maintain
2. Automated - operates locally and in realtime across many users simultaenously
3. Citizen hardware agnostic - doesn't require voluntary opt in or devices

With the help of Table 1 we would like to very briefly describe the methods that can be used to measure emotions. Some of them rely on assessing brain activity as fMRI which measures brain activity by detecting associated changes in blood flow and EEG which measure electric activity of the brain. fMRI can show us very interesting dynamic maps of how brain works but it need very expensive and complex equipment and it can not be used outside of laboratories. EEG assess brain cortex activity and some patterns of activity are related to stress, emotion and cognitive works. EEG devices require the application of some (3/120) electrodes in contact with the skull, so even this technique does not fit the purpose of measuring in a natural, non intrusive way.

Given the above overview, automated facial coding is the only method to allow observation without human interference. In fact, University of San Diego learned that computer based facial coding outperformed humans because they can collect reactions a human eye overlooks. Add in other sensory signals like voice pitch analysis and mobile gesture control and we have many ways to determine stress.

We found that an automatic emotional recognition technology must:

1. Assess the level of individual stress, moment by moment, and provide guidance and useful solutions to its reduction and for limiting its consequences on attention and decision making.

2. Aggregated data from many workers by time and location to arrive at an understanding of the internal and external weaknesses of the transport system.

5 Facial coding technology

Dr. Paul Ekman was one of the first who studied expression of emotions, his most influential work revolved around the finding that certain emotions appeared to be universally recognized, even in cultures that were preliterate and could

Table 1 Emotions measurement methodologies

	fMRI	EEG	GSR	Interviews	Observations	AFACS	ASP
	functional magnetic resonance fMRI	Electro encefalogram EEG	Galvanic Skin Response GSR	Intercept interviews of citizens and transit employees	Viewing videos with stress experts	Automatic Facial Coding System	Automated Biometrics
esay to install	×	–	✓	✓	✓	✓	✓
automated	×	×	✓	×	×	✓	✓
citizen hardware agnostic	×	×	×	✓	✓	✓	✓

not have learned associations for facial expressions through media [8]. Another classic study [9] found that when participants contorted their facial muscles into distinct facial expressions (e.g. disgust), they reported subjective and physiological experiences that matched the distinct facial expressions. His research findings led Ekman to classify six emotions as basic: fear, angry, disgust, happiness, sadness, surprise.

Expression of emotions as a signal of stress: the tech side

We have developed a very advanced system for automatic face analysis and facial expression recognition in particular. To interpret the movements of the face as an expression of the emotions we use a coding system, called FACS (Facial Action Coding System), that defines 32 atomic facial muscle actions called Action Units (AUs). With FACS, every possible facial expression can be described as a combination of AUs. It enabled social scientists and psychologists to use mathematical and statistical theory to study facial expressions.

This method enables us to conduct AU detection with continually improving accuracy while remaining subject independent and maintaining soft real-time computation requirement.

5.1 Emotions detectors

We made some choices to detect the expressions of emotions in a natural, challenging setting.

• Facial appearance: we consider features with the aim to capture changes in face texture, such as those created by wrinkles and bulges, as well as changes caused by facial motion.

• Dynamic head poses/ positions: we work with a technology that as described above looks for facial appearance and specifically prominent edges of a face, rather than facial points. This means that while individual points may be obscured or appear different our system is able to learn the characteristics of a given emotion for this different environment, making it applicable in the real world.

• Dynamics of facial expressions: besides the shape of facial expressions, their dynamics play an important role in the interpretation of human facial behaviour. An increasing body of research is warning against ignoring the dynamics. Psychologists have found a difference in duration and smoothness between spontaneous and deliberate expressions, e.g. between polite and amused smiles. While facial expression dynamics are seen as essential for categorising complex mental states such as pain and moods.

• Combinations of facial expressions: we analyse combinations of emotions and the sequence in which they occur to understand emotional and stress states [10].

6 Stress detection in smart cities

Conceptually, most urban centres are (or soon to be) wired for Internet or mobile data connections and have multiple cameras already present which may capture people's feeling while in the transport system of a smart city as shown in Figure 1. Technology allows us to measure emotions and stress while driving a vehicle, as in Figure 2, waiting for a subway, buying tickets, boarding a bus or simply through points of constraint like ticket barriers or border control. An effective system would need to use capture tools like smartphones, webcams or microphone and GPs devices to collect data. This data then goes to the cloud for data analysis that decodes signals to emotions and reports back to city stakeholders like transport employees, police or city planners.

We require only:

• Internet connectivity

• Proper computing power if local recognition is required

Figure 1 *Webcam applied to a rearview mirror*

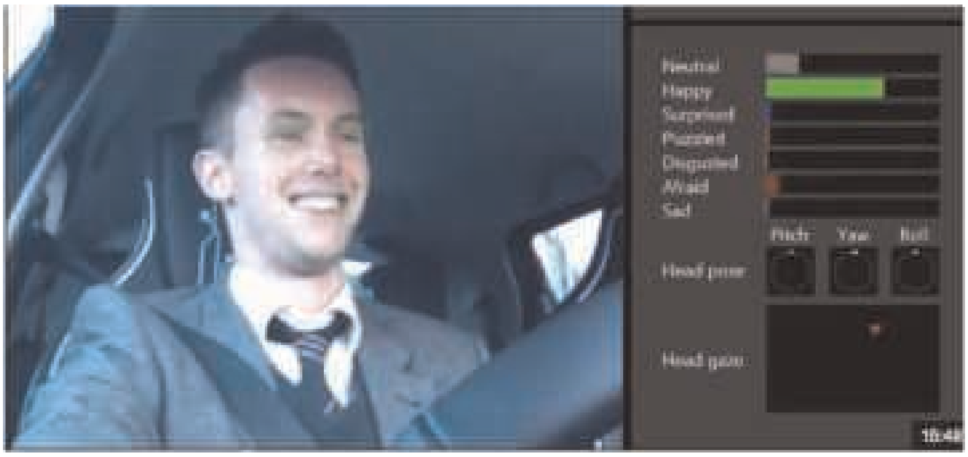

Figure 2 *Real time face detection and emotion coding while driving*

7 Stress response in smart cities

Collection and storage of (big) data and their processing, as well as the construction of machine learning algorithms to identify emotional clustering in different areas of the transport system requires a structure to the one shown in Figure 3.

Data scientists develop machine learning algorithms to classify the areas of stress and design solutions. Clustering algorithms can dynamically draw a “city stress map” as shown in Figure 4. With this tool you can understand in advance the structural and contingent causes of a possible crisis situation and take appropriate action. Predictive algorithms may allow us to anticipate potentially critical situations and provide appropriate solutions.

This enables not only the capture of millions of stress measures in real time, but also the quick distribution to response units and city planners.

The measurement of individual emotions is the first step of a system that integrate a multitude of affective, biometrics and environmental data. The development of wearable and environmental sensors is growing rapidly and the quantity of data a city designer can leverage is greater every day. Traffic, temperature, overcrowding, weather all can be factors influencing emotional response. Smart city designers will develop automatic way to filter and analyze data and to match environment and human reaction.

8 Safe transport in smart cities

With an emotionally smart city, we believe that accident prevention will increase along with crime prevention and the design of less stressful urban environments. Specifically, we see three immediate safe transport use cases with potential for positive economic implications:

1/ Transit Employees

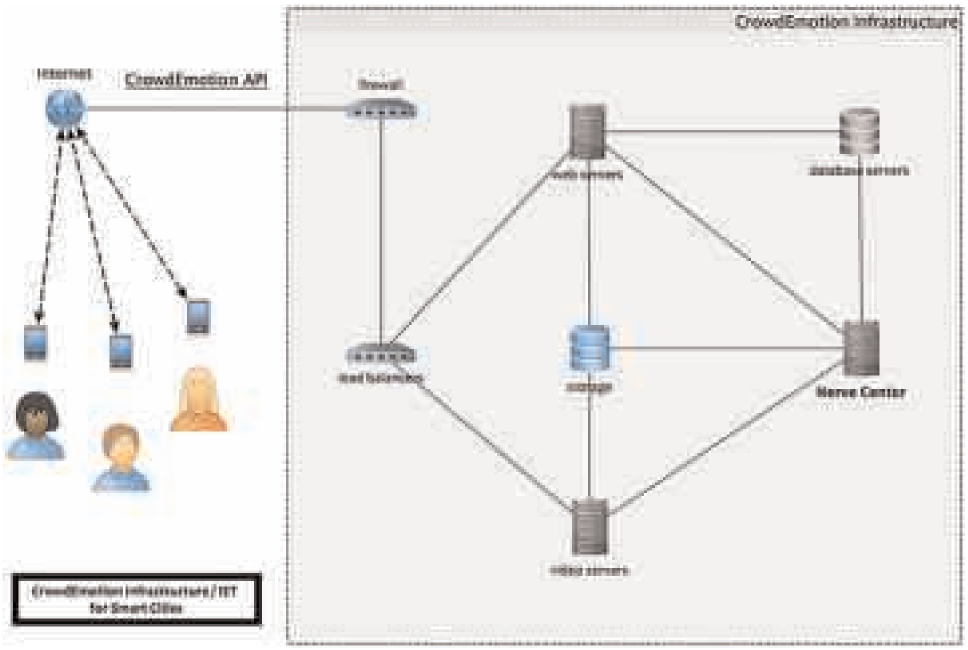

Figure 3 *Infrastructure for real time emotion/ stress detection*

Figure 4 *Real time urban stress detection*

• By monitoring public transit stress levels, we can immediately understand which drivers and employees are prone to have a stress induced accident during their shift and pro-actively respond.

• Additionally, by aggregating the data on transit employees we can understand high stress routes and positions to insure better job design that reduces stress and hence accidents on the job.

2/ Public Safety

• By monitoring stress and anxiety, we can detect crowd areas that cause high stimulus and require the presence of police or public employees to deter a negative incident

3/ Urban Planning

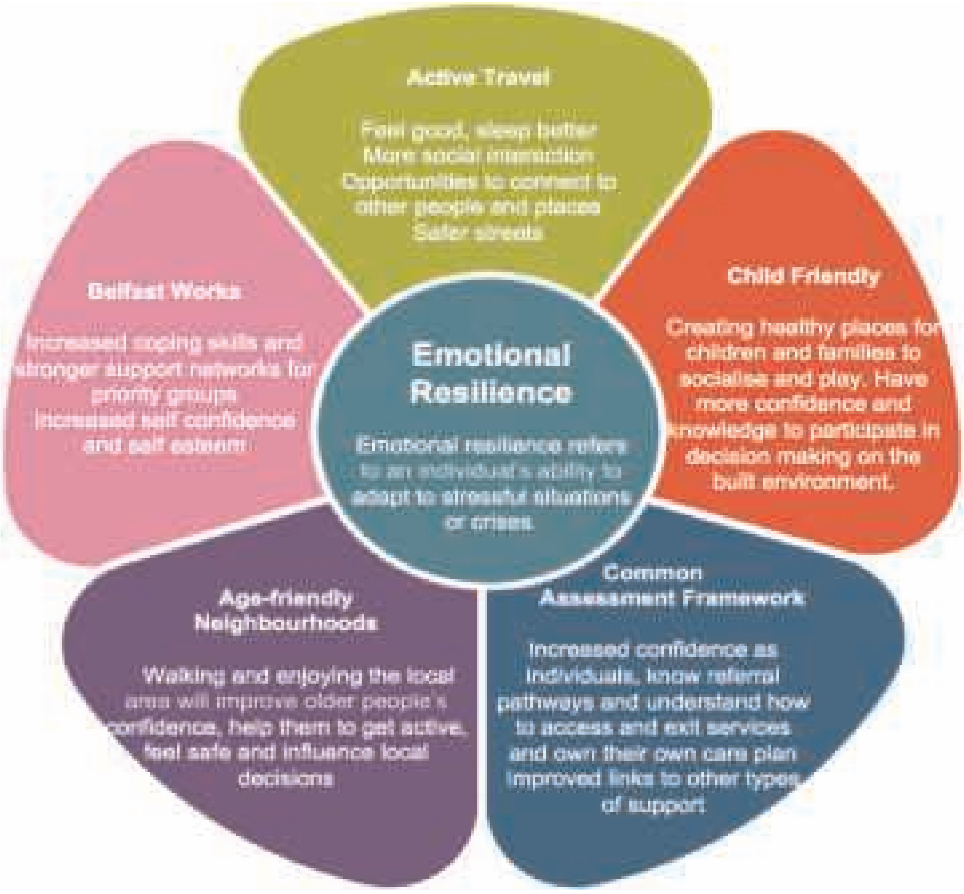

Figure 5 *Emotional resilience as a tool for managing social complexity, Belfast City Council Framework for Action*

• With monitoring systems in aggregate, we understand which areas of the city are subject to higher emotional stress and can counter with urban design and planning. One area to explore here is emotional or mood design.

Conceivably all of the above can individually increase resilience while contributing in aggregate to the safety and stress reduction of the cities of tomorrow.

9 Future steps

Some cities are already building strategies to develop the emotional resilience of the population such as "The Belfast Strategic Partnership (BSP)" in Figure 5, which has launched the first Emotional Resilience consultation in Belfast, called: 'Building Emotional Resilience Strategy 2014-17'.

As we can see the emotional resilience influence many aspects of citizens' lives, in this paper we have considered the emotional resilience as a factor in preventing accidents in public transport.

Our intention is to address a topic that is developing in parallel with the technology: the use of biometric, wearable and always connected devices will change the landscape and the everyday life in the cities of the future.

10 Conclusion

It is clear that the human driver is limited in the number and the complexity of the tasks he or she can perform at any given time, hence it is impossible to completely prevent mistakes from occurring. The prevalence of human error therefore means that it is therefore important to create an environment for the driver so that his or her slips, lapses and mistakes can be diminished, detected and recovered.

By capturing the emotions of citizens and transit employees we can identify and respond to emotional stress within a smart city to increase safety.

The field of study encompasses affective neuroscience, computer vision, real-time machine learning and complex systems design.

We've discussed how emotions contribute to stress, which contribute to accident rates causing unsafe environments. Using affective biometric sensors and high powered computing technology, that is just starting to exist in cities today, we can start leveraging the power of citizen emotions to drive safe urban transport and cities designer create the emotionally smart cities of tomorrow.

We would like to stimulate the curiosity and the interest of specialists, planners and engineers in conceiving and designing systems that integrate emotional assessment in the structure of cities public transport.

We would like to stimulate new research that may lead to indicative results as those achieved in other fields where measurement of emotion is applied, for example in the early detection of depression or in the evaluation of the effectiveness of advertising.

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Systems architectural and dynamics analysis to ensure resilience of utilities in Tactical Bases in an operational environment

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Abstract: Tactical Bases established by the UK and its allies in Afghanistan have ranged from small patrol bases housing infantry platoons with very basic levels of support to large and complex conurbations, housing thousands of personnel and providing levels of service not previously possible during military campaigns. The logistics burden imposed by these bases is considerable and the supply chains and infrastructure subject to hostile action, meaning that there has been significant emphasis on ensuring bases can be both more resilient and efficient while continuing to provide assured support to operations. In particular, water, waste and electrical power utilities are critical to enabling military operations, and their resilient and efficient provision also represents the principal challenge confronting base facility managers and logisticians. This paper reports on a study undertaken to expose the critical relationships between logistic constraints, utilities provision and operational benefits. The approach taken to the study was to describe a generic base through a systems architecture approach with a focus on understanding base functions and developing a series of Use Cases that describe the lifecycle of the base from its initial planning through to departure as well as the activities undertaken by the base during the daily cycle of operations. A detailed 'map' was developed to show the causal relationships between domains (covering the water, waste and electrical power utilities, infrastructure, sustainment and protection) and operational drivers and benefits. This Causal Map was verified with feedback from experienced base facility managers and users. Systems Dynamics Modelling was then undertaken to quantitatively assess specific information and resource flow relationships. The results of the study were then presented using Benefits Mapping to provide clarity regarding which factors facility managers could manipulate to best assure their ability to deliver the operational benefits expected from such bases. The study findings have been validated by operational experience and are considered to have application in assessing the complex relationships relating to resilience in, for example, camps initially established as part of relief operations, their subsequent extension, and for the developments of established and emerging towns and cities.

Keywords: Tactical Bases, Utilities, System Dynamics modelling, Use Cases, Benefits Mapping

1 Introduction

The UK has amassed an immense amount of knowledge from the development and operation of Tactical Bases during recent operations in Iraq and Afghanistan. These bases range in size from small checkpoints occupied by up to 30 soldiers to Camp Bastion which, at its peak, was home to in excess of 21,000 people and covered the same area as the town of Reading [1]. A range of analytical techniques have been used to improve the efficiency of Tactical Base design, construction and management. These techniques remain available for the development of Bases for possible future operations. The techniques outlined in this paper are considered to have merit not only for analysis of requirements for future Tactical Bases but also for determining which measures have the greatest potential for improving the resilience of emerging cities.

The UK has identified a number of themes that define how the context for military operations will change [2, 3]. These themes will apply to future Tactical Bases and are also relevant to emerging cities:

- **Climate Change**. Climate change as well as contributing to instability may also mean that UK forces are operating, supported by Tactical Bases, in climatic extremes.

- **Globalisation**. The UK will be increasingly dependent on global resources for its prosperity. Tactical Bases may need to be established anywhere where instability or conflict effects access to these resources.

- **Energy Resources**. The demand for and cost of energy resources will increase. This may be a cause of instability as well as a driver for more energy efficient equipment, including that used in Tactical Bases.

- **Urbanisation**. By 2040 65% (6 billion people) of the world's population will live in urban areas with 2 billion of those possibly living in slums [2]. The movement of population to urban areas will occur primarily in Africa and Asia and its rapidity may result in instability.

In addition to these themes, which influence the 'problem space' for Tactical Bases, there will be changes in the nature of the technology that is available for Tactical Bases, in particular the technology that enables the water, waste, energy and communications utilities. Increasingly the defence community will draw upon systems, services and personnel from commercial sources in order to have access to the best and most cost effective solutions. UK Tactical Base development is already adopting civilian standards with the objectives of having access to a larger supplier base and enabling integration within existing civil infrastructure where available [4].

The UK Armed Forces define a Tactical Base as [5]:

> '[A] static location whose position is primarily influenced by tactical considerations such as the need to dominate key terrain, vital ground or provide logistic support to combat operations. It is used by our Forces as a base to support tactical/local operations; therefore tactical and logistic considerations determine its location.'

UK Tactical Bases are characterised in terms of [5]:

- **The operational use of the base**. Larger Bases have multiple roles, however smaller Tactical Bases are typically focussed on generating on a daily basis, or surging in response to a specific need, patrols that can go out into the adjoining area in order to provide reassurance to the local community and deny ground to adversaries. The process of generating patrols involves providing the safe space, systems, facilities and services needed for personnel and their equipment to have their 'operational capability' restored.

- **The design life of the base**. Bases are categorised according to their design lives which range from less than six months to in excess of three years.

- **The number of occupants of the base**. Tactical Bases typically 'step-up' in size in line with unit sizes from small (housing a 30 person Platoon) through mid-size (around 300 person Company) to large with in excess of 1,000 people. The focus of the study reported in this paper was on smaller bases ranging in occupancy from 30 (Platoon) to 300 persons (an augmented Infantry Company).

- **The level of austerity in the base**. Ranging from Field Conditions, essentially 'camping with kit', to an Enduring Base where a range of equipment is deployed in order to enable long term use. Larger bases exist, such as Camp Bastion, which will have a range of uses and a life, size and level of comfort far in excess of what is provided on smaller bases. Larger bases may include hospitals, airfields, gymnasia and repair facilities with capabilities similar to those in the UK. They will boast infrastructure that is largely civilian in design and semi-permanent in nature. In contrast, smaller bases have much more limited roles and will be established using a greater proportion of temporary and military infrastructure systems to provide for greater resilience and consequently with much less emphasis on comfort.

The study reported in this paper resulted from Army Headquarters' continuing need to improve its capability to design, construct and maintain Tactical Bases on future operations. The study posed the following questions:

- How can the efficiency of utility provision to small bases (with up to 300 occupants) be improved?

- Can possible interventions relating to equipment, personnel, operating procedures and other elements of capability be identified, assessed and prioritised?

- More specifically:

    - How can small Tactical Bases be more efficiently managed?

o Can renewable energy sources make utilities provision more efficient?

o What are the principal drivers of cost and efficiency?

o What is the link between utilities, cost and operational benefits?

The study takes into account the UK Ministry of Defence's Sustainable Development Strategy [6] which has set targets for reductions in greenhouse gas emissions, waste production, water consumption and dependency on fossil fuels. While these targets will be met largely from the Ministry of Defence's permanent estate (i.e. mostly from buildings and facilities in the UK) and 'business as usual' activities, they are also influencing operations and the design of front line equipment. This is because fuel economy, a smaller infrastructure footprint and reduced dependence on the supply chain will allow greater operational flexibility in addition to supporting environmental targets.

The United Nations defines 'Resilience' as the 'ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner' [7]. This definition applies as much to Tactical Bases as it does to emerging cities. As well being resilient to 'acute' occurrences, such as natural disasters or conflict, the design of Tactical Bases and emerging cities will increasingly have to take into account the 'chronic' problems caused by environmental change and shortages of food, water and energy.

Tactical Bases differ from emerging cities in a number of important respects, the former typically having a shorter lifespan, being much smaller and having a much less diverse population under a command and control form of governance which is more directive than that of a city. Moreover, because Tactical Bases are needed where there is current or potential hazard, typically in the form of military actions, they are designed, from the outset, to be resilient to a range of significant hazards, coming from both the natural environment and man-made threats. Tactical Bases are continually confronted with direct and indirect threats, to for example their supply chains, that echo what cities would only expect to experience following a disaster. There are a number of other parallels that can be drawn between Tactical Bases and emerging city resilience:

- Tactical Bases are typically focussed on providing only the types of essential services needed by the occupants, namely: Sustainment, Utilities (i.e. water, waste, energy and communications) and Protection. These services will also be the focus of resilience efforts for emerging cities.

- Tactical Bases are constructed and supported using similar equipment to that which would be used during recovery by emerging cities (for example mobile electrical generation and distribution systems, temporary water extraction, treatment, storage and distribution systems and temporary accommodation and working facilities).

- Tactical Bases are, and will continue to have to have the capacity to be, constructed in difficult environments which may be similar to those that follow natural disaster.

2 Approach

The overall approach to the study was to create causal maps and System Dynamics models in order to provide structured representations of Tactical Base operation, fully supported by evidence drawn from existing research and stakeholder engagement. The approach comprised the following elements:

- **Pilot maps**. Initial Level 0 and Level 1 Causal Maps were developed.

- **Initial research review**. As part of the development of the pilot map and model development process, a range of doctrine and standards and the outputs of a range of previous research undertaken into Tactical Bases were reviewed. Tactical Base research has looked into water, waste, energy, communications and human-machine interfaces.

- **Stakeholder interviews**. Stakeholder interviews were conducted with Tactical Base stakeholders including occupants (from cavalry, infantry and artillery units recently returned from Afghanistan), base facility managers from the Royal Engineers and those responsible for the acquisition and support of base systems and services. The pilot map provided a structure for the interviews and was adjusted based on stakeholder feedback.

- **System Architecture**. Develop high level system architecture for the Tactical Base that identifies the key operational nodes and Use Cases.

- **Benefits Mapping**. Identify and quantify the Operational Benefits required from Tactical Bases and the necessary measures, enablers and interventions.

- **System Dynamics modelling**. Systems Dynamics modelling allows the relationship between resource and information flows to be characterised. Previous research had developed individual System Dynamics models for each Base utility (water, waste and energy). For this study a single utilities System Dynamics model was developed, applicable to small Tactical Bases (with up to 300 occupants).

- **Verification and Validation**. In order to ensure that the models were correct, a plan for verification and validation was developed and implemented. For the study, Verification was defined as the process for assessing how well the Maps and Models created represent how military stakeholders *think* utilities are provided. Validation was the process for assessing if how military stakeholders *think* the provision of utilities is achieved is correct. Verification was undertaken by confirming, during the stakeholder interviews, that in their view the Level 1 Causal Map was correct and refining it where it was not. Validation was achieved by reference to actual, quantitative evidence and by reference to Doctrine as captured in the system architecture.

3 Mapping and modelling the problem space

Figure 1 shows the Level 0 Causal Map for the Tactical Base. The Map consists of three parts: Operational Drivers, the Domains of service provision and Operational Benefits.

Current deployments by UK forces in Afghanistan (initially Operation VERITAS and latterly the Helmand-focussed Operation HERRICK) and the earlier deployment in Iraq (Operation TELIC) have defined some key Operational Drivers, which are dictated by circumstances or policy and which are outside the control of Tactical Base designers, managers and occupants:

- A hostile natural and operational environment with very limited or no host nation support.
- Very limited existing infrastructure and resources.
- Long lines of communication (supply chains).

The Domains that characterise the systems and services that constitute the Base are:

- **Infrastructure**. The physical structures that constitute the base such as buildings, roads, pipes and walls.

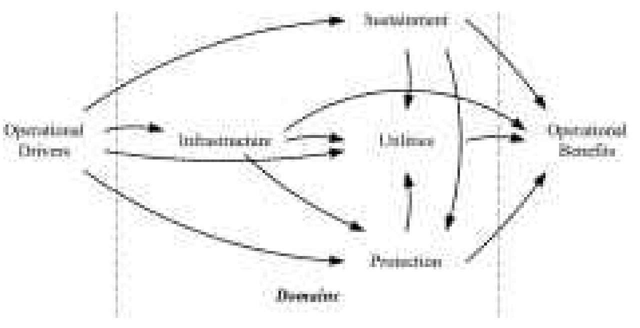

Figure 1 *Level 0 Causal Map for Tactical Bases. Operational Drivers determine the required and actual provision across the infrastructure, sustainment, utilities and force protection Domains which in turn contribute to the delivery of Operational Benefits*

- **Utilities**. The services that enable the infrastructure to function: water, waste and energy. Communications was also included within this domain as being the means of passing 'demand' and 'supply' messages between the individual nodes with the Tactical Base.

- **Sustainment**. The services that enable the people and equipment within a base to survive: primarily food, supplies, equipment support and welfare.

- **Protection**. The services that protect the infrastructure, people and equipment within the base in an operational environment.

Changes to the outputs provided by the Domains, such as interventions which have a positive or negative impact on the availability of resources, will have an impact on the key Operational Benefits for Tactical Bases, identified as follows:

- **Risk to life**. For instance, reducing the need for resupply convoys in order to expose fewer logistics personnel to danger less often.

- **Cost**. Improving the efficiency of providing utilities in order to reduce operating costs. Reducing energy use in order to reduce fuel (typically in the form of diesel) costs noting that this includes not only the initial procurement price but also the costs of moving that fuel along fragile supply chains to remote base locations. More efficient provision of energy should also reduce the cost of deployed infrastructure and utility provision (in terms of capital costs).

- **Operational Capability**. Operational capability for small Tactical Bases is primarily, but not exclusively, concerned with the ability to generate patrols on a daily basis and to provide, when needed, a surge in patrols.

The Level 0 Causal Map was broken down to an additional level of detail, informed by the output of previous research. The resulting Level 1 Causal Map (in its initial, 'Pilot' version) was used as a tool during stakeholder interviews and was progressively refined based on the feedback received. The Level 1 Causal Map, shown in Figure 2, provided additional understanding of how Operational Drivers may impact on the Domains and how, in turn, the changes in provision in the domains impact on the Operational Benefits.

Benefits Mapping is an accepted technique for identifying and quantifying benefits and the necessary measures, enablers and interventions [8]. A Small Tactical Base Utilities Benefits Map, shown in outline in Figure 3, was created in which the relationships between enablers and benefits were identified. Enablers are inputs to utility provision that can be changed. Intermediate benefits occur and can be

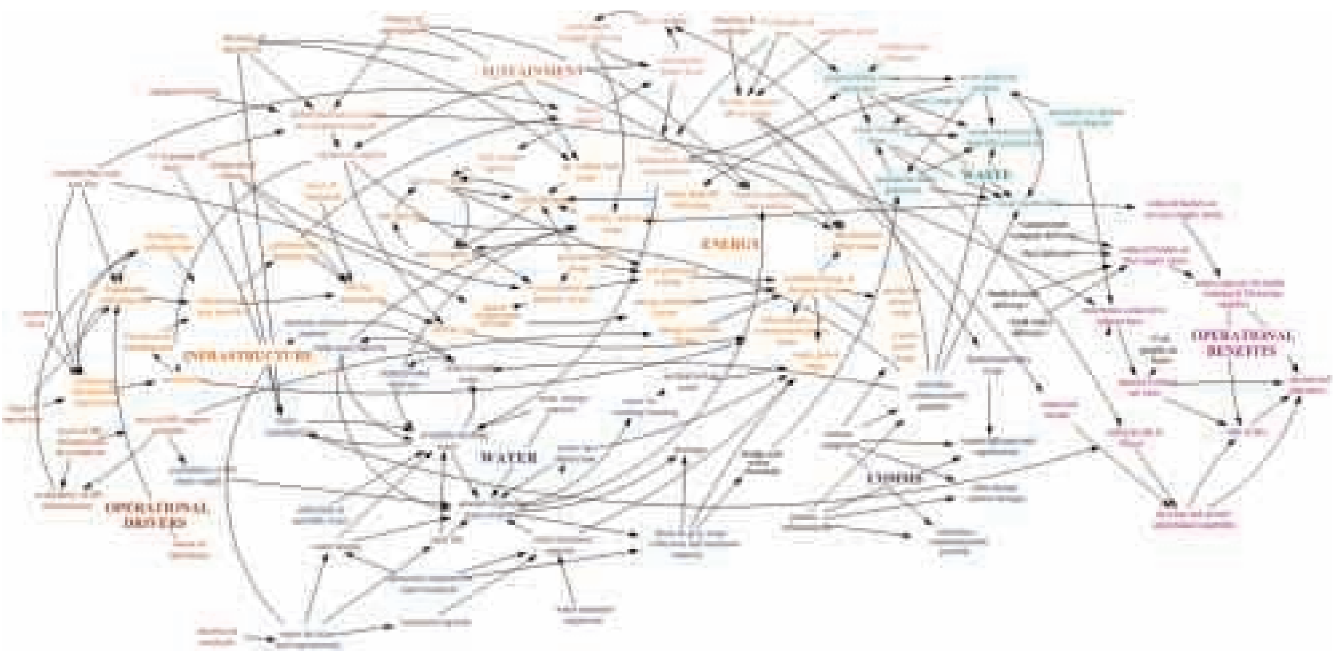

Figure 2 *Level 1 Causal Map. Showing an additional level of complexity compared to the Level 0 Causal Map, this diagram illustrates the complex relationships between operational drivers, the domains of service provision including the utilities (water, waste and energy as well as communications), sustainment, and operational benefits. Base protection issues are omitted.*

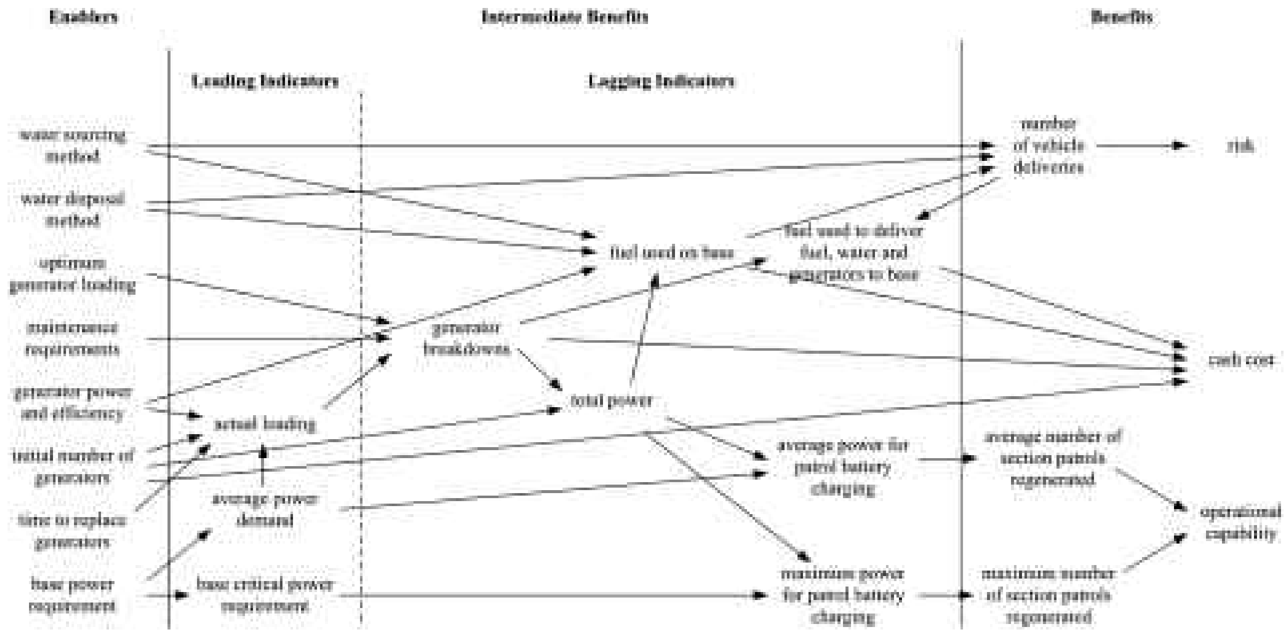

Figure 3 *Benefits Map for Tactical Base. The quantifiable key operational benefits relate to the risks associated with resupply convoys, the cost of sustaining Tactical Bases and operational capability in terms of ability to generate patrols.*

measured at the Base. The key areas in which operational benefits were needed were identified as operational risk (particularly relating to resupply convoys), cost and overall operational capability.

4 Current issues

During the interviews stakeholders were asked to identify, against the Level 1 Map, problems and issues, benefits and instances where there was divergence from Doctrine (the 'standard operating procedures' for armed forces which range from low level tactics to grand strategies). Doctrine is important because it provides the central, assumed way in which units will operate; if there is divergence from Doctrine then operations can rapidly become disjointed. In the armed forces Doctrine is meant to be coherent and comprehensive, covering all aspects of military operations and all eventualities that can be reasonably foreseen. No direct equivalent to Doctrine exists in the civil environment although the United Nations Office for Disaster Risk Reduction (UNISDR) provides high guidance on Resilience measures [9].

Analysis of the Level 1 Map identified three key areas where the effectiveness of Tactical Bases is constrained:

- **Base Equipment Support**. It is critical that base systems are fully supported, in particular through the provision of sufficient skilled maintenance personnel. Recent operations have seen personnel with the requisite skills needed to maintain base water, waste and energy systems diverted onto more pressing operational roles. Enduring operations have seen contractors displace uniformed personnel in many equipment support roles, especially in larger Bases with more elaborate Force Protection measures. Smaller Tactical Bases are more reliant on military engineers with the training needed to operate in more exacting threat environments.

- **Austerity Levels**. Because current operations have persisted for so long even small Tactical Bases have become progressively less austere. The additional comfort, while yielding more sustainable operational capability, presents a increasing burden on the Tactical Base's infrastructure and supply chain. It was also found that, from a morale point of view, consistency was important both in terms of (i) ensuring that Bases do not get worse over time (or better, for short periods, and thereby setting unrealistic expectations) and (ii) maintaining 'equality' within Bases with all occupants living in equal comfort. These factors would appear to apply to emerging cities where any real or perceived inequality between income groups in terms of vulnerability to or ability to recover from hazards can be a cause of unrest.

- **Size and Life**. The intended occupation size and design life of the Tactical Base drive the provision of infrastructure and systems. However occupation size and design life have, in recent operations, tended to be much larger and longer than originally intended. The lack of excess capacity in infrastructure and the complexity in scaling up the systems that use that infrastructure has meant difficulty in dealing with growth and life extension. This is a significant factor for emerging cities where assumptions and decisions made during initial construction regarding population densities and utilities provision may constrain future resilience.

5 Potential issues in future theatres

The feedback received from stakeholder interviews was focussed on experience of recent operations. These operations have taken place in particular environments which are not necessarily going to be representations of future operations. In order to ensure that a flexible approach to Tactical Base capability is supported the study validated the benefits map and System Dynamics model using Use Cases developed as part of a high-level system architecture model of the Tactical Base and a set of endorsed scenarios that describe possible future operations.

Use Cases were developed in the context of a selection of Ministry of Defence Architecture Framework (MODAF) views [10]. MODAF provides a standardised means of describing an enterprise architecture. In terms of this study, the enterprise may be considered to be the Tactical Base and to encompass the capabilities the base provides and the systems, services and organisation that it needs in order to operate. In Figure 4 the logical, 'capability boundary' of the Tactical Base is shown in the context of internal and external nodes. The links between these nodes are also shown, comprising flows of material (supplies, waste water), data (orders, reports, requests for supplies) and services (accommodation).

Use Cases were categorised for three distinct lifecycles namely:

- The overarching **Long Term Capability Lifecycle** (higher level 'H' Use Cases) which encompass the lifecycle for acquiring the systems and services required to be able to have the latent or contingent capability necessary to build and maintain a Tactical Base if the need arises.

- Within the 'H4: Deploy Capability' Use Case, the **Operational Lifecycle** comprises Infrastructure Project Management ('PM' Use Cases) which includes initial design and build phases and Facilities' Management ('FM' Use Cases), which covers the ongoing operation including the scaling up and down of the Tactical Base.

- Within the 'FM2: Operate (Deployment Term)' Use Case the **Daily & Recurring Activities Lifecycle** operations (low level 'D&R' Use Cases) which relate to the specific services provided by the Tactical Base.

These Use Cases are illustrated in Figure 5 where they are linked to the organisational 'actors' who have a specific responsibility for or another interest in the Use Case. Use Cases in the Operational and Daily & Recurring Lifecycle were further broken down and analysed in more detail in terms of specific activities, information needs and resource requirements.

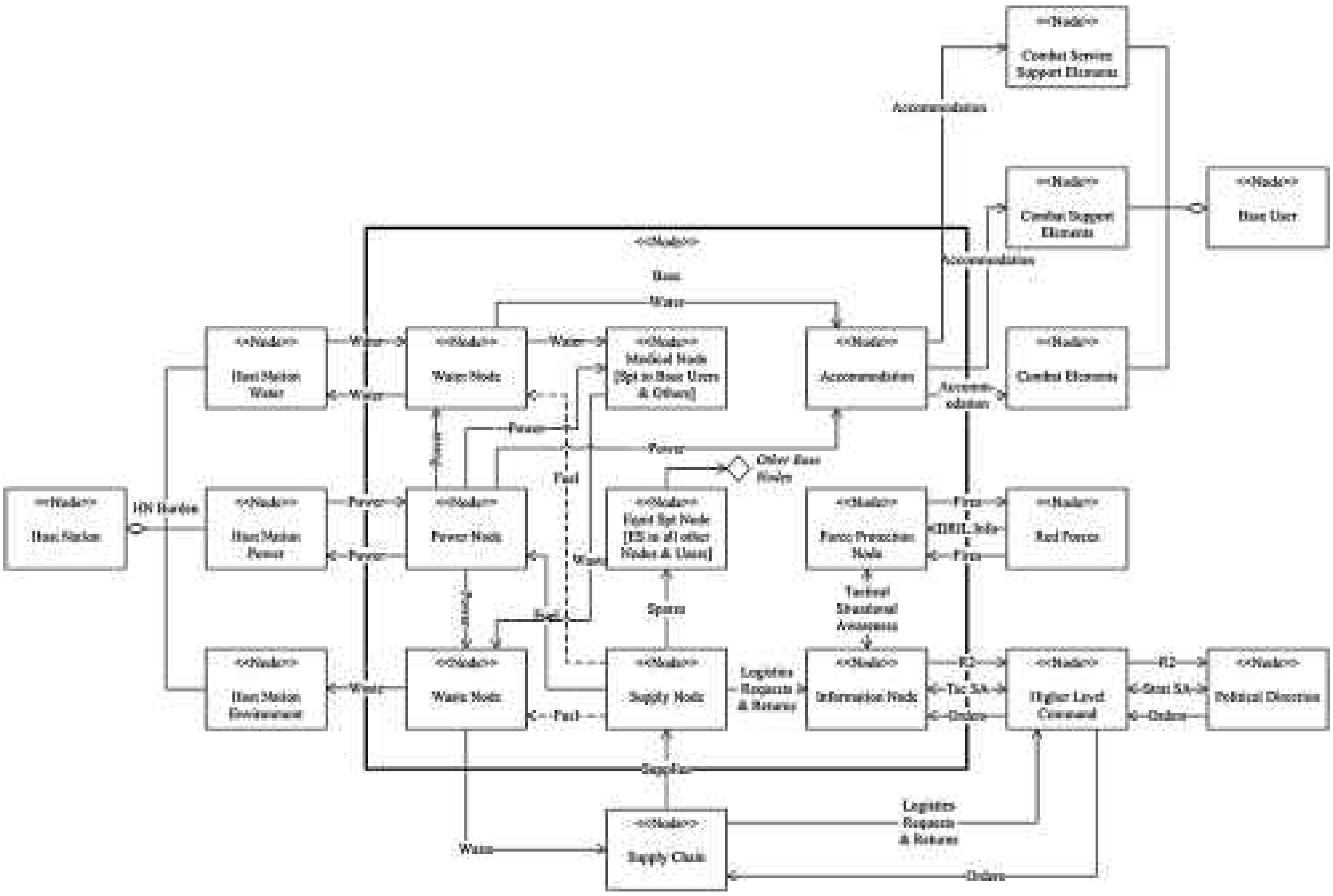

Figure 4 *MODAF Operational View (OV-2) Operational Node diagram for a Tactical Base. This diagram shows the 'capability boundary' for the Tactical Base and the key internal and external nodes that influence its operation*

The UK Ministry of Defence has defined a series of endorsed scenarios that are used to test future concepts and capability requirements. For this study the characteristics of three such scenarios, chosen to reflect different operational environments and tasks, were used to identify Use Cases that had significant impact on the operational benefits. The recurring capability gaps were identified as:

- **Lack of Heating, Ventilation and Air Conditioning (HVAC) capability for smaller bases**. Occupants sleep better when they are in environmental conditions that they find tolerable.

- **Inefficient use of generators**. Diesel generators operate most efficiently at around 80% loading, which also provides for greater reliability. However efficiency is difficult to achieve when an 'assured supply' of electrical power is needed for vital equipment. The need for 'assured supply' and redundancy has implied running multiple generators at lower loading, and therefore less efficiently, rather than fewer generators at a higher loading. Generators have not been available in theatre with the different power capacities which can allow supply to be more closely matched to changes in demand.

- **Dependence on bottled drinking water**. Measures to reduce the dependency on bottled water and therefore on the Supply Chain.

6 Impact of changing utilities provision

The study next developed a series of System Dynamics models in Vensim® for each of the Domains, as described in the Level 1 Causal Map. A simplified (on the basis of the stakeholder interviews) and integrated version of these models was developed for the smaller (300 person and less) Tactical Bases which were the focus of the study. This integrated Small Tactical Base System Dynamics model could then be applied to understanding the impact of changes in utilities provision on the primary operational benefits.

The structure of the Small Tactical Base System Dynamics model, as implemented in Vensim®, is shown in Figure 6. The model consists of the three utilities domains (water, waste and energy), the operational drivers and constraints, intermediate measures and the key operational outputs (the maximum and average number of patrols that can be generated on a daily basis).

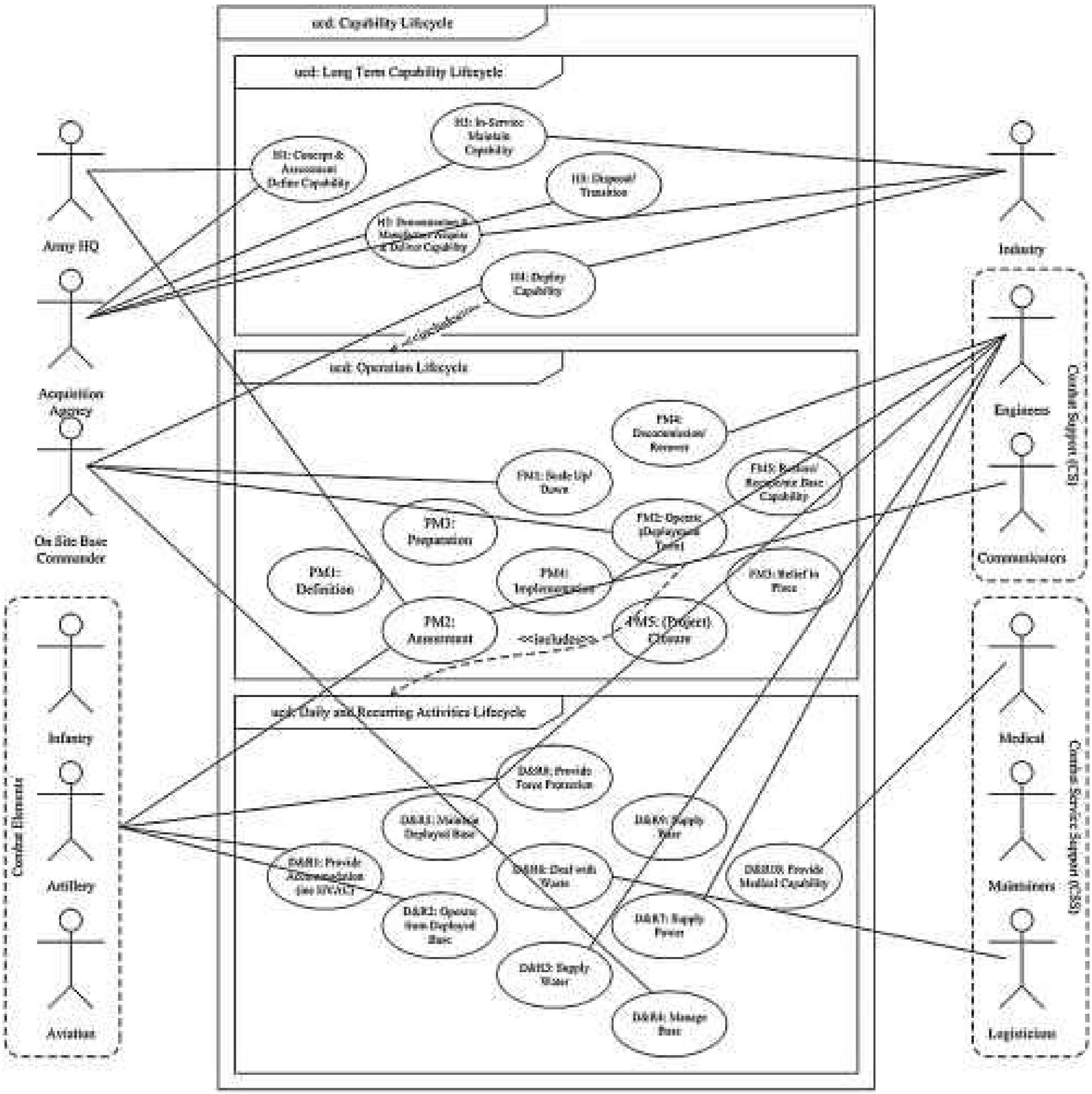

Figure 5 *Use Case Diagram for Tactical Base Lifecycles. Use Cases were defined across three lifecycles. Organisational 'Actors' were linked with the Use Cases*

A subset of the Use Cases was overlaid onto the Small Tactical Base Benefits Map, as shown in Figure 7. For each of the enablers (relating to the water, waste and energy utilities) one or two possible ways of changing utility provision for achieving an improvement were identified. This identification has been done in the context of a 30 and 100 person and Level 1 and 2 austerity bases operating over a one year period.

The results of testing these options in the Small Tactical Base System Dynamics model are listed in Table 1.

Analysis of the results from use of the Small Tactical Base System Dynamics model suggested that the key issue to be addressed is 'generator breakdowns' driven by 'actual loading'. The number and power of generators has the greatest impact for the level of change needed although reducing the base power demand has the widest effect.

7 Discussion

The approach described in this paper enables the efficacy of different possible interventions to the provision of utilities

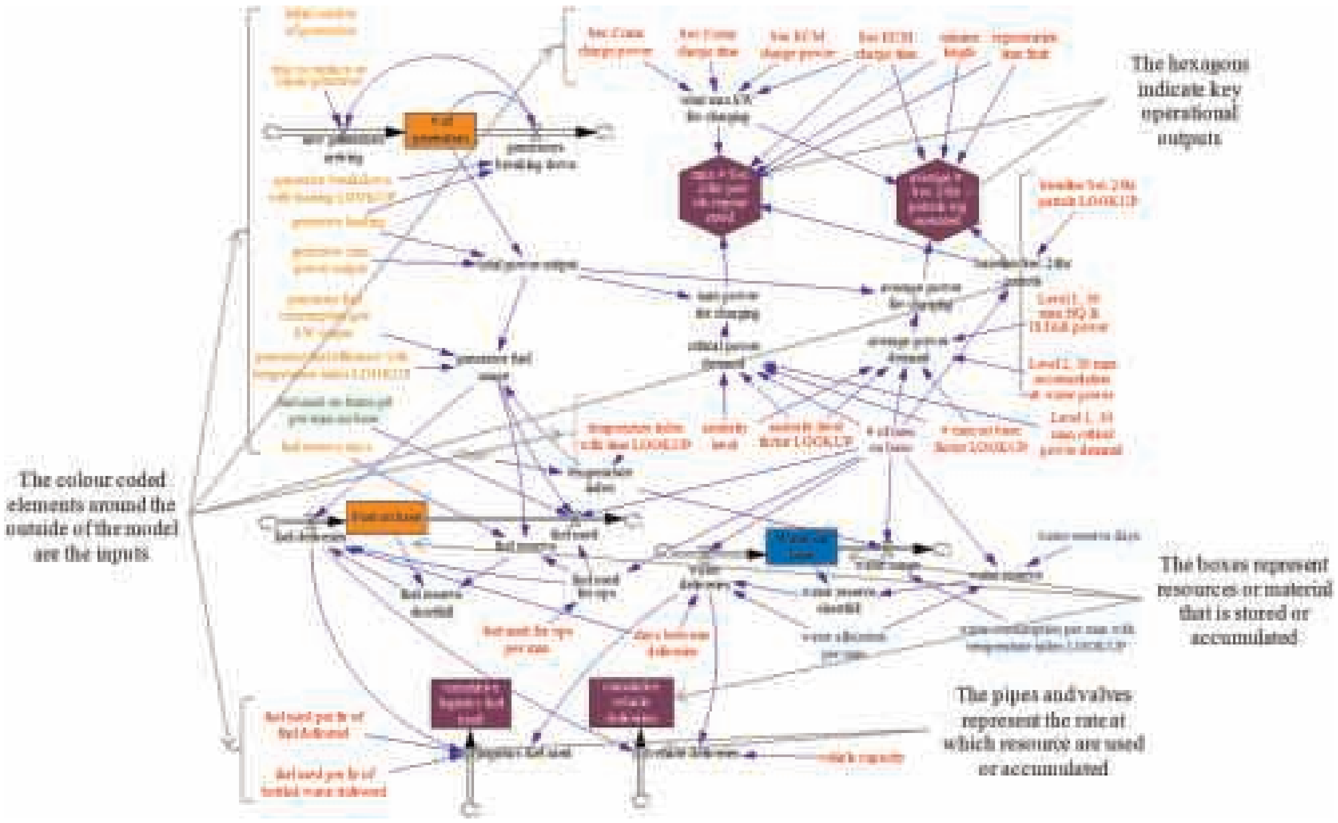

Figure 6 *Structure of the Small Tactical Base System Dynamics model created in Vensim®. Model consists of three utilities domains (water – blue, waste – green, energy – orange), and the operational drivers and constraints (red), intermediate measures (black) and the key operational outputs (the maximum and average number of patrols that can be regenerated on a daily basis – shown in the hexagons)*

on Tactical Bases to be assessed in terms of a limited number of benefits. Using this approach would allow assessments to be made that can be used to inform business cases for specific investments in emerging cities. The approach is also applicable to assessing where research may best be undertaken for more generic improvements to emerging city resilience. There are limitations in applying the lessons of this study to emerging cities. Tactical Bases are small in

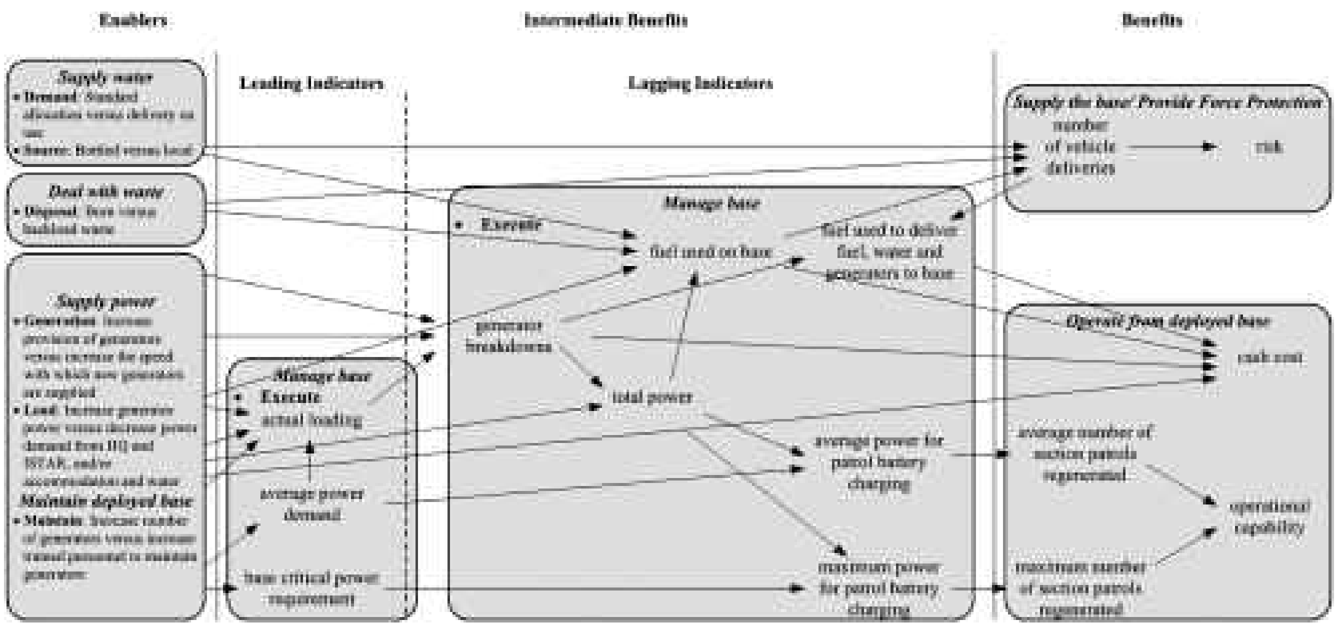

Figure 7 *Use Cases overlaid onto the Small Tactical Base Benefits Map*

Table 1 The impacts of changing utility provision on operational benefits as provided by the Small Tactical Base System Dynamics model.

Enabler	Impact
Water	• Resupplying water on the basis of usage ('pull') rather than a standard daily allocation ('push') would reduce risk (in terms of exposure of personnel running resupply convoys) and cost by around 10% across Tactical Base sizes and austerity levels. • Using locally sourced water could reduce risk and cost by up to 20% across Tactical Base sizes and austerity levels, depending on the cost and energy requirements of purchasing water or extracting and treating locally.
Waste	• Back loading waste (i.e. not disposing of it at the Tactical Base) achieves a very small improvement in cost, from reduced fuel usage, but with a large increase in risk assuming the disposal vehicles are in addition to, and not part of, supply convoys.
Energy	• Increasing the number or power of generators issued by 20% gives the same doubling of maximum patrols regenerated as reducing lead times for generators by 34%, but with twice the cost saving. • Increasing generator power by 20% or reducing power demand by 30% give similar cost savings. Increasing generator power doubles the maximum patrols whereas reducing demand nearly doubles the average number of patrols regenerated. • From the interviewees' experiences of maintaining 8–40 kW generators in theatre, halving the maintenance effort is compensated for by a 17% increase in the number of 8–40 kW generators. • Comparing all the cases, increasing the number or power of the generators has a greatest benefit, compared to the improvement needed, but reducing the Tactical Base power requirement has the widest range of benefits. • The routes through the benefits map from each case to the benefits they drive, show that the key bottleneck is 'generator breakdowns' driven by 'actual loading', with 'average power demand' as a secondary driver. • The key issue is 'generator breakdowns' driven by 'actual loading'. The number & power of generators has the greatest impact for the level of change needed although reducing the Tactical Base power demand has the widest effect.

comparison to cities, and this brings into question the scalability of the findings outlined in this paper. However a consideration of resilience at a 'micro' scale may be useful, not least when considering how to make individual city blocks less dependent on city-wide services.

The study found that additional work was required to confirm a number of findings, including those listed in Table 1. Specifically further studies should determine if:

• The primary, basic, measurable, benefit of utilities on a small Tactical Base is the rate of regeneration of patrols.

• Consistency of power availability is the biggest driver of both morale and operational benefits.

• Austerity level should be replaced as a key characteristic for Tactical Bases with a metric more directly linked to the provision of electrical power (i.e. setting an operation output based on the number of patrols needing to be regenerated for each stage of an operation).

• The main drivers of efficiency are the cost of generators, fuel used to generate power, fuel used by vehicles to deliver fuel and water and the number of deliveries made.

The following observations can be made about the applicability of the specific findings of the study listed above to the resilience of emerging cities:

• Where resources are limited the identification of a small number of critical benefits is useful. This will focus resilience efforts. The United Nations' 'Ten Essentials for Making Cities Resilient' is a useful starting point for deriving critical benefits [11].

• That consistency of power availability is the key driver of morale and operational benefits is not an unsurprising finding and is one likely to be mirrored in emerging cities. Evidence from Iraq suggests that that the lack of assured electrical power from the grid means that drinking water is not always pumped and that private households and businesses have to pay for their own generators and fuel [12].

- Defining Austerity levels to be achieved in time following a disaster may be a useful means of prioritising when and the degree to which services are restored. Electrical power, as demonstrated by the previous observation, may be a useful proxy for doing this.

- Efficiency, in direct cash terms, may not be a useful measure of the effectiveness of resilience in emerging cities because the response is, ideally, a short term one where effectiveness is the key driver. However measures that can be designed into cities, such as efficiency and the use of renewable energy sources to increase organic power generation capacity, can reduce dependency on external support.

Further observations can be made regarding the effectiveness of the approach used in the study and its applicability to developing more resilient emerging cities. Stakeholder interviews have been an important means for verifying the analysis undertaken. When undertaking an analysis of a specific emerging city's resilience, a city-specific framework similar to that outlined for Tactical Bases in this paper should be used to obtain views from experts in that city's governance, protection and utility systems. More broadly, a generic framework can be used to elicit the knowledge of those that have held responsibility for governance, protection and utility provision in cities that have experienced acute disruption, for example due to natural disaster.

A System Architecture approach to 'designing' resilience is likely to be useful. Use Cases are an effective means of describing activities relating to a Tactical Base across different lifecycles, who is responsible or benefits from those activities and the requirements for information and resources. Implementing a modelling approach, as outlined here, would allow cities to better describe the needs of stakeholders and analyse which measures, across the utilities, should be prioritised.

Consideration of the different lifecycles (Long Term, Operational and Daily & Recurring) was useful as it demonstrated where lower level Use Cases were constrained by decisions made at a higher level. For instance, when policymakers determine that a Tactical Base is only to be in place for a short duration it will be constructed and equipped accordingly, and typically in an austere manner. Should the life of the Base be extended, it will be found to be more austere, less efficient and more expensive to run than if it had been constructed using more enduring infrastructure. In emerging cities, an understanding of the longer term lifecycles of the built environment should ensure that there is an understanding of how unduly optimistic decisions may have later adverse effects on the capacity to be resilient. Use cases that make up the shorter term (e.g. Daily & Recurring) lifecycles represent a means of measuring the effectiveness of resilience and the ability of an emerging city to return to normality.

Benefits Mapping allows measurable key operational benefits from the Tactical Base to be identified. For small Tactical Bases sustainment, utilities or protection capabilities exist only to provide the key benefit, which is to regenerate patrols. Emerging cities, looking to identify and assess interventions that would aid recovery from possible future hazards, should identify measurable key benefits. These may be traffic volumes and speeds, school attendance levels or supermarket stock levels. System Dynamics modelling is a comparatively lightweight means of identifying and characterising 'bottlenecks' in the provision of services. It could, therefore, be used as a precursor to more elaborate modelling or simulation. Likewise, with the advent of 'big data' and the 'Internet of Things' (in which systems, even at low levels, are enabled by network connectivity to send and receive data) some judicious System Dynamics modelling can allow focus to be maintained on the data that really matters.

8 Acknowledgements

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Security design and resilience planning for rail transport systems

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Abstract: The World Health Organisation has stated that currently more than half of all people live in an urban area [1] and forecast that this will continue to grow. With the constant expansion of cities, many are utilising the benefit of rail, metro or underground (subway) transport systems to facilitate growth. In this context, ensuring the security and resilience of rail transport systems through their life is crucial to keeping a city operating effectively. Due to the very nature of the openness of transport systems and the numbers of people utilising such systems, they have been a soft target for crime and terrorism. There are well documented examples of terrorist attacks occurring such as in London [2], Moscow [3], Madrid [4] and Tokyo [5]. Between 1970 and 2008, 7% of terrorist incidents have attacked British transportation targets. This is consistent with the global average [6].

Examples of crime are numerous and are dealt with on a daily basis. Between 2011 and 2013 British Transport Police recorded 697008 offences in trains or at railway/underground stations [7]. Other research found that following an analysis of nearly 1000 terrorist attacks on transportation that attacks on transportation resulted in far greater fatalities [8].

Transport hubs and their links are therefore a large focal point for security stakeholders (e.g. security providers, rail companies, and governments) in making these places safe for users. An effective rail type transport system has to balance cost, functionality, security and risk. In doing so therefore, it will never be possible to provide a fully secure solution that will provide complete protection against all security threats, while still permitting sufficient access in order to permit its operation. In addition to security threats, planners also need to consider other threats and hazards from power cuts, strikes, natural disasters and other perils. To ensure the resilience of transport systems, a combination of appropriate design, planning, staff training, and risk acceptance is required. Done right, this will enable the transport system to be more resilient against risk. Security and resilience practitioners involved in transport projects are vital to the success of large scale projects, even in what are considered to be relatively benign environments. While some attention has long been provided to threats, hazards and ensuring resilience, modern approaches have recognised the benefits of careful planning to reducing risk and avoiding unbudgeted costs, in construction and operations of transport networks. Although security and resilience design can be costly, its benefits in risk reduction have proven it to be an enabler and producer of value to some of the world's biggest cities and most complex transportation projects.

Keywords: Security, Design, Risk, Resilience, Planning

1 Introduction

A well-developed risk methodology can be used as an overarching tool to identify, minimise and tolerate risks as stated in [9] and [10]. The author has extensive experience in utilising a risk-based approach for designing in security and resilience for rail projects. This paper highlights the benefit of a multi-disciplinary approach to manage risk, security and resilience from an early stage to provide a structured process to designing the correct level of security and resilience into the transport system while mitigating risk though its lifespan.

2 Strategy

Successful security and resilience is usually based on a combination of people, technology and processes [11]. Technology is represented by the security design element while the risk methodology, business continuity and crisis management element is given in the processes. Finally the operational security facet represents the people in this equation. A combination of these facets is currently seen as best practice as described in this document and in reference [12].

The security design focusses on pre-empting any security threats by trying to design out potential security issues from the start. Following determination of the risks, where possible these will be designed out during the design stages. The remaining risks will then have to be managed operationally using staff. This focusses on existing issues. To cater for "what if", business continuity will deal with how to keep the business running and crisis management will deal with what to do if something actually goes wrong. These procedural measures will significantly decrease most security risks further to an acceptable level of residual risk.

The risk assessment methodology is what ties all the aforementioned mitigation methodologies together. The Security Risk Assessment Methodology (SRAM), see reference [13], focusses on defining the unmitigated (gross) risks, evaluating each one in turn to determine what approach will be taken with it and, where necessary, identifying risk mitigation measures. The final step is to define the final mitigated (net) risks, according to the process highlighted in Figure 1. The following section highlights the risk treatments utilised to mitigate the gross risks.

3 Security design

There is an established link between implementing security design and the reduction of fear [14]. Primarily, security design will focus on threats such as crime, terrorism, anti-social behaviour and vagrancy. Other less common threats such as, for example, protestors can also be designed for.

In general, security can be broken down in to two main categories: security at the main transport hubs i.e. stations and security for sections linking or facilitating those transport hubs.

Station security design should be based a multi-disciplinary based approach: elements designed in for security will often affect other disciplines and vice versa. An integrated design approach must therefore be taken.

Figure 1 *Risk assessment stages*

Due to the crowd densities at railway stations, they will be classed as crowded spaces and will require protection against terrorist attack and crime [15]. The requirements for the security systems should be defined by use of operational requirements process [16].

The security design measures mentioned above are also very relevant to assets such as control centres, depots and stabling yards. Other assets critical to the overall rail system are, for example, bridges, tunnels, electrical substations, intervention shafts and cabling.

4 Operational security and policies

Operational security is the effective use of rail (security) staff to obtain a security effect. The rail industry has standards in place to produce and coordinate procedures for the management of operational security [17]. Designing in security can remove a certain amount of risk however the remaining risk will have to be managed operationally through non-security and security staff [14].

Staff with a security function should be trained appropriately in dealing with (security) issues at the station. To be able to effectively undertake this role, staff should be selected accordingly for their suitability in this role. There is a cost/quality and motivational element related to the industry specifically for security staff. Low wages rarely attract skilled employees and this must be taken into consideration when attracting and retaining security staff [18].

Training will prepare staff for most eventualities. Pro-active staff will assist in deterring crime and spotting potential issues before they occur. To provide a sense of security at stations and other locations, security staff should be visible through their presence as a static guard role / passenger information role or through roaming patrols. Staff should make sure areas are well maintained, and that regular inspections are undertaken. Issues encountered on inspections should be dealt with as soon as possible to not attract other crimes or anti-social behaviour e.g. graffiti will attract other graffiti artists so should be removed as soon as possible. The proper equipment to remove graffiti or repair vandalised items should be located at the station.

How the station is secured, run and maintained should be stated in the security policies and procedures of the station [14]. These procedures should be compiled with the input from the necessary security stakeholders such as the police, department for transport, local councils and local security forces. Items included in these policies and procedures are wide ranging but may include: cash handling, emergency response, how to respond to crimes or wilful damage. This should include which security stakeholders to liaise with in case of an event occurring. All crimes and other incidents occurring at the station should be recorded and monitored to prevent similar incidents from re-occurring.

To assess the public's perception of security, customer satisfaction surveys can be undertaken which provides useful feedback to the station operator. This process is used in the UK as defined in reference [14].

5 Business continuity, crisis management and emergency response

5.1 Emergency response

Emergency response arrangements which focus on restoring and rebuilding rail infrastructure following an incident, should be flexible and tailored to reflect situations encountered in the rail industry, for example, as given in reference [19]. The risks need to be constantly reviewed so that adequate response measures can be defined. The persons involved in the response need to prepare effectively for these response scenarios so that the right decisions can be made at the right level of authority. To inform the people involved there should be a clearly defined method for dissemination of information. All response stakeholders need to be identified so that an integrated approach can be defined on how to respond efficiently using effective means of communications [20].

The response capability can be built on existing capabilities already existing in the rail industry such as e.g. maintenance, planning or other functions involved in solving day-to-day issues.

From a practical perspective, applying fire drill-type procedures to identifiable emergency scenarios can save valuable time. Emergency response manuals should contain easily readable checklists and useful contact information. Rehearsing responses to emergency situations can increase confidence levels in dealing with challenging and unfamiliar situations.

5.2 Business continuity

Business continuity plans and procedures identify critical functions and activities and document the recovery of those functions and activities within a predefined timescale. Within the rail industry, the requirements for these timescales are usually very short. The process of asking the questions for a business impact analysis can often be of greater use than the documents themselves, as planning encourages resilient thinking. Questions around what people, resources and systems would be needed in the event of a disruption can be asked and answered today. A best practice document has been published [21] which can be used by organisations of all types and sizes.

5.3 Crisis management

Crisis management can encourage resilience in individuals and organisations through developing an efficient team approach to managing an unforeseen rail-related crisis. Regardless of the nature of the incident, certain elements can be predicted, such as persistent demands for information from a variety of stakeholders including rail passengers, rail operators, families, the media, regulators and senior management, even when there is either too little, or too much information, to share. The stress and confusion of a crisis can be simulated through a structured and progressive approach to training, developing the behaviours, attitudes and activities that would be required during a business as unusual event. This training should occur throughout all levels of the rail management. A best practice document can assist to implement this [22].

6 Risk assessment methodology

When focussing on risk treatments, concepts of proportionality, relevance and effectiveness are key points [23]. To achieve this, an effective security risk assessment should be conducted using a recognised risk assessment methodology e.g. rooted in the ISO 31000 risk management framework. This is the successor to reference [24] and other associated standards such as [25] and [26]. The risk methodology described in this document [13], also incorporates aspects of other leading international methodologies given in references [10] and [27] - [30]. The basic approach follows ISO 31000 [10] as shown in Figure 1.

The general philosophy is that risk assessments should be dynamic, iterative, responsive to change [10], delivered with a flexible approach, and to an international best-practice standard. It should be tailored to the specific tangible rail assets: e.g. station, deport, tracks, sub-stations etc., intangible assets e.g. ability to operate, reputation, as well as people, staff, contractors, operators etc.

6.1 Terminology

A risk is defined as follows: *A potential event that will have foreseeable consequences for assets and the resultant impact(s) on objectives and success criteria*[1]. Another definition of risk highlighted in reference [10] is: *effect of uncertainty on objectives.*

In [31] the risk is defined as being comprised of:

$$\text{Risk} = \text{Likelihood} \times \text{Impact}. \qquad (1)$$

Likelihood is based on the threats (T) and the attractiveness of assets as targets and the control measures to deter, delay, detect and deny (D).

[1]Adaptation of definitions found in references [25] and [30]

Impact is based on the consequences of loss (C) and the measures to respond and recover (R) [13].

How the values are calculated is outside the scope of the document however it is necessary to understand the relationship between which factors affect likelihood and impact as shown in Equation (1). Risks can be presented in a risk sheet which highlights all relevant information regarding those risks and the related scoring for each value as defined by Equation (1).

6.2 Threat (T)

Threats are assessed, considering capability and intent of the source and the modus operandi employed [13].

6.3 Attractiveness of asset to source

The relative attractiveness of each asset to the threat source is considered. The more attractive the asset, the higher the likelihood of attack [13].

6.4 Measures to deter, delay, detect and deny (D)

Broadly, the principle is the better the measures are to deter, delay, detect and deny, the lower the likelihood of the threat being successful in achieving its goal [13].

6.5 Consequences (C)

The consequences of the risk event at the asset are considered in turn during risk analysis. A consequence table is used to define the consequence of loss in terms of: environmental degradation, injury to people, reputational damage, loss or interruption of capability and processes and financial loss [13].

6.6 Measures to respond and recover (R)

The principle is the better the measures to respond and recover, the lower the impact will be for the organisation [13].

7 Risk assessment process

The following section highlights the risk assessment process as shown in Figure 1 and as defined in [10] and [13]. Each risk assessment stage will require engagement with the relevant stakeholders.

7.1 Establish context

The following forms part of "establishing the context":

Mobilisation – establish expectations, success criteria and (risk) parameters relevant to the rail company, users or stakeholders.

Information review – collate and review all internal and external rail operators' information for the assessment e.g. policies, procedures, drawings and designs.

Threat assessment – identify and analyse sources of threat to the rail company, methods, capability, intent and targeting patterns.

Stakeholder liaison – consult all relevant internal and external stakeholders as agreed with the rail company.

Asset characterisation – identify and agree rail assets to be included within the scope of the risk assessment; determine the consequences of loss and identify critical assets.

Vulnerability review – review the location to identify security hazards. Determine relative attractiveness of rail assets as targets. Evaluate the effectiveness of existing / planned control measures (deter, detect, delay, deny, respond, and recover). Consider measures directly implemented by the rail company, users, stakeholders and wider security measures and vulnerabilities.

7.2 Risk assessment

The following form part of the risk assessment phase:

Identify – Identify risks and document these in the risk register. Consider: source (internal, external threat actor, hazard), assets at risk, timing / proximity, and likely risk event scenario(s).

Analyse – Determine likelihood and impact of identified risks, taking into account risk as defined in Equation (1).

Evaluate – Determine whether risk can be accepted or requires a risk response (treat, transfer, tolerate, terminate).

7.3 Evaluating the risk

By utilising the various mechanisms highlighted in this paper to increase security and resilience of the asset, the risks can usually be evaluated to determine the best method of response. To put this in to context, effective security design can help decrease the value of D and therefore the value of the likelihood. Effective use of persons to obtain a security effect can help decrease the value of D and also that of C and R and therefore the value of the likelihood and impact. Business continuity management and crisis management can help decrease the value of C and R therefore the value of the impact. When looking at risks, the "4T's" for risk responses will apply as defined in [13] and [32]:

• Treat the risk – take action to reduce the likelihood and/ or impact of the risks as discussed in this paper.

• Transfer the risk – take action to move the risk or a part thereof to another party e.g. through insurance

• Tolerate the risk – an organisation can decide to tolerate the risk even though the risk may be classed as unacceptable

• Terminate the activity – an organisation can decide to cease activities or change procedures to eliminate the risk

To determine the risk appetite in a multi-stakeholder environment can be very challenging especially as each stakeholder will have their own wishes. Workshops can be an effective tool for agreeing risk appetite however risks appetites in commercial rail organisations can greatly differ from government security stakeholders.

8 Risk treatment

Risk treatments can be utilised to mitigate the risks [10]. Where risks are to be treated, a plan should be developed which details mitigation activity (expressed as an operational requirement). The risk treatment methods which are usually agreed with all stakeholders have been split down in to procedural, technical and operational in this document.

A change in threat profile throughout the lifecycle may result in changes in risk. Therefore risk treatments should be scalable and this must be taken into consideration when designing the rail facility e.g. does the station entrance have enough space to incorporate searching and screening facilities should this be required in the future?

8.1 Risk treatment – technical

Examples of some of the many elements included in the security design of stations are given below and are taken from amongst others [12], [14] and [20]:

• Pedestrian modelling – designing pedestrian routes so that station users do not cross paths / bump into each other which facilitates pick-pocketing

• Architectural design – design out vulnerabilities such as recesses, ledges, and places to hide items, choice of anti-scratch / graffiti materials, materials which can be easily replaced and are non-frangible

• Structural design – by designing and building facades to resist blast loads in correct manor, the effects from an (accidental) explosion can be minimised. This is valid for the structure itself but also for cladding materials and fixings

• Single points of failure – areas where, for instance, all power and communications cabling come together and are readily accessible to an outsider. There should be diversity of power and communications supplies to increase resilience

• Cash handling – facilitating cash handling by providing easy access to the ticket machines and also minimising the distance the cash handlers have to walk to the van. Installation of cash machine in the station

• Public realm design – designing the areas outside the station to increase feeling of security for station users such as landscaping

• Lighting design – lighting which will support CCTV and also increase natural surveillance internal and external to the station

• Perimeter barriers – designing fencing or wall to deter access from external adjacencies

• Electronic security – design of (perimeter) intruder detection systems, access control, CCTV to deter and detect security threats

• Vehicle parking and access – design of parking areas to provide a safe environment for car and bicycle users and to slow down vehicles, create stand-off and deter and protect against hostile vehicles

• HVAC system – making sure air intakes are not readily accessible to the general public

• Waste management – provision of bins, storage of waste, location of storage facilities and access to and removal of waste

• Retail units – design of retail units in or near the station and how to minimise and security threats due to these

• High risk adjacencies – threats from any adjacent building to the station

• Information provision – indicate clearly where people need to go

Examples of site specific elements included in the security design are:

• Control centres – design of diversity i.e. resilience of systems to be able to manage multiple station control rooms and design of measures to protect staff

• Depots and stabling yards – design of protection at perimeter and at train entrance, minimising entrances, restrict vehicle access on to site, prevent theft of materials and minimise any electrical interference

• Rail bridges – design against the throwing items, the bridge deck being breached and column failure

• Tunnels – design against breaching, blockages, leakages / floods

• Electrical substations – design for diversity and resilience of supply

• Intervention shafts or access locations – design secure access hatches and tamper evident locks / seals

• On-train security – design for protection of staff and passengers and create sense of security through design similar to that found in station design i.e. "feeling of being secure"

• Track-side – design against unauthorised line side access leading to theft or vandalism and provide track-side surveys to plot access points and identify potential weaknesses. A successful example is given in reference [33]

8.2 Risk treatment – operational

Examples of mitigating risks using operational security are given below and are taken from [14]:

• Security awareness training and how to deal with aggression

• Background checks of staff

• Security staff training

• Overt utilisation of staff and PA systems

• Good security in the booking office and staff areas and use of personal alarms

• Good maintenance and cleaning regime in place

8.3 Risk treatment – procedural

As described in [21] and [22], examples of procedural risk treatments are:

• Develop security, business continuity, incident and crisis management plans

• Keep security and response plans and procedures up to date

• Identify response teams for business continuity and crisis management

• Support response teams through regular and appropriate training

• Audit plans and procedures and frequency thereof

• Define responsibilities and ownership

8.4 Governance and assurance

Following evaluation / treatment of the risks, processes and decisions need to be made that will define actions, define responsibility and verify performance. This governance must be in place to assure that appropriate measures are taken to tackle the risks and that once these measures have been taken that there is a high level of confidence that it has been done correctly. Part of the governance process is to review these risks and treatment of the risks [34].

9 Conclusion

This paper outlines a methodology for identifying, minimising and tolerating risks by utilising design, resilience planning, operational security and procedural means. From a security perspective, a proven risk methodology with effective risk treatments provides an effective decision tool for senior management to decide what elements need further mitigation and what residual risks can be tolerated.

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The role of models in improving the resilience of cities

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Abstract: This paper presents an assessment of three of the differing roles that models, calculators and the analysis of data play in enabling cities to develop the infrastructure required to realise greater resilience. Cities are addressing their resilience in the face of increasingly complex environmental challenges and diminishing timescales. This work discusses case studies, exploring the strengths and limitations of models in informing the decision makers who are addressing the development agenda. The scope of activities undertaken under the banner of resilience is vast; this paper focuses primarily on models for the development of low carbon energy infrastructure in cities and master planning for resilience.

Keywords: Resilience, model, infrastructure, cities, sustainability, investment

1 Introduction

As the world's population increases and urbanises, it is the engineers, planners and policy makers who face the challenge of delivering society's expectation of continued prosperity, within the constraints of our planet's limited resources. It is estimated that by the middle of this century, the number of people living in cities will increase from 3.4 billion in 2009, to 6.3 billion in 2050. This will represent approximately 70% of the total estimated global population [1]. It is therefore predominantly in cities where these challenges will be focused.

The requirements of the population for access to energy, water, transport, healthcare, food and shelter are addressed by the infrastructure in cities. Dependence on items of critical infrastructure is most evident during times when these systems fail to meet the needs of the population. Shock events such as blackouts, droughts, acts of terrorism and flooding will test the capacity of infrastructure to operate outside their normal design conditions. It is during these shock events that the interdependencies of a city's infrastructure systems are also highlighted. As an example, after heavy rain and flooding in the UK in 2007, the Ulley Reservoir near Rotherham came close to breaching. Had this occurred, it was recognised that a number of key infrastructure assets would have been impacted, including the M1 motorway, a major primary electricity substation and gas network connection for the city of Sheffield [2].

Continued investment, upgrade and modernisation of infrastructure is essential in ensuring the resilience of critical systems and the safeguarding of the population. Increasing uncertainty, given a changing climate, highlights the need for new and existing infrastructure to be prepared for shock events. The frequency and severity of these events appear to be increasing, as illustrated in Figure 1.

When faced with the responsibility of deciding where investment in infrastructure should be targeted, engineers, planners and policy makers look to past events for understanding and evaluating risks which informs the selection of future actions. Throughout the decision-making process and during implementation, modelling is an increasingly useful tool to communicate and deliver evidence-based guidance that decision makers rely upon to improve the resilience of cities.

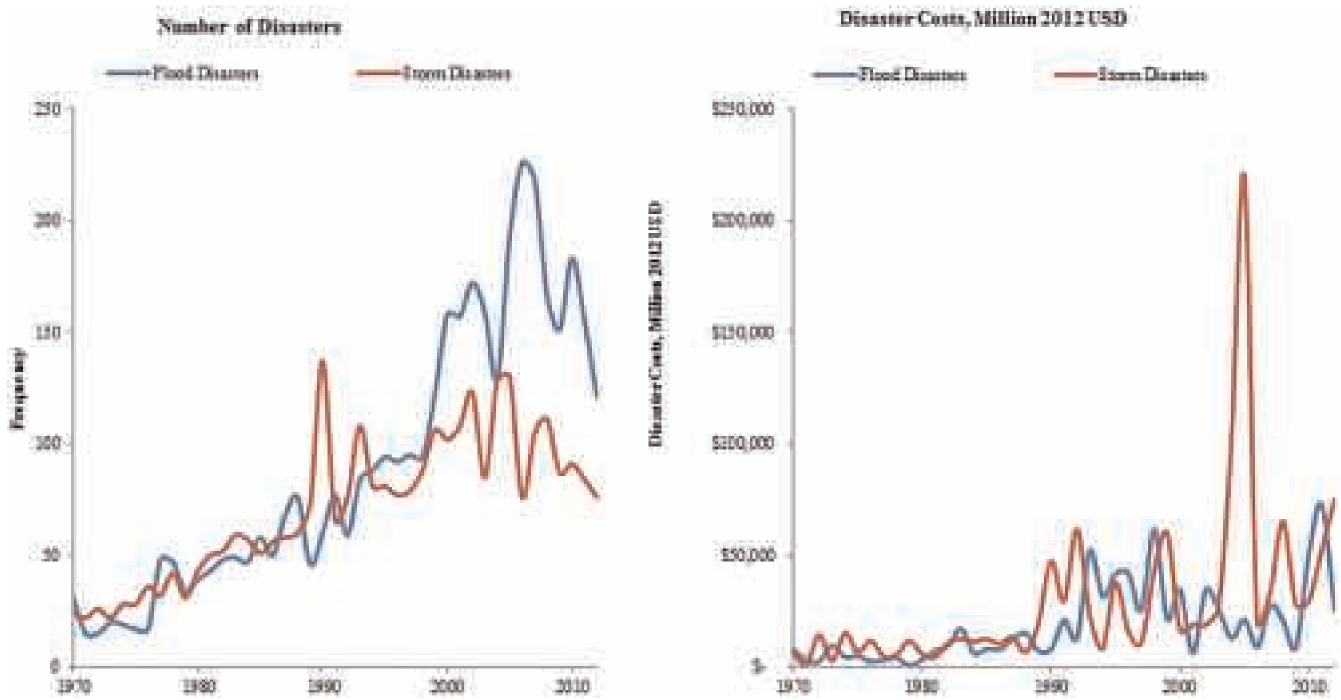

Figure 1 *Frequency and costs of disasters 1970-2012, collected from EM-DAT: The OFDA/CRED International Disaster Database [3] and adjusted for inflation*

2 What is Resilience?

2.1 Definition

The origins of resilience are founded in ecological systems, describing the capacity for a natural system to maintain or recover functionality, following an unforeseen event or change in conditions. The principle is adopted in engineering, which uses the term to describe the ability of systems to restore functions to "business as usual" after an unforeseen event, or to continue a service following a change in conditions. The same principles of resilience apply to cities and communities, which can be described as complex systems for the purpose of assessing their capacity to withstand challenges. These challenges will be faced by a city in a variety of forms, but can be classified as either shocks or stresses [4].

2.2 Shocks

Shocks are unexpected events which occur over short periods of time. The impact of a shock on a city will depend on the unique characteristics of that city, such as its geography, climate and infrastructure. Examples of shocks facing a city include severe flooding, major transport accidents, terrorism, severe weather events, industrial accidents, and riots.

2.3 Stresses

Stresses are factors which build up over a prolonged period of time, resulting in challenging conditions for a city. Examples of stresses that may be experienced by a city include excess population growth, food shortages, and changes in climate, aging infrastructure, drought or water shortages.

2.4 Application in cities

In global average terms, urbanisation of the world's population has been steadily increasing for many years and this trend is expected to continue. Within this trend, there are localised examples of rapid growth, typically in response to industrialisation advances. It is estimated that 10 million people from rural China migrate annually to China's ever-expanding megacities. The growing concentration of populations in cities places an increasing demand on infrastructure.

Since the demand for resources and security is most highly concentrated in densely populated cities, these are the areas which present the most significant risks when faced with shocks and stresses. There are a number of institutions established to study and address issues associated with resilience in cities, including the UN's Making Cities Resilient campaign [5] and the Rockefeller Foundation's 100 Resilient Cities (100RC) project. The 100RC project aims to assist "cities around the world become more resilient to the physical, social and economic challenges that are a growing part of the 21st century" [6]. 100RC describes five characteristics of a resilient city:

1. **Constant Learning:** The ability to internalise past experiences with robust feedback loops that sense, provide foresight and allow new solutions.

2. **Rapid Rebound:** The capacity to re-establish functions, re-organise and avoid long-term disruptions.

3. **Limited or Safe Failure:** Prevention of failures rippling across systems.

4. **Flexibility:** The ability to change, evolve and adapt to alternative strategies in the face of a disaster.

5. **Spare Capacity:** Ensures that there is a backup or alternative available when a vital component of the system fails.

These points provide a city with a framework with which they can assess the capacity of its infrastructure, systems and emergency planning to mitigate the impact of a shock or stress. These concepts are applied to cities across wider fields than just tangible infrastructure assets. For example, in addition to having a resilient electrical grid or water network, assessments of resilience can be equally be applied to an economy, as illustrated by the city of Detroit, which filed for bankruptcy in July 2013 [7]; or to a community, demonstrated by the London riots in 2011 [8] [9]. While important socioeconomic facets of a city should be included in the assessment of a city's resilience, they are often far harder to measure and quantify through modelling.

2.5 Resilience differs to sustainability

Resilient development differs to sustainable development in its aims. Sustainable development, as defined in the widely adopted Brundtland definition [10] is *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. This differs slightly from resilient development, which recognises an additional requirement, that meeting the needs of the present will require an evolving approach which adapts to the changing environment.

3 What are the challenges facing cities looking to achieve resilience?

Identifying risks to a city presents a significant challenge in itself. Engineers use their understanding and experience of the impacts to predict what the likely magnitude of a stress or shock event may be in order to assist decision makers to allocate resources. Models are often used to quantify the costs of taking action, and help estimate benefits to the city in order to ensure the resources are allocated in the most effective way. Projects which do not receive the investment represent an opportunity cost to the city.

There are two considerations a city makes when seeking to achieve its aim of improving its resilience:

1. In which actions should a city invest its resources?

2. What are the barriers to making that investment?

3.1 Where should a city invest?

Investment at a city level can be distinguished between that undertaken by the government, and that undertaken by individual citizens or businesses. In each case, a similar process is applied to the decision making, which is an assessment of risk. When presented with a foreseeable shock or stress, the city is faced with a decision; should the risk be mitigated through investment in new or additional infrastructure? This requires an assessment of the potential impact of the risk and the likelihood of its occurrence. In undertaking the assessments of likelihood and impact, models play an important role in the decision making process, since modelling a scenario can provide information driven by a number of complex interdependencies and statistical probabilities.

Figure 2 depicts how a city government or authority may assess the need for intervention and investment to address risks faced by the city. In cases which are believed to have a low severity of impact at the aggregate level. This aggregate impact could either be a low impact across a moderate proportion of the population, or a severe impact for a small fraction of the population. In these cases, the individual might be expected to take action to mitigate the risk (the lower quadrants of the matrix, cases 3&4).

As the severity of the impact at the aggregate level increases, the government might be expected to undertake the mitigating action (the upper quadrants of the matrix, cases 1&2). The nature of the mitigation will then depend on the likelihood of the risk occurring. In cases where a shock event is highly likely, investment in ensuring that the

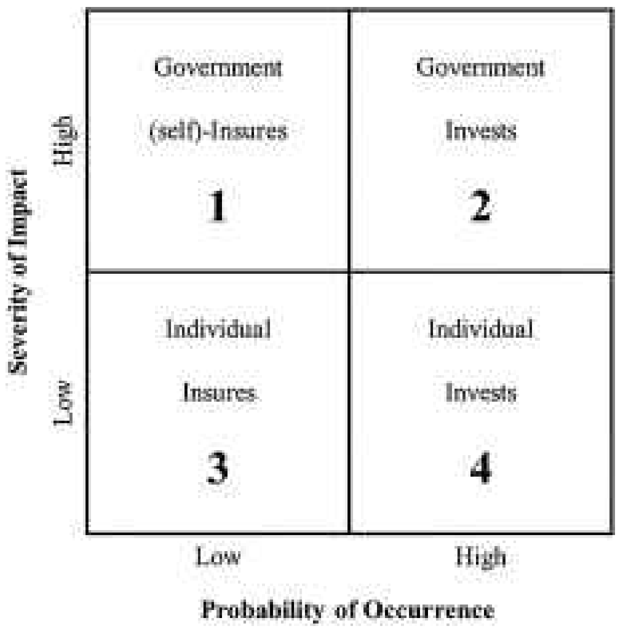

Figure 2 *Whether to insure or invest; the role of government and individuals in mitigating risks. Adapted from [11]*

impact is reduced is undertaken, an example being investment in the Thames Barrier for the prevention of flooding in central London. As the likelihood of risk reduces, the justification for expenditure to mitigate is harder. For example the impact of a meteorite strike would be unlikely to warrant investment, rather the government might self-insure against the occurrence, and intervene if and when it does happen.

By estimating the likelihood and impact of these risks, models play a key part in the decision making process when deciding to invest in making cities more resilient.

3.2 Barriers to investment

3.2.1 Constrained Capital and Resources: The most obvious and restricting factors facing projects aiming to improve the resilience of cities are resource constraints. There is a finite amount of capital and human resources available to a city for investment in infrastructure projects. Policy decisions which drive investment in cities undergo extreme scrutiny to ensure they are the optimum course of action. This scrutiny is undertaken with the use of models to assess options and estimate outcomes.

3.2.2 Uncertainty associated with prediction: It is not simply the case, however, that the model can assess a variety of policy and investment decisions and select the optimum, since there is an element of prediction involved based on the best assumptions engineers, scientists, economists and planners can make. In every case, there is an degree of uncertainty when working with imperfect data.

Estimates of factors driving the requirement for investment, such as changes in climate patterns, sea levels and extreme weather events delivered by scientific models, struggle to provide the assurance required for large investments. It therefore takes a significant body of historic and predictive evidence to focus decision makers towards an action.

Imperfect information is also present in the estimated benefits arriving following an action. This could be predicted economic benefits, such as increased business continuity, employment or efficiency arising as a direct result of mitigation. In many cases, the benefits associated with a resilient city, capable of thriving through shocks and stresses on its population and infrastructure, will not be directly financial. This understanding is extremely difficult to account for when appraising an investment decision. The lack of certainty associated with the information results in a higher risk being associated with the investment. This perceived higher risk results in the investor's requirement for returns rising before resources can be allocated.

3.2.3 The time value of money: Since investment in infrastructure is often for long term projects, the returns may be realised far into the future. The practice of discounting future costs and revenues results in long term projects being harder to justify than shorter term projects. The UK Government publishes investment guidance in The Green Book, which details how the discount rate or Social Time Preference Rate [12] used for long term investments is calculated. Long term projects are typically assigned lower discount rates; however, the practice of discounting the savings made through investment in long term resilience initiatives can act as a barrier if the selected rate is too high.

4 The role of models in understanding and improving the resilience of cities?

The primary role of a model is to communicate evidence-based outputs which act as a framework when making a decision. In all cases, the use of models relies upon understanding the factors influencing current and future demands on resources associated with the project, and to present this understanding in the form of comparable terms (typically financial). Some factors, such as the cost of energy for a new piece of infrastructure, will be conveniently quantifiable in the short-term; however additional layers of complexity arise from associated assumptions such as the carbon intensity of that energy. Outputs are based on multiple interdependent assumptions which can lead to models being extremely complex in their structure and content. Decisions made using modelling should be taken with knowledge of the interdependencies and sensitivities associated with the assumptions.

Models represent an important tool for decision makers, investors and stakeholders. The following examples illustrate some of the roles of models in improving the resilience of cities.

4.1 Models assisting policy decisions: The 2050 Pathways Calculator

When faced with numerous choices to be made when addressing shocks and stresses, each with difficult to predict and complex outcomes, models can help simplify issues to assist policy makers through visualisation. Tools, such as DECC's 2050 Pathways Calculator [13], are examples of a model simplifying a complex problem to allow users to understand the impact and sensitivities in the UK's energy mix.

The Pathways Calculator is a model which allows a user to test the impact of various options to decarbonise the UK's energy supply and reduce the demand for energy. The calculator shows the potential impacts actions will have on decarbonising the UK's energy supply, relative to the UK government's target to reduce carbon emissions by 80% by 2050, relative to 1990 levels. To reach this target, policy makers will have to select mechanisms favouring actions

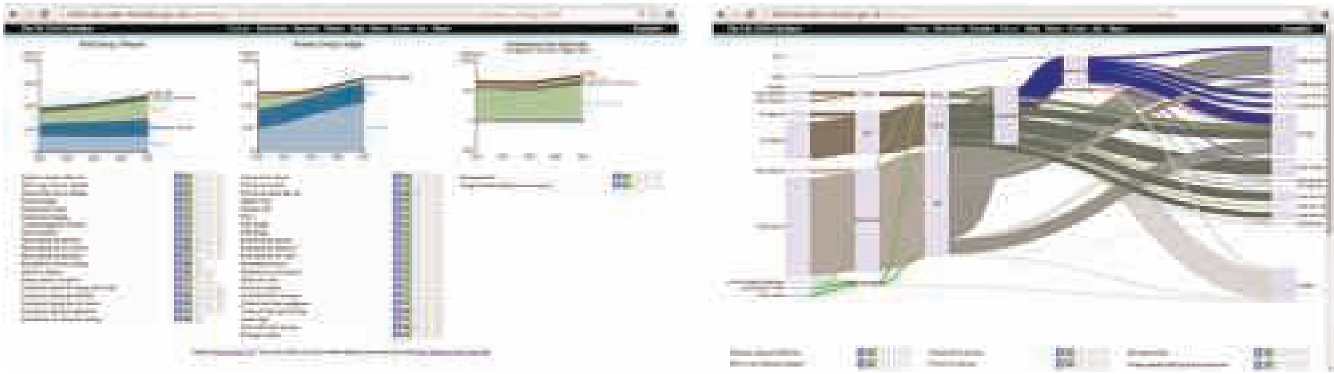

Figure 3 *Screenshots from DECC's 2050 Pathways Calculator Models courtesy of Department of Energy and Climate Change [13]*

which may have interdependent impacts on various areas of energy use such as transport, heating and electricity generation.

The calculator allows a simplified assessment of the impacts of various actions, taking into account some of the complex interdependencies, which have been modelled by engineers, scientists and economists. A clearer understanding of the impacts and level of action required in order to meet the targets provides more clarity in the debate between policy makers when selecting options for support.

This simplification requires significant technical rigour in the underlying technical assumptions, but allows non-technical users to test actions and show their contribution towards the goal of meeting the decarbonisation target. The model estimates how uptake in technology choices impacts the flows of energy on the scale of an entire economy and carbon emissions arising. The outputs from the calculator are presented in graphical format for ease of communication, see Figure 3.

The outputs from the model are not intended to be individually precise, but instead provide a robust measure of the relative impacts of options open to policy makers. These models are constrained by our ability to define the possible future scenarios, portray the complex world around us, and forecast the sensitive interdependencies in order to assess resilience.

Following the implementation of this approach in the UK, similar calculators have been developed in China, India, Belgium, South Korea, and Taiwan, with another 14 countries planning to develop similar models. A global calculator project is currently under development, increasing the scale of the decisions to the global system [14].

The logical next step for a model of this nature would be to include other socioeconomic indicators that are driven by the decisions made by the user. To be successful, large scale resilience projects cannot just focus on climate resilience, but must try to take account of the full spectrum of social, technical and environmental challenges. Models of this type can be used to tackle issues beyond the decarbonisation of the energy sector, such as levels of energy security and affordability to users. In order to attempt to facilitate decision making when faced with these interdependencies, approaches taken in models such as the 2050 Pathways Calculator show an example of a model simplifying and facilitating policy debate.

4.2 Models optimising investment decisions: Techno-economic modelling

City systems are interconnected in complex ways. What makes a city 'resilient' is not easy to define and often not understood until after a shock event occurs. It is however, widely recognised that in order to improve the resilience of cities and to mitigate the negative impacts of cities on the environment, continued investment for improvement and adaptation is required in a city's supporting infrastructure. Investment in infrastructure is often extremely large in scale. In the UK alone, current spending plans by HM Treasury indicates that over £100 billion of capital will be invested in specific projects between 2015-2019 [15].

Models are commonly produced for specific decision making processes in infrastructure investment to allow investors, planners and engineers to assess and optimise the project before committing substantial resources. Models play an important role in understanding the implications of decisions and optimising the performance of projects and large investment decisions are rarely made without a detailed model of the operation of the project over its lifetime. The purpose of these project models includes the following:

1. Determine the boundaries for the project. By modelling the technical and commercial operation of a large scale infrastructure project, the limiting boundaries of the system can be established. In the case of renewable power generation, this could be the energy output of the system, thus informing the optimum technical design of the solution.

2. Identify factors to which the performance of the project is highly sensitive. Issues such as fluctuation in energy prices or labour costs can be significantly detrimental to the performance of a project. By modelling these fluctuations, risks can be identified and measured so that a fully informed investment decision can be made.

3. Act as a focal point for negotiations. Large scale engineering projects which aim to improve the resilience of cities will undoubtedly have multiple stakeholders, contractors and operating parties. A shared project model can act as a focal point for negotiations between these parties to ensure that each is fully aware of the technical and commercial operation of the project. Following the decision to undertake a project, the project model will stand as a record of the agreed principles.

Resilience projects will require a sound economic case in order to receive sufficient investment. The decision process applied to project investment is also applied to resilience projects. There are four main elements in the decision making process:

A. **Cost of taking action today** to mitigate impact of shock. The best estimate for undertaking a risk mitigation action today. This should be adjusted for optimism bias and project risks.

B. **Future cost of impact** if the shock occurs and action had never been taken. An accurate estimate of the impact of an unexpected shock event occurring is by nature extremely difficult to calculate. It will have three components: Firstly, direct costs associated with the repair to the system. In the example of a power cut to a city, this would be the cost of repairing the electrical network. Secondly, the indirect costs associated with the power outage, made up of the shortfall in economic activity due to the power outage. Finally, the other, less tangible impacts such as an increase in crime over the period when power was out, or increased health risks from delayed medical care. These costs are extremely difficult to quantify due to the interdependencies of systems within cities.

C. **Likelihood of shock occurring**. Every shock or stress facing a city will have an associated probability of occurrence within a given timeframe.

D. **Discounting factor** to account for the time value of money: The practice of discounting future cost and savings is based on the time value of money, such that money is valued higher in the present day than in the future. The rate at which money is discounted in the future is dependent several factors including the perceived risk, length of investment and required return. The UK Government publishes guidelines for calculating the discount rate in The Green Book, [11] based on estimates for risk and anticipated performance of the economy over the investment period. In the UK the rate is recommended to be 3.5% for public sector projects. Private investors are likely to require higher discount rates.

The decision to invest in a resilience project should proceed when the condition shown in equation (1) is met:

$$\text{If} \qquad A < (B \times C)D \tag{1}$$

The investment in the resilience project will be deemed to have an economic case to proceed if the cost of taking the action today is less than the impact if no action is taken, factored by the likelihood of the action and discounted over the period of investment. If this condition cannot be met, then the prudent economic action would be to insure against the shock occurring.

Models have a role in this economic appraisal to derive the values of A, B, C and D in equation (1). Cost models are developed to determine the likely cost of a project (A), a variety of technical and macroeconomic models attempt to determine the impact of shocks and stresses to a city (B) and statistical models are developed to determine the likelihood of the occurrence of a shock or a stress (C).

The use of the discount rate applied to the appraisal (D) has a significant impact on the decision making process, since it effectively penalises projects addressing risks in the longer term. This approach has been undertaken commonly on projects to maximise the economic returns to society. However, since resilience issues can be addressing risks over a very long timeframe to address uncertain outcomes, discounting of this kind of investment should be treated with caution.

To create models for high level decisions, a body of evidence and experience is needed to deliver confidence in the underlying assumptions. The ability of models to effectively express messages to decision makers can be inhibited by complexity where there is imperfect data. In the context of resilience, the unknowns are in the form of the interdependencies between infrastructure sectors. A city's healthcare sector will be intrinsically linked to its transport sector and energy supply, however understanding these interfaces in enough detail to identify weaknesses that become dangerous when under shock or stress conditions is a significant challenge for engineers.

4.3 Communication of complex issues and collaboration: The London Heatmap

Any large scale project is likely to require an interdisciplinary approach across private and public partners. In the case of a project looking to improve the resilience of a city, this will include planners, engineers, investors, contractors, politicians, the public and more. Coordinating the endeavour is a substantial challenge, but one which can be assisted through the use of a model to assist with conveying the concepts and communicating with the various parties

Figure 4 *Screenshots of The London Heatmap, reproduced courtesy of The Mayor of London and London Heatmap [16]*

involved. An example of such a model is the London Heatmap [16].

The Mayor of London established a target for the city to deliver 25% of the city's energy through decentralised means by 2025. Decentralised energy relates to the production of useful heat and power distributed throughout the city, as opposed to large-scale generation in power stations connected to the city by long transmission lines. This policy was adopted with the aim of delivering additional, smaller electrical and heat generation throughout the city at the point of consumption, and to connect users to heat networks.

Heat networks distribute hot water to domestic and commercial properties from distributed energy centres where the heat is generated. The technology has been developed to offset the use of the piped natural gas infrastructure in high density areas. It offers a decarbonisation option for the generation of heat through the use of larger, more efficient technologies such as cogeneration and heat recovery from industrial energy sources.

Heat networks have been used as an approach to heating the built environment for many decades; however the UK is only recently driving the expansion of the technology through local energy policies. The existence of the London Heatmap allows greater collaborative work to be done across the industry. The site is used by city planners, developers, engineers, economists and the wider public during the development of projects. The collaborative approach with wider market knowledge over the existence and planned expansion of networks ensures that development and policy risks are reduced, facilitating the organic growth of infrastructure across the city.

The model shows the density of gas use in the city for heating and the location of existing and planned heat networks (as shown in Figure 4), and is used to monitor and identify opportunities for the delivery of decentralised energy projects.

An opportunity in this context is an area where there is a means of generation and consumption closely located, which could connect under a supply and consumption agreement. In London, this is most commonly using cogeneration technology. The use of cogeneration, or combined heat and power (CHP) plant offers a lower carbon solution when compared to gas boilers and electrical grid connections, since the heat from generating electricity is captured and put to use. The London Heatmap presents the location of CHP plants and areas of high density energy demand. This information is used to inform the energy strategy adopted for new developments in the city which could harness a nearby

Figure 5 *Screenshots of The San Francisco Energy Map, reproduced courtesy of San Francisco Department of the Environment and CH2M HILL [16]*

opportunity, and can identify areas for existing producers and consumers to connect for mutual benefit. The model allows users to identify points of generation and consumption, measure distances for connection and is a focal reference point for the industry. Since its establishment in 2007 the site has grown in use and now attracts over 100 visitors each day [17]. The London Heat Map is administered and maintained by the Greater London Authority which updates data regarding the fuel usage in the city and the extent of the network infrastructure. The London Heatmap has therefore become an on-going and open source record of the city's infrastructure.

The spatial mapping of large datasets to assist in the development of resilient infrastructure is an increasingly popular approach. The city of San Francisco has adopted similar mapping techniques, focussing on the delivery of solar and wind powered energy infrastructure (see Figure 5). San Francisco uses a GIS model to map sites across the city and provide a collaborative resource hub for stakeholders [18].

The same concept is being adopted on a national scale, including models detailing renewable energy resources existing in the UK [19], heat demand in the UK [20], and wind resource availability in the USA [21].

5 Future trends in modelling

Models offer a critical tool in planning for and delivering the improved resilience of cities. In order to increase their capacity to support cases for worthwhile endeavours and quickly discard projects which do not represent the best use of resources. There are areas in which attention should be directed.

5.1 Availability, completeness and robustness of open source data

The value associated with the results of a modelling exercise will be directly linked to the underlying data and assumptions used by the model. The availability of measured data for use in analysis greatly improves the confidence in the findings. When making potentially large investments, robust data should be sought wherever possible.

Trends in technology have increased the ease with which data can be collected and analysed by the order of a step change in recent years. Availability of 'Big Data', data sets that are too large and complex to manipulate or interrogate with standard methods or tools, presents an opportunity to answer questions regarding system interdependencies through statistical techniques. When collecting information, care should however be taken to ensure that issues with confidentiality and privacy are not compromised.

5.2 Transparency and Consistency

When undertaking the modelling of complex systems, problems are solved and issues addressed on a case by case basis. While good practice is communicated in academia and industry, there exist no standards for modelling techniques. Various computer packages exist to allow modelling, each with benefits and specific targeted uses. When presenting findings for consultation and discussion, the more transparency and consistency that can be demonstrated, the stronger the case for the findings will be. It is recognised that there will not be a one-size-fits-all approach to many complex modelling applications, however for discussion and audit processes which follow the process, transparency and consistency are key.

5.3 Collaboration on similar problems

The challenges faced by cities when addressing resilience are often shared by cities around the world. In many cases, cities considering taking action towards resilience can look to other cities worldwide that may have undertaken the same action. Through collaboration and the sharing of knowledge, cities can transfer learning, share designs and improve on the imperfect data that hamper the assessment and delivery of resilience actions. Examples of this collaboration can be found through existing city networks such as the 100RC and C40. The C40 is a network of cities committed to combatting climate change through action at a municipal level. Their approach to the collection and sharing of information and data is illustrated through their work including the recent Climate Action in Megacities report [22]. The report presents a summary of the 8,068 actions being taken by 63 of the world's largest cities. Knowledge sharing on this scale can increase the combined learning effect and give confidence in the models for improving the resilience of cities in the future.

6 Conclusions

Models play a vital role in unlocking decisions for the development of a city's resilience by clarifying the impact of decisions and allowing decision makers to ask "What if?". Used at various stages in the decision making process to design and test options for delivery, the application of modelling can help policy makers make informed choices, investment opportunities can be tested and optimised, and the delivery of infrastructure can be facilitated through collaboration.

The tools used for assessing options for a resilience project, such as delivering low carbon energy infrastructure, or upgrading a city's defences to natural shocks, should be appropriate to the level of detail required. Policy makers use models to understand the interdependencies of a city's infrastructure and the likely impacts of an action, as demonstrated by DECC's 2050 pathways calculator. Investment decisions are made utilising models to understand the sensitivities, risks and economics behind a project to satisfy the allocation of resources, as demonstrated by project models. Collaborative models such as the London Heatmap allow stakeholders to work together to achieve a desired outcome, by providing a focal point for the multi-disciplinary input to the project.

Modelling is an essential part of the selection and optimisation of projects and can help ensure resources are best allocated to serve a city's long term needs. The process of converting decision-influencing factors into evidence-based decisions is the primary goal of models used by engineers, planners and economists, and enables the delivery of the best outcome for the city.

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The resilient city and the role of cyber-physical systems

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Abstract: Cities face a number of serious challenges that affect their competitiveness, sustainability and increasingly their occupants' safety and security. In response to these challenges, investment is made in complex city infrastructure projects. Given the complexity of the systems architecture, and interactions between physical and cyber domains, the paper shows how a truly multi-disciplinary approach can be adopted to address the challenges. It introduces an analysis methodology for use by these multi-disciplinary teams to allow the dependencies and interactions of cyber–physical systems to be explored. The methodology is demonstrated using the disparate CCTV systems in a UK city. The analysis methodology offers a systematic way to study the cyber–physical systems and to identify any safety, security or resilience issues that need to be addressed in the design or operation of the systems.

Keywords: Smart cities, cyber–physical systems, resilience, cyber security, trustworthy software, critical infrastructure

1 Introduction

Cities are facing a number of serious challenges that affect their competitiveness, sustainability and increasingly their occupants' safety and security. Challenges arise from a variety of sources including the complexity of the engineering infrastructure supporting the city; the need to manage energy and water use; the impact that severe weather events or natural disasters can have on densely packed urban areas, and protection against terrorism and domestic extremism. We see increased use of information and communications technologies to connect and manage the complex cyber–physical systems that support, sustain and protect the city. These systems include those delivering energy (electricity, oil and gas), managing water (including fresh water distribution, wastewater, sewerage, and flood alleviation), providing transportation and logistics services, producing food, supporting the removal, recycling or disposal of domestic and business waste, and providing security. This use of information technology, described as a hyper-connected world by the World Economic Forum [1], creates additional vulnerabilities affecting the availability, safety, security, reliability and resilience of these complex systems or indeed systems-of-systems.

Future cities are being talked about as 'smart cities', where complex interactions between cyber–physical systems aim to improve the quality of life of citizens and to proactively manage demand for scarce or costly resources. Current projections indicate that 60% of the world's population will be urbanised by 2030 [2]. The increasing population numbers and a rising demand for energy and water by urban dwellers will require innovations in the operation of these utilities. For example, the smart grid is seen as an opportunity to encourage individuals to make choices about how and when they consume electricity. However, this creates a complex demand management situation, which will require finer-grained dynamic control over power generation and storage assets than is currently the case, so as to maintain grid and voltage stability. Large crowds and congested public spaces present attractive targets for criminals, terrorists and the need to manage public safety. The increases in city populations will therefore place significant demands on city managers responsible for traffic control, maintaining law and order, and managing major public events.

The increasing use of technology is not without risk, particularly with regard to the resilience and cyber security of critical city infrastructure. Future cities will evolve into sophisticated platforms or systems-of-systems-of-systems with complex matrix style interconnectivity resulting in a greater degree of automation and system autonomy. Humans will no longer be in the loop, and relegated to the role of supervisor or maintainer, with a new breed of ‘Cyber Janitor’ being developed. The complexity of these interacting systems will challenge existing safety and security engineering models, as new complex or cascading failure modes arise out of unforeseen or emergent system characteristics.

This enhanced interconnectivity, which enables sophisticated man-to-machine and machine-to-machine interactions, will necessitate new approaches to both systems engineering and information security. Cyber–physical systems need to be designed and built to achieve high levels of resilience, so they will continue to operate under adverse conditions. Where this is not possible they require a design that allows them to degrade in a controlled manner and to be readily restored to full operating conditions once the adverse situation is resolved.

This paper examines some challenges to be addressed if we are to understand and manage the potential future impacts of these developments. It starts by considering some of the issues that affect the engineering of the future city, and then examines the nature of cyber–physical systems and their evolution of the city as a platform. To understand the requirements affecting the future city, this paper considers a city from three perspectives: the context of its data and systems, understanding resilience and an approach to deriving its cyber security needs. These perspectives form the basis of a comprehensive analysis methodology under development by the authors.

2 Engineering the future city

Cities evolve over time and depending on their structure and geography they create different challenges in maintaining their competitiveness and sustainability. This evolution can result in complex management arrangements, particularly where significant redevelopment has occurred, e.g. the changes to former dockland areas in UK cities (London, Salford, Liverpool, Cardiff, etc.). These redevelopments often create sizable areas that are under the day-to-day management and control of private sector operators rather than the local city council. Creating future cities will present significant technical and economic challenges for both developed and developing nations.

The World Health Organisation anticipates that almost all population growth in cities over the next 30 years will occur in developing countries [3]. It estimates that by the middle of the 21st century, the urban population of developing counties will more than double. This growth will result in the expansion of existing cities and development of new ones. Areas where these cities will develop are often on coastal plains, putting them at greater risk from severe weather events, coastal erosion and changes in sea levels [4].

Developing countries may face difficult choices regarding the installation of smart infrastructure, in particular regarding how much spare capacity may be built in for future expansion or growth versus the cost of acquiring the capacity in advance of the demand. Choice of technology may also be a significant factor; some of the solutions currently on offer have yet to be tested in complex live settings. In the developed world a significant challenge will be the maintenance and continued development of historic cities. These cities developed over a number of centuries, their layout may be sub-optimal, thus constraining land use. Their existing infrastructure often lacks capacity or is reaching the end of its economic life, for example the crumbling Victorian sewers in London designed for a population of 4 million against a current city population that is approximately double that [5, 6].

For the developed countries, decisions will be required on the extent to which existing infrastructure is suitable for upgrading to become part of a smart infrastructure. For example, in the UK there is a major programme to roll out smart meters [7]. The new meters are installed as direct replacements for existing meters, with a new telecommunications infrastructure deployed to handle interactions between the meters and power network data centres [8]. However, the full benefits of this new cyber–physical system are unlikely to be realised without significant enhancements to improve network resilience of the existing power distribution network, thus allowing reliable dynamic control [9].

Regardless of the location, a critical factor affecting benefits delivered by investment in city infrastructure is the engineering quality of implemented cyber–physical systems. The proposed hyper-connectivity will require a new rigour, to ensure that the delivered solutions are safe, secure and resilient. Inter-connected systems can create new failure modes and cascading failures. This was demonstrated in the United States on 14 August 2003, when at least 50 million people lost power and discovered the myriad of necessities that electricity provides in the modern world [10]. This event was triggered by a failed power line in Ohio, which in turn set off a cascade of events resulting in the largest blackout in North American history. It crippled much of the north-eastern United States for two days. Had this event occurred during a severe winter freeze it could have caused a significant loss of life.

Following this blackout, studies show that in interdependent networks a very small failure in one network may lead to catastrophic consequences [11]. The study found that randomly structured networks, e.g. social networks, degrade slowly as nodes are removed or cease to operate. In real world situations this might mean there is time to diagnose and address a problem before a system collapses. By contrast, cyber–physical systems typically have more critical nodes, which will increase the instability and contribution to significant cascade failures and effects.

3 Cyber–physical systems and the city as a platform

There are a number of definitions of cyber–physical systems [12, 13, 14, 15]. Features they have in common effectively describe control systems, which may be networked or distributed (i.e. employ a networking and/or communications capability), incorporate a degree of intelligence (either being adaptive or predictive), and work in real time to influence outcomes in the real world. These definitions also point to the very diverse nature of cyber–physical systems, which will be found in transportation, utilities, buildings, infrastructure, manufacturing, health care and other business sectors.

Although cyber–physical systems have many similarities with traditional data processing systems, for example, their networked or distributed nature and a degree of automation, it is the real-time nature of their interactions with the physical world which is a significant difference. The interactions with the physical world are made by using sensors to detect and measure physical parameters, and actuators to control physical processes. Control functions of cyber–physical systems involve feedback loops, allowing data about their environment and physical processes to be collected and computed. Depending upon the degree of autonomy, decisions may be made automatically as to whether to change the state of an actuator or to alert a human operator.

Critical infrastructure systems are predominantly cyber–physical systems, whose design generally includes safety critical functions. Their failure would have significant economic or social impact. Society expects these systems will operate in a safe, secure and consistent manner [16]. This becomes increasingly important with the growth of mega cities and increasing population densities in existing cities. In response to environmental, demographic and societal pressures, cities can no longer conduct business as usual. Traditional city models developed during and since the Industrial Revolution are no longer appropriate, the transport and utility infrastructures are becoming unsustainable and require major investment [17]. Active traffic management is already being used on UK motorways (e.g. parts of the M1, M4, M25 and M42), supported by the use of overhead variable speed displays, traffic speed sensors and an increased density of traffic cameras. This type of IT-based technology may be used in cities to manage and maintain traffic flows during periods of peak congestion.

Expectations of the populace are encouraging city leaders to improve their city infrastructures. In response, some cities are embracing the concept of the 'city as a platform'; this is a hyper-connected urban environment that harnesses the network effects, openness, and agility of the real-time web [18]. To date, the focus of most activity regarding the 'city as a platform' has been on access to data, leading to development of smartphone apps and portals to allow citizens to 'connect' with city services and its institutions [19, 20].

These developments are not without serious privacy and civil liberty concerns. If the city services are accessed via a smartphone, the user may be located or tracked using either GPS or other location tracking functionality on the device. Even if this functionality is disabled, anonymity is difficult to assure when the user accesses the Internet via Wi-Fi or can be tracked due to the set-up of their browser [21]. Recent events may hinder the take up of the data services, for example, the 'Heartbleed' bug, which affected a version of the OpenSSL [22] and had an impact on individuals' security and privacy.

Operating as an integrated platform, the future city will be a complex system. To understand both resilience and cyber security requirements for the city, we need to understand the proliferation of functions in this hyper-connected world [23]. Where functions in individual cyber–physical systems interact, they will often create new functions, and these will proliferate over time. To protect these complex systems we need to understand their network of functions, relationships and interdependencies. A study of critical

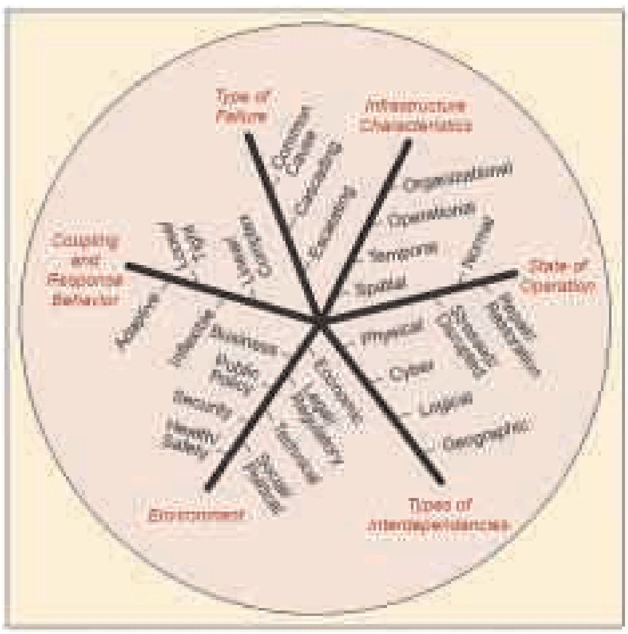

Figure 1 *Dimensions describing interdependencies*

infrastructure independencies [24] led to the identification of six dimensions, shown in Figure 1, which can be used to examine cyber–physical systems and the infrastructures that support them.

Understanding the interdependencies between city systems and infrastructure is important to deliver resilience, and cyber security in a future city. This requires a broader understanding of the operation of the 'city as a platform'

4 Future cities analysis framework

To achieve a broader understanding, we propose an analysis framework, which examines the critical city infrastructure, illustrated in Figure 2, to explore the future city and its infrastructure from three perspectives: context, resilience, and cyber security. The analysis framework is used to focus on critical city infrastructure and related services.

From a city perspective the concept of critical infrastructure is not well defined. In the UK, the critical national infrastructure (CNI) is defined as: "those facilities, systems, sites and networks necessary for the functioning of the country and the delivery of the essential services upon which daily life in the UK depends" [25]. The UK Government determines criticality based on a Criticality Scale [26], which ranges from Category 5 – "This is infrastructure the loss of which would have a catastrophic impact on the UK", to Category 0 – "Infrastructure the impact of the loss of which would be minor (on a national scale)".

These definitions could be adapted for a city, to encompass the elements necessary for the delivery of essential services to the populace who are resident and/or work in the city and focusing criticality at the city rather than national level. The critical infrastructure needs to address both the city's normal operating state, and its ability to effectively respond to natural or other disasters [27]. The definition of a city's critical infrastructure is based on four factors:

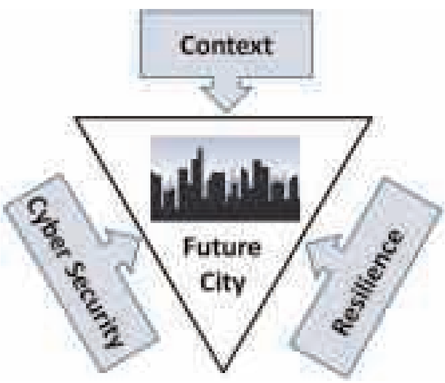

Figure 2 *Analysis framework for secure and resilient future cities*

- the impact on delivery of essential societal functions and services, e.g. to provide water, food and shelter, and to maintain law and order;
- the economic impact on the well-being and viability of the city, e.g. the ability to operate as a business and financial centre and provide employment;
- the impact on life, health and well-being of city occupants, e.g. to provide medical and social services to protect and care for citizens;
- the ability to respond to major incidents or disasters, e.g. to provide emergency services including sites to manage emergency operations and to provide housing in the event of a disaster.

At a city level the definition of critical infrastructure has been extended to include education and leisure facilities as these can have a critical role in emergencies. For example, in Hurricane Katrina the New Orleans Superbowl was used as an emergency relief centre. Large open spaces, such as parks or sports fields can also be used as locations for temporary accommodation or to provide alternative sites for managing disaster operations in the event of a natural disaster [27].

4.1 Understanding the context

A smart environment must be able to both detect the current state and context of the environment and determine what actions to take based on the available data and information [28]. To establish the resilience and cyber security requirements for a future city's cyber–physical systems, the seven dimensions of cyber [29] need to be analysed and the context under which they are operating understood.

1. **Human** – The human dimension of a future city needs to be understood, both from the aspect of how people are impacted and influenced by the city platform, to how people impact and influence the design and evolving nature of the city platform. How do people individually and collectively interact with the city data and systems? What are the implications of these interactions and any interfaces used to interact with the city data or systems? Are there any ergonomic or usability issues regarding these interactions? Who will need access to the city data and systems? What access controls will be required (e.g. can an individual create, read, update or delete the data, and what level of control does an individual have)?

2. **Awareness & Understanding** – What level of awareness and understanding is required by individuals who are associated with the creation, use and maintenance of city data throughout its lifecycle? What level of awareness and understanding is required by individuals who have access to control functionality of city systems? How does this

Table 1 Components of critical city infrastructure

Critical City Infrastructure	Part of the CNI
Communications	Yes
Education (Schools, Colleges, Universities)	No
Emergency Services	Yes
Energy (Electricity, Gas, Oil/Petroleum products)	Yes
Financial Services	Yes
Food	Yes
Government (City administration)	Yes + National government
Health	Yes
Leisure (Parks, Sports Facilities)	No
Transport (Road, Rail, Air, Waterborne)	Yes
Water	Yes

awareness and understanding vary by individual, role and stakeholder group?

3. **Information and Data** – What information and data, especially sensor data, do the city cyber–physical systems require to function? How is this encoded? How and where is it stored? What would the consequences be if the data were lost and therefore no longer available? Who owns the data? How is it made available and what restrictions are there on its use?

4. **Electromagnetic Spectrum** – What channels, technologies and parts of the overall spectrum, including electro-magnetic spectrum, are used to communicate and share city data between city systems and with any users who need to access or use it? What channels, technologies and parts of the electro-magnetic spectrum are used to control and integrate city systems? To what extent are the communications confined to the city or will remote access be required?

5. **Systems** – What are the totality of city systems that are involved in the creation, use, maintenance, storage and transmission of city data? To what extent are these systems dedicated to a specific city? Are the city systems shared by different activities? Are the systems accessible by any third parties, either within or outside the city? What are the typical operating lives of the city's systems? For any existing city systems, how long before they become unsupportable, obsolete or need to be replaced for business and/or operational reasons?

6. **Infrastructure** – What physical and electronic infrastructure is used to create, access, process and store city data, including any communications and networking components? To what extent is this infrastructure dedicated to city systems, or is it shared with different activities and/or with third parties? What dependencies does the infrastructure have on other critical services or infrastructure? Are there any critical supplies required to ensure the ongoing operation of city systems and any processes or services they support?

7. **Environment** – What are the Smart City environmental factors that need to be taken into account? The Societal, Technological, Economic, Environmental, Political, Legal, Ethical and Demographic (STEEPLED) considerations associated with the creation, use, management and exploitation of city data? What are the STEEPLED considerations associated with the design and operation of city systems? Is the city data processed, stored and used within a single jurisdiction or are multi-national jurisdictions involved?

4.2 Resilience of a city's cyber–physical systems

Work by the Rockefeller Foundation and Arup has led to the development of the City Resilience Framework [30], which provides a lens through which the complexity of cities and factors that contribute to a city's resilience can be examined. The Framework defines a resilient system as having seven qualities:

- Reflective – is accepting of the inherent and ever-increasing uncertainty and change, and designed with mechanisms to enable continuous evolution;

- Robust – can withstand impacts of hazard events without significant damage or loss of functionality;

- Redundant – availability of spare capacity and/or alternative ways to accommodate disruption, extreme pressures or surges in demand;

Table 2 Relationship between categories, key indicators and system qualities

Category	Key Indicator	Reflective	Robust	Redundant	Flexible	Resourceful	Inclusive	Integrated
People	Minimal human vulnerability		■			■	■	
	Diverse likelihoods and employment			■	■		■	
	Adequate safeguards to human life and health	■					■	
Organisation	Collective identity & mutual support						■	■
	Social stability and security					■	■	■
	Availability of financial resources and contingency funds			■		■		
Place	Reduced physical exposure & vulnerability		■	■	■			
	Continuity of critical services	■	■	■	■	■	■	■
	Reliable communications & mobility	■		■	■	■	■	■
Knowledge	Effective leadership and management	■			■			■
	Empowered stakeholders	■			■		■	
	Integrated development planning	■				■	■	

• Flexible – system can change, evolve and adapt in response to changing circumstances;

• Resourceful – a city's ability to restore functionality of a critical system, potentially under severely constrained conditions;

• Inclusive – addressing shocks and stresses at a city level and preventing isolation of vulnerable groups;

• Integrated – specifically integration and alignment between city systems enabling them to function collectively and respond rapidly though shorter feedback loops.

In developing the Framework, the research identified twelve key indicators, which are grouped into four categories and relate to system qualities as illustrated in Table 2 [30]. The twelve key indicators affect the city as follows:

1. Minimal human vulnerability – the need to maintain a basic level of provision of food, water, sanitation, energy and shelter;

2. Diverse likelihoods and employment – the need for a broad range of skills, trades and professions allowing the city to operate as a social and economic centre;

3. Adequate safeguards to human life and health – a need for effective health systems to prevent illness and spread of diseases, and to provide emergency healthcare;

4. Collective identity and mutual support – active community engagement, strong social networks and social integration;

5. Social stability and security – effective law enforcement, crime prevention, justice and emergency management;

6. Availability of financial resources and contingency funds – robust economic system, capable of creating, sustaining and investing in appropriate city infrastructure;

7. Reduced physical exposure and vulnerability – environmental policy, land use planning, building standards, protecting critical infrastructure;

8. Continuity of critical services – environmental management, flood risk management, maintaining critical infrastructure and continuity planning;

9. Reliable communications and mobility – diverse, affordable and available multi-modal transport systems, information and communications technology networks, capacity management and contingency planning;

10. Effective leadership and management – effective business and civic leadership, supported by stakeholder engagement, and emergency planning;

11. Empowered stakeholders – through education, training, research and knowledge transfer enabling people and organisations to take appropriate action in a crisis;

12. Integrated development planning – the presence of a strategic city vision, subject to regular reviews and consultation, providing guidance on city-wide development.

These indicators are important as they provide a holistic view of resilience as it applies to a city. Weaknesses in individual areas can affect the overall resilience of the city. A resilient city is one that has effective city leadership, good infrastructure, social cohesion, collective identify and relative prosperity. This is illustrated in the contrast between the recovery of Port au Prince, Haiti following an earthquake in January 2010 and New York's response to Hurricane Sandy in October 2012 [30]. The latter achieving rapid reinstatement of city systems and services, with civil order maintained throughout.

4.3 Defining cyber security for cyber–physical systems

The future city will be a complex environment comprising a variety of technologies, existing and emerging. The cyber security approach adopted may vary considerably, depending on factors such as asset and systems complexity, ownership and use. It may also be affected by the supply chain supporting design, construction operation and occupation of individual assets or systems. It is thought that applying current information security practice to deliver cyber security of the city as a platform will be extremely complex if not impossible. The fragmented ownership of individual components within the platform, diverse interfaces and constant change will all limit the effectiveness of traditional control measures.

Cyber security of cyber–physical systems is complicated by the real-time nature of the systems and the potential safety critical elements of their functionality. Applying the traditional CIA triad [31], i.e. Confidentiality, Integrity and Availability, which is heavily used by the information security community, does not adequately address the safety and control aspects of cyber–physical systems. An alternative approach that combines engineering good practice with information security may be achieved by adapting the Parkerian Hexad [32] with the addition of safety as a seventh element.

To provide flexibility and accommodate change, this approach is best addressed as a set of cyber security principles or attributes [33], thus allowing appropriate solutions to be adopted, based on the nature of the cyber–physical systems and potential vulnerabilities. These principles are:

- Confidentiality
- Possession and/or Control.
- Integrity.
- Authenticity.
- Availability.
- Utility.
- Safety.

The analysis framework, which is summarised in Figure 3, is intended to be a structured approach to analysing city infrastructure and systems. Due to the interdependencies between city systems and services, it should be applied on a city-wide basis and not simply focused on single systems or services. Whilst the framework is intended to work at an overall systems level, by addressing the interactions and dependencies of the 'city as a platform', it can also be used within systems to understand complex sub-system relationships and behaviour.

With rapid advances in the technology employed in 'smart' cities the use of regular reviews is critical, to monitor changes in systems and infrastructure, and to identify new dependencies and emergent functionality arising from systems integration or interconnectivity.

5 Applying the framework to city infrastructure

With the increasing sophistication and integration of city systems and the need to protect their growing populations

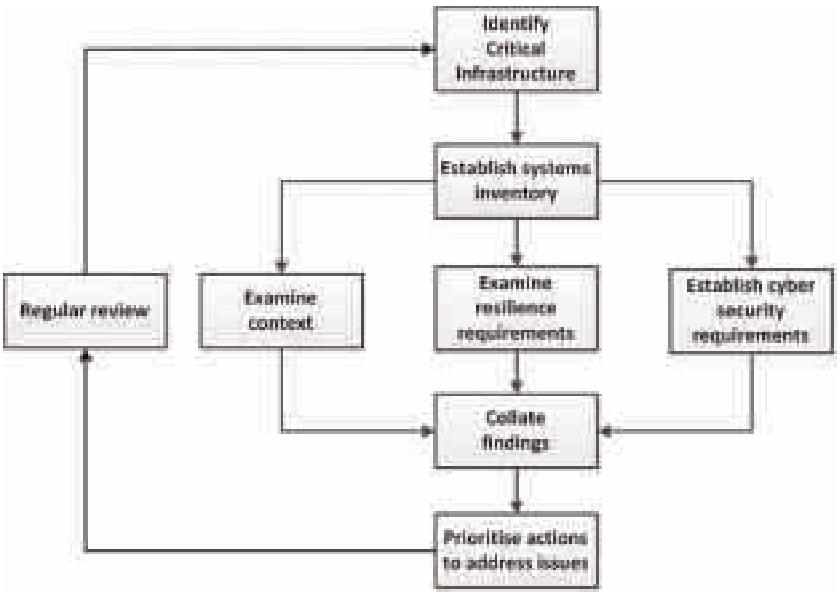

Figure 3 *Applying the analysis framework to a city*

in the event of serious incidents, there is a need for city planners to consider risk, resilience and cyber security in a holistic manner. To illustrate how the framework can be applied to part of a city infrastructure, this paper examines the CCTV systems in a major UK city. The city's CCTV system is a cyber–physical system, comprising a control system, communications and networking systems, cameras that can pan, tilt and zoom, video and audio signal processing and storage, and a video wall for the display of the camera feeds. At present the cameras are all manually operated, but in future the CCTV systems could be upgraded to provide a degree of autonomy for tracking, alerting when movement is detected, and detecting certain types of suspicious behaviour.

In this example, the city is a major commercial and tourist centre that stages a number of well attended major outdoor events each year. In the past terrorist-related bomb scares have required evacuation of parts of the city centre, and an incident involving serious public unrest caused damage to a number of commercial properties. The city centre comprises a number of distinct areas as illustrated in the schematic at Figure 4. For this analysis, five specific areas are highlighted:

- A civic area, which comprises city council and related offices. Within a building in this area there is a control room (1) for the CCTV systems controlled by the city council. The control room is manned 24×7 and also provides some call handling services on behalf of the council. The control room can communicate with the local police using a police radio set and periodically receives email from the police with photographs of individuals, e.g. where a court has ordered they should not enter a specific area in the city centre. The council control room is designed and operated as a secure area, with some physical hardening, but the building itself is adjacent to the highway and is potentially vulnerable to a hostile vehicle attack.

- A mixed use area, comprising bars and restaurants, tourist features, flats, some prestige office space and two car parks. The area includes some public open spaces which are used for major events. It is a privately managed area and has a control room (2) which operates the CCTV within this area. There are no council operated cameras inside the area, but the council has some distant coverage of the area's water frontage. The control room is located in an unprotected building and vehicles are regularly parked close to it. It is vulnerable to both vehicle and pedestrian attacks.

- A retail area, which is largely pedestrianized and is privately owned and operated. Within a site's small management suite there is a control room (3) which manages the CCTV within the area as a service for the retailers. There are no council operated cameras inside the area, but there is limited coverage of entry/egress points.

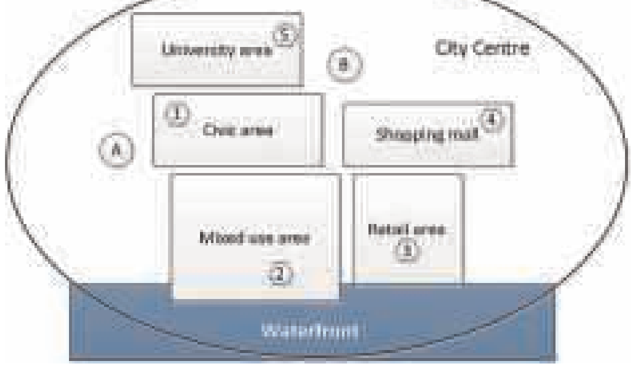

Figure 4 *City centre areas and control rooms*

The management suite is located within the shopping precinct, in a building where there is access control but minimal protection. In the event of a serious incident in the building or nearby the control room would have to be evacuated.

- A large shopping mall with an integral car park. Again a small management suite includes a control room (4) for CCTV cameras located in the mall. There are no council owned cameras inside the mall. Outside the mall, council owned cameras provide some coverage of the car park and pedestrian entrances. The management suite is located in a secure area within the shopping mall. Other than the access control it is not afforded any additional protection. In the event of a serious incident in the shopping mall or nearby the control room would have to be evacuated.

- There is a large university area close to the civic area. This area has some council controlled cameras on main thoroughfares. The university has its own CCTV system and control room (5). This is a standalone facility managed by the university, with no connectivity or direct interaction with the other control rooms.

- Elsewhere within the city centre the local police authority has a control room (A) with access to feeds from council owned cameras and the city highways department has a traffic control room (B), with feeds from some fixed highways cameras and access to feeds from council owned cameras.

There is limited connectivity and integration between control rooms 1 to 4. The council control room (1) can receive live CCTV feeds from control rooms 2, 3 and 4, but it has no direct access to or control over the cameras. If one of these control rooms is busy or disabled, the operators in the council control room may be unable to access these feed or redirect coverage to an area of interest. Similar arrangements exist for sharing of images between the council control room and the police and traffic control rooms. Following a recent upgrade of the CCTV system in the mixed use area it is no longer possible to pass feeds to the city control room due to system incompatibilities.

6 Analysis and discussion

In comparison with rural areas, due to their population densities and often transitory populations, cities can be fragile places, where social stability depends on the smooth operation of a city's infrastructure and services. In dense conurbations, social order can breakdown or violence can flare as a result of unplanned events. A relatively minor incident or grievance may trigger public disorder, which can rapidly spread as grievances are shared via social networks or the media. The smooth and efficient operation of CCTV systems within the city centre will therefore makes a significant contribution to public safety and security.

CCTV systems are generally expected to fulfil three purposes:

- To allow real-time monitoring of public spaces to spot potential problems before they occur

- To provide recorded images as evidence which may be used after an event to determine who, what, where, when and how the event occurred

- To allow control rooms to monitor pedestrian and vehicle flows and activity in public spaces so that in emergencies the responding services can be directed to the required places

The analysis in this section uses the Future City Framework described in section 4 of this document, to examine the efficiency, efficacy and resilience of the CCTV systems described in section 5.

Context: The logical place to start this examination is the city and systems context, which is assessed using the criteria in section 4.1. Considering each of the seven dimensions in turn:

- Human – CCTV systems are widely used in the UK for security and safety monitoring. The public probably thinks there is much greater integration of the systems and might be concerned by the relatively rudimentary systems used to coordinate tracking of suspects or events as they cross area boundaries. There are ergonomic issues in the council control room where CCTV operators are also required to provide call handling services. The current distribution of CCTV operator functions across the city centre control rooms creates inefficiencies and could result in a serious loss of control if an incident simultaneously affects more than one of the areas.

- Awareness and understanding – In the UK all CCTV operators are required to be trained and registered [34, 35]. The current division of responsibility across five separate control rooms could lead to dysfunctional operation during a crisis or major incident. In the city control room the hybrid roles, CCTV operation and call handling, are not complementary

- Information and data – The camera feeds are identified by camera numbers, e.g. Camera 21 within the displayed feed and highlighted on the controller's workstation. This information is of limited utility when the feed is being shared with another control room. The camera feeds are recorded and stored in the control room for the system that camera is connected to, i.e. feed data from cameras controlled by the council are recorded and stored in the council's control room. The requirement is that data should be available for a month, with older data overwritten when no longer required. This may be an issue if any of the control rooms were damaged or destroyed in an incident with the consequential loss of evidential data.

• Spectrum – The CCTV cameras operate over a fixed cabling system. The systems have been deployed over an extended period, so there are a variety of camera models in use, offering different capabilities, resolutions and performance in low light conditions.

• Systems – Different systems are used in each control room and following the upgrade of control room (2) there are now technical incompatibilities that are preventing the sharing of CCTV feeds with the council's control room. There is no common ownership or responsibility for these systems.

• Infrastructure – The current distribution of control rooms is sub-optimal. With the exception of the council control room, the rooms are not hardened and are not resilient or fault tolerant.

• Environment – The UK is current at a heightened state of security alert, with the threat of an attack judged as a strong possibility. Continued vigilance by city and security authorities plays an important part in protecting the public and property, whether from domestic extremists or terrorists. The efficient and effective use of CCTV resources can provide round the clock coverage of vulnerable city areas, thus reducing the threat and preventing economic and social damage.

CCTV systems can provide critical situational awareness for the management and control of public spaces. Based on the contextual information, the current organisation of control rooms is sub-optimal and does not offer a robust or cohesive command and control function to support the city in the event of a major incident affecting one or more of the areas described in section 5.

Resilience: The next aspect to consider is the City Resilience Factors that were described in section 4.2. The seven factors are:

• Reflective – The CCTV system(s) need to be able to accommodate changes in the physical environment, e.g. the opening of new premises which changes the risk profile of part of an area. This may require cameras to be moved or reconfigured to enhance coverage of the area. The system needs to be designed to facilitate such reconfiguration without compromising the system.

• Robust – As the cameras are located away from the control centres, there is a need to consider the robustness of the connectivity between the cameras and the CCTV control system. A plain hub and spoke architecture is vulnerable to damage to the spokes (i.e. the communications and networking connectivity to the camera). The need for diverse routing of cables is particularly important as cables are often damaged during 'streetworks'.

• Redundant – The existing systems showed little or no redundancy. Failure of individual cameras could not be mitigated and there was no redundancy of the control centres. A loss of any of control centres 1 to 4 would have a severe impact on the city's ability to manage major incidents or to control large public events.

• Flexible – The fixed nature of the connectivity to the cameras and the lack of integrated command and control are both limiting factors in the design of the system. The current architecture is relatively inflexible and would be difficult to enhance whilst the city operates a number independent CCTV systems. An integrated design with the ability to control a camera from more than one control centre would offer greater flexibility

• Resourceful – It is unclear whether the city could quickly restore functionality to the overall CCTV system in the event of loss of damage to control rooms of multiple cameras. The technical compatibility issues suggest that there are management process issues between control centre operators as this issue has existed for some time and there did not appear to be a plan to resolve it.

• Inclusive – The CCTV systems are an important tool to allow city managers, law enforcement agencies and the emergency services to manage the city centre in the event of a major incident. The dual use of the city control room would be stressed during such an event and could result in loss of service and support to vulnerable groups.

• Integrated – There is currently minimal technical integration between the CCTV systems discussed in section 5. Operationally there is constant liaison between control rooms to handle day-to-day incident management, but this does not appear to extend to the management of systems issues and incompatibilities.

Cyber Security: The final aspect to consider is the cyber security of the CCTV systems, by examining the seven attributes described in Section 4.3.

• Confidentiality – The data recorded from the CCTV feeds is subject to the provisions of the UK Data Protection Act and UK ICO guidance on operation of CCTV systems [36]. The data is recorded and stored in the individual control rooms, with the organisation that operates the control room performing the legal function of Data Controller. The control rooms are all managed as restricted access areas, so the legal provisions for protection of and access to personally identifiable information are being addressed.

• Possession and/or control – The use of email to communicate between the different organisations operating control rooms suggests that the CCTV systems are potentially vulnerable to malware or phishing attacks from the Internet. The CCTV control systems should have no access to the Internet and the operator workstations should not be used for email or web browsing.

• Integrity – The integrity of the system could be compromised as described above. This risk can be reduced by ensuring that the CCTV systems operate on their own network and that appropriate control systems related security measures are implemented to protect any connections to other systems.

• Authenticity – Provision of appropriate mechanisms to assure the authenticity of recorded, exported and replicated CCTV data are standard features of any CCTV system procured for security and public order purposes. This is essential so that the authenticity of video data can be validated throughout its evidential life.

• Availability – None of the control centres are located in purpose built high-availability accommodation. Given the significance that loss of one or more control rooms could have on managing the city centre in the event of a serious incident, the control rooms should be constructed to a standard similar to high availability data centres, i.e. Tier 3 or Tier 4 performance [37].

• Utility – the utility requirement has already been compromised by the upgrade of systems in control room 2 such that the CCTV feeds are no longer compatible with systems in control room 1. Maintaining utility of CCTV data is of paramount importance if it is to be relied upon for evidential use by law enforcement investigators and prosecutors.

• Safety – The CCTV system fulfil an important public safety function, this will be undermined if control rooms 2, 3 and 4 are not design to achieve a high degree of resilience. Their location in commercial premises is indicative of a build to normal commercial standards rather than the higher standards expected of facilities providing a command and control function. The location of control room 2 is a serious weakness in the management of this area as it could be unintentionally compromised.

Discussion: The above analysis of the city's CCTV systems suggests that they are not fulfilling the three purposes in an efficient, effective or resilient manner, specifically:

• The real-time monitoring of public spaces is potentially hampered by the lack of integration of the systems and the incompatibility between two of the systems.

• The systems can record images for use as evidence, but they may be incomplete due to coverage issues and the recording systems are effectively single points of failure which could be destroyed if an event significantly impacted a control centre location.

• The control rooms do not allow integrated monitoring of the flows and activities in public spaces. There are a number of serious gaps in coverage and there is a significant risk that poor decisions could be made if events cause anomalous flows across boundaries between the areas or if the event occurs on a boundary causing disruption in adjacent areas.

Systems like the CCTV system described in section 5 are barely fit for purpose today and are unlikely to meet the future needs of the city. The development of smart cities or mega cities where there is greater reliance on information and communications technologies represents a significant challenge for city authorities. As standalone systems these technologies are often significantly less reliable than physical assets, whether as a consequence of failures in components that make up these complex systems or due to errors in the design and coding of their software. A city suffering frequent systems outages and/or disruptions, or unable to proactively manage disturbances in crowded places may become a volatile environment.

In the past, resilience studies focused mainly on geophysical issues and on the physical engineering aspects related to the protection of infrastructure from natural events, such as earthquakes, tsunami and extreme weather, or from terrorism related activity. However, the increasing volumes of cyber–physical systems necessitate the development of new techniques to allow the complexity of, and relationships between, these systems to be understood. The situation is further complicated by the emergent nature of many cyber–physical systems, with incremental deployment of enhancements and upgrades onto existing infrastructure. For example the remote control of physical security barriers, or use of programmable signs to provide information and direction to pedestrians and vehicles. Where upgrades involve information and communications technologies, system designers often attach Internet-facing elements to legacy systems or make use of wireless technologies. Both of these developments introduce significant cyber security and resilience vulnerabilities as demonstrated in the US by hackers attacking road signs [38].

The systems architecture of a future city is likely to be constantly evolving, with new components added and existing elements progressively upgraded or replaced. At any instant, the future city is therefore likely to be a complex hybrid of established, proven systems, with known constraints and defects, and newer systems whose behaviour and performance are still being established. It is likely that technical standards will also evolve over time, so systems will be built to differing risk profiles, availability and security standards. The analysis in this section demonstrates the use of the Future City Framework to adopt a holistic approach to analysis and assessment of city systems and their associated processes.

7 Conclusion

The expectation of future cities is that information and communications technologies will be harnessed to deliver a safe, secure and sustainable environment for their rapidly growing populations. This dependence on technology is not without significant risk as the complex cyber–physical systems that are already being developed will increasingly interact with each other. When the systems start to behave as a platform, the city becomes exposed to cascading failure modes, where apparently unrelated events may cause significant disruption or even loss of life.

The analysis framework described in this document provides a structured, systematic way of examining cyber–physical systems, to identify any safety, security or resilience issues that need to be addressed in the design or operation of the systems. Its use has been demonstrated to allow a structured examination of a city's CCTV systems from three perspectives which combine information about environmental, societal, process and technical dependencies and risks. This approach is not intended to replace the technical risk assessment techniques used in systems engineering. Instead it provides an approach which may be used at city level to explore vulnerabilities in the design and use of complex integrated cyber–physical systems.

By using the analysis framework described in this paper, managers can consider the city level risks and vulnerabilities to inform both system planning and design. It should also enable the city authorities and infrastructure owner to make informed decisions about where systems need to be reinforced or re-engineered to improve resilience and reduce cyber security risks.

Without a clear framework such as the one proposed here, it will be difficult to analyse the complex interactions and relationships between cyber–physical systems in a future city. The approach to systems thinking outlined in this paper enables multi-disciplinary teams to adopt a common approach to sharing information about the operation, dependencies and potential vulnerabilities of their systems or infrastructure. Using this consolidated view should enable security and resilience issues to be identified and addressed.

8 Acknowledgements

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Development of innovative detection and expert systems for road tunnel monitoring

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Abstract: In Germany road tunnels on major roads which are longer than 400 m have to be monitored permanently. For that purpose the tunnels are equipped with a multitude of monitoring and detection systems whose data and messages are transmitted to tunnel control centres. Due to the higher traffic density, the increasing number of tunnels to be monitored and road users' demand of higher safety and security levels, the strains on operating staff of tunnel control centres have continuously been growing. Therefore, innovative approaches have been developed in two recent German research projects: RETISS – Real Time Security Management System, and ESIMAS – Real-time Safety Management System for Road Tunnels. Both systems are designed to allow faster and more efficient reaction of tunnel operators in order to maintain the capacity and availability of transport infrastructures but also to improve the safety and security of road users.

Keywords: online, risk analysis, risk assessment, tunnel monitoring, expert system

1 Introduction

A major task of road owners and operators is to ensure the availability of the major transport links since road infrastructure is vitally important for the national economy and mobility. Even minor restrictions or failure of individual elements of the road network can lead to major traffic disturbances, whose consequences are high economic costs and negative effects on the environment. Bridges and tunnels in particular are key elements of the road network. They are highly vulnerable and often have a bottleneck function due to geographical boundary conditions. Severe accidents, e.g. with hazardous goods, terrorist attacks and extreme weather events are the major threats to these key infrastructures.

On German major roads today 108 tunnels longer than 400 m are being operated. They all have to be permanently monitored. Therefore, tunnels are equipped with various monitoring and detection systems providing a multitude of data and messages which are transmitted to tunnel control centres. Due to the higher traffic density, the increasing number of tunnels to be monitored and road users' demand of higher safety and security levels, the strains on operating staff of tunnel control centres have continuously been growing.

To be able to maintain a high safety and security level, road infrastructure owners and operators have to know the current safety/security level of their infrastructure objects at any time. For that purpose current data on traffic density, vehicle types and loads, broken vehicles as well as the number of persons on the site have to be available. Furthermore, information on hazardous goods transports, persons leaving their vehicles or behaving conspicuously and other safety and security relevant information are of interest. Knowing that allows taking preventive measures as well as reacting promptly and correctly in case of event. Hereby, the assessment of the current hazard situation of the respective object or the overall road section is of vital importance. However, so far there have not been suitable tools for fusion and online assessment of single bits of information provided.

2 Development of innovative detection and expert systems for road tunnel monitoring

Therefore, innovative approaches have been developed in two recent German research projects: RETISS and ESIMAS. Both developed systems are designed to allow faster and more efficient reaction of tunnel operators in order to maintain the capacity and availability of transport infrastructures but also to improve the safety and security of road users.

The main objective of the RETISS - Real Time Security Management System was to improve the availability of road transport infrastructures and to protect their users, especially against major accidents or terrorist threats. It was designed to provide real-time information on the current security level of road tunnels and bridges to operating staff in charge and support them to take the most appropriate preventative control measures and, in the case of incidents, the best mitigative measures. While RETISS was a first step towards an automated real-time system for critical road infrastructure, its approach was taken up and further extended by ESIMAS in order to improve its user-friendliness and related aspects of the human-machine interface. Furthermore, ESIMAS was designed to account for a wider complexity of single information and last but not least, to bring the system closer to market implementation.

The innovative approach of the ESIMAS - Real-time Safety Management System for Road Tunnels consists of the holistic consideration of all individual bits of information provided by tunnel monitoring and incident detection systems, their automated real-time evaluation and assessment and the development of an expert system which enables tunnel operating staff to derive appropriate risk and hazard control measures or strategies from a set catalogue with computer support. A decisive difference to RETISS is its focus on safety-related issues (e.g. technical failures, accidents) rather than on security-related ones (which is a matter of the information input and the events considered) while both operate on a common basis and function principle. ESIMAS started end of 2011 and lasts until 2015.

2.1 Objectives

Today, operation and safety management of road tunnels are mainly based on individual data provided by information and detection systems installed in tunnels, which are transmitted to tunnel control centres. During the past few years it has become more and more difficult for tunnel operating staff to evaluate and assess the provided information and to take prompt and appropriate measures.

Therefore, the task is to achieve the fusion, plausibilization, prioritization and real-time risk assessment of all incoming safety or security-relevant data, thus providing the basis for a continuous, online assessment of the situation [1]. The major objectives of the project are:

- Reduction of the strain on operators by a mostly automatized system

- Holistic consideration instead of individual data

- Automatic evaluation and assessment of increasingly dense information (provided by multiple detection systems)

- Data fusion and plausibilization, continuous, real-time assessment of the situation/risk

- Automatically generated recommendations how to proceed/what action to take and integration of innovative measures to cope with events.

2.2 Approach

First of all, software-based approaches for existing and new sensors are examined and further developed with regard to specific problems related to the operation of tunnel/traffic control centres. Hereby, particularly combined approaches, i.e. involving different sensors, in view of improved detection reliability are taken into account. Then, methods concerning the analysis, assessment and correlation of different sensor data provided by available and new detection systems in road tunnels are analyzed. Based hereon, the real-time determination and visualization of the currently prevailing safety or security level is undertaken. From the results obtained recommendations for measures to be taken to reduce the potential risk can be derived and a prototype for the human machine interface is developed. This allows decision support for tunnel operating staff in hazardous situations, taking into account preventive as well as mitigative measures. The developed individual components of both systems are currently tested and validated in existing German tunnels. Finally, general recommendations concerning the application of real-time safety management systems will be formulated and a prototype for a human-machine interface will be developed [2].

2.3 Sensors in road tunnels

The equipment of German road tunnels has been defined in the “Richtlinien für die Ausstattung und den Betrieb von Straßentunneln” (RABT, ed. 2006) [3]. These guidelines stipulate a multitude of different sensors for operation monitoring and control as well as for incident management. All data provided by the installed sensors are available at the tunnel control centre. Since at present the different detection systems are not logically related, a cross-system evaluation and assessment does not take place or to a very limited extent only. The innovative approach within

Figure 1 *Tunnel monitoring and detection systems within ESIMAS [4]*

both RETISS and ESIMAS therefore requires a comprehensive fusion and plausibilization of all data relevant for the safety or security level.

Besides the usual systems in road tunnels like measurement devices for CO_2, visibility, flow and lumination, fire detection cables, video monitoring, inductive loops and height control also non-default detection systems are further developed and tested.

Infrared cameras, for example, allow detecting overheated vehicles or vehicle parts reliably and early in free-flow traffic and thus, can prevent critical events in tunnels. Moreover, a combination of loop and Weigh-in-Motion System (WIM) is applied in ESIMAS, too. It acquires traffic situation, traffic volume and composition as well as the load conditions of trucks and allows their analysis and assessment with regard to safety-relevant events.

However, automatic incident detection by video is currently hardly used. Within the framework of ESIMAS it will be examined how automatic video detection in combination with other detection methods can be used for an early and reliable detection of incidents [5]. Equally the algorithms are to be optimized regarding reduced rates of false alarms due to changing light conditions.

Figure 1 gives an overview on the detection systems available on the ESIMAS demonstrator.

2.4 Data fusion and validation

A major challenge is the reasonable data fusion and plausibilization of measured data and information provided by usual detection systems, for example, like

- Fire detection cables for fire alarm
- Visibility measurement devices for smoke detection
- Alarms when emergency exits are opened and emergency call stations entered
- Traffic data acquisition devices acquiring traffic volumes by inductive loops

with additional data and messages of new sensor systems, for example, like

- Systems detecting vehicle silhouettes by optical cameras
- Laser scanners to determine the vehicle type
- Infrared scanning to detect overheated vehicle parts
- Video detection by digital video evaluation to detect accidents, fires, hazardous goods, conspicuous objects etc.
- Traffic data acquisition to determine traffic composition by means of further developed inductive loop technology
- Surface sensors to measure total vehicle loads or axle loads in free-flow traffic ("Weigh-in-Motion – WIM").

The provided data offer manifold possibilities to conclude certain events. Hereby, the different potential events can lead to safety relevant initial events or initial events like

- Accident/collision
- Fire/smoke
- Event involving the release of hazardous goods according to ADR (European Agreement concerning the International Carriage of Goods by Road) [6].

Figure 2 below illustrates the data fusion process and levels including the plausibilization of the measured data and information of the detection systems.

2.5 Risk analysis

The operating mode of a tunnel is safe/secure if there is no reasonable risk of impairment. The real-time risk analysis allows making statements on the currently prevailing safety or security level in a tunnel. Risk is determined applying the method of the quantitative risk analysis (QRA) [8] taking into account the presumed degrees of damage as well as the probabilities of occurrence of certain safety or security relevant events. Risk is defined as follows:

$$\text{Risk} = \text{degree of damage} \times \text{occurrence probability}$$

In an online process the occurrence probabilities as well as the degrees of damage are dynamic factors which have to be taken into account appropriately when quantifying the risks.

Figure 3 illustrates the general flow of the online-risk analysis process.

2.6 Determination of occurrence probabilities (fault tree analysis)

Occurrence probabilities are determined for initial events using fault trees and using event trees for the states after the initial event has occurred. Figure 4 shows the bow-tie logic diagram which schematically represents the relationship between fault tree and event tree.

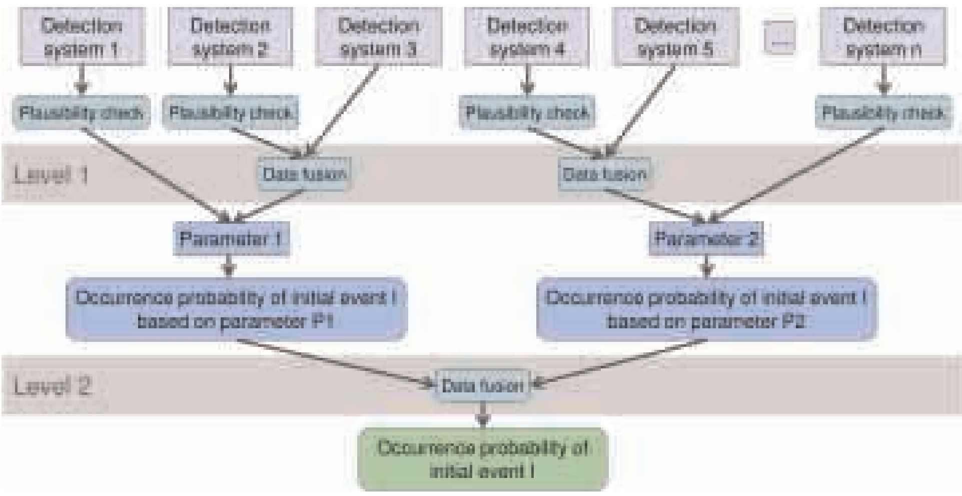

Figure 2 *Flowchart of the data fusion process [4], [7]*

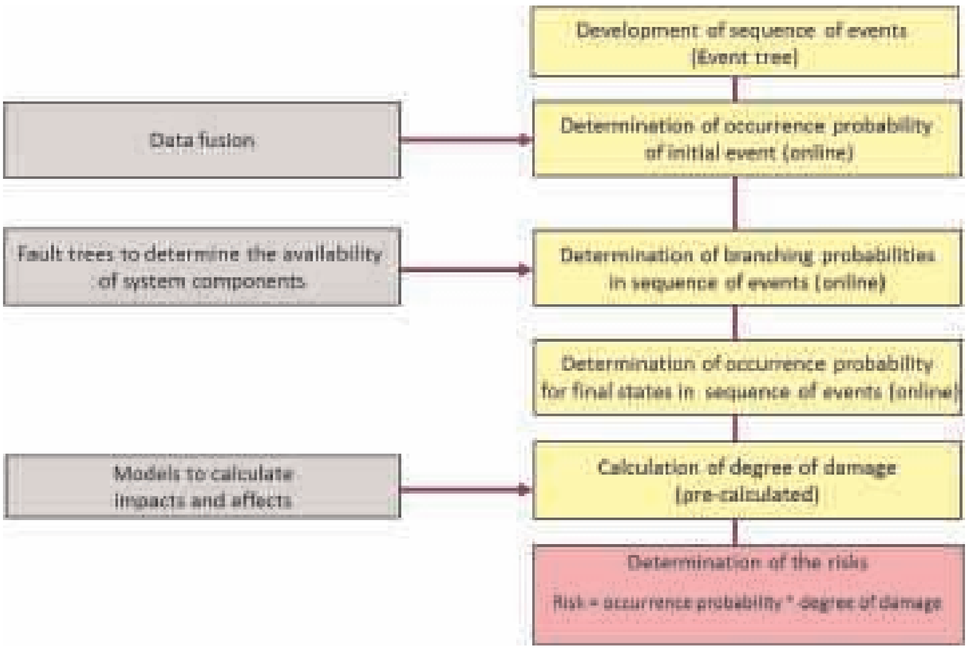

Figure 3 *Flow chart of the online risk analysis [4]*

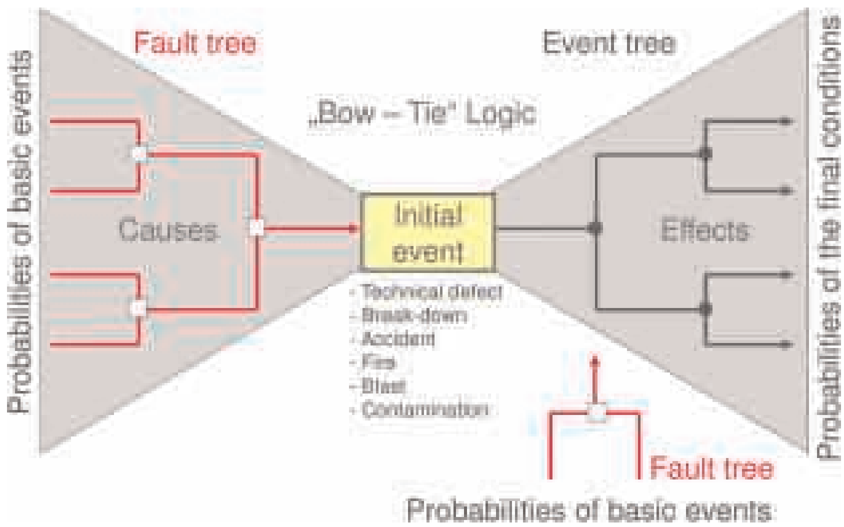

Figure 4 *Bow-tie logic diagram [4]*

2.7 Event tree analysis

Starting from an initial event, whose occurrence probability results online from data acquisition and data fusion, all possible intermediate stages up to the final states of the system are deduced and quantified with regard to their probability to be expected. Process modelling starts with the identification of the possible reactions of the system, i.e. the response to safety and security systems as well as to human intervention. Starting from the initial event, the requested system responses are queried, hereby distinguishing success or failure. At this point, the course of events branches into further intermediate stages. In analogy to the initial event these intermediate stages are examined for system responses. Thus, various different branches of the course of the event arise until the final state is reached. For a better visualization of this course of the event so-called event trees are used.

The branching probabilities are then estimated using fault trees, in which the current availability of system components is taken into account online. Finally, the occurrence probability of the final states results from simple linking of the occurrence probability of the initial event with the branching probabilities in the course of the event. Calculating the respective magnitude for each final state by impact and effect models and linking it with the correspondent occurrence probabilities results in the risk value. Figure 5 below shows the schematic diagram of an event tree.

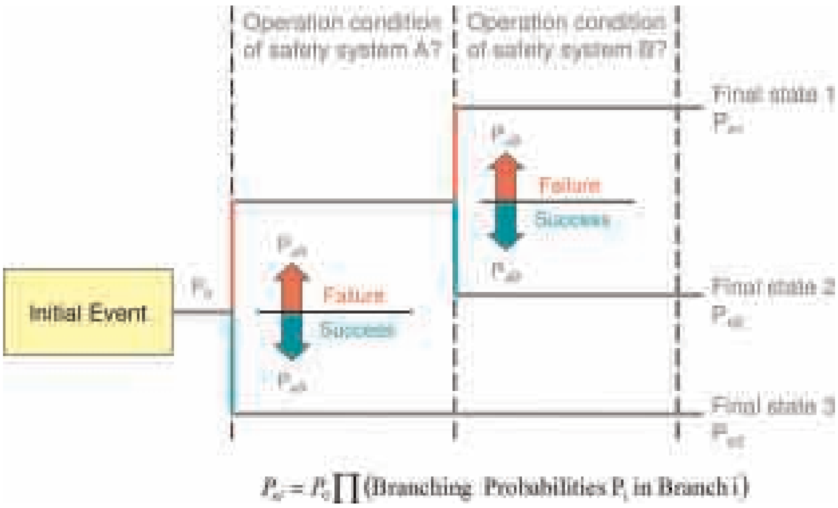

Figure 5 *Sequence of events to determine occurrence probabilities [9]*

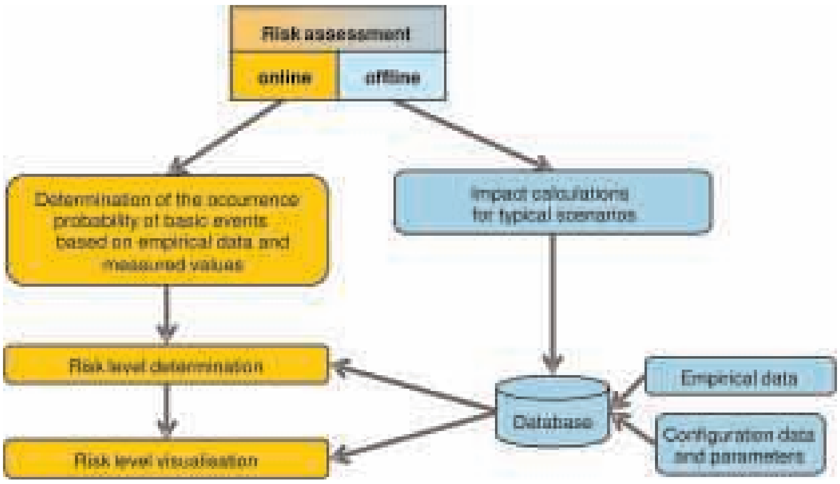

Figure 6 *Risk assessment procedures [4]*

2.8 Quantification of the extent of damage

The quantification of the degrees of damage to be expected depends on the occurrence probability of the initial event. Whereas the degrees of damage for more frequently occurring events (e.g. accidents) can be taken from statistics, the degrees of damage for less frequent events (like fires, explosions, contamination etc.) can only be determined by using highly sophisticated simulation tools to calculate the impacts and effects. For the impact calculations CFD[1] models are taken and for the effects calculation evacuation models are used. However, due to the time effort required, the CFD calculations cannot be performed in real time; they have to be carried through offline. In order to be able to assess the situation, e.g. as regards smoke propagation, still in real time, selected scenarios are pre-calculated and stored with their results in the system database.

[1]CFD: Computational Fluid Dynamics

The objective of the online risk analysis is the temporally discrete determination of the safety level based on online acquired data concerning the occurrence probability and the availability of the system components. Hereby, both individual risks like collision, fire, fire after collision, fire due to self-ignition etc. and tunnel-specific overall risk have to be identified. The results of the online risk analysis are risk values determined for certain time intervals. Figure 6 shows the main steps of an online risk analysis.

2.9 Risk assessment

The risk analysis and the assessment procedures rely on

- Data which are processed in real-time and
- Pre-calculated results based on models.

Consequently, the system architecture is composed of both an online and an offline part.

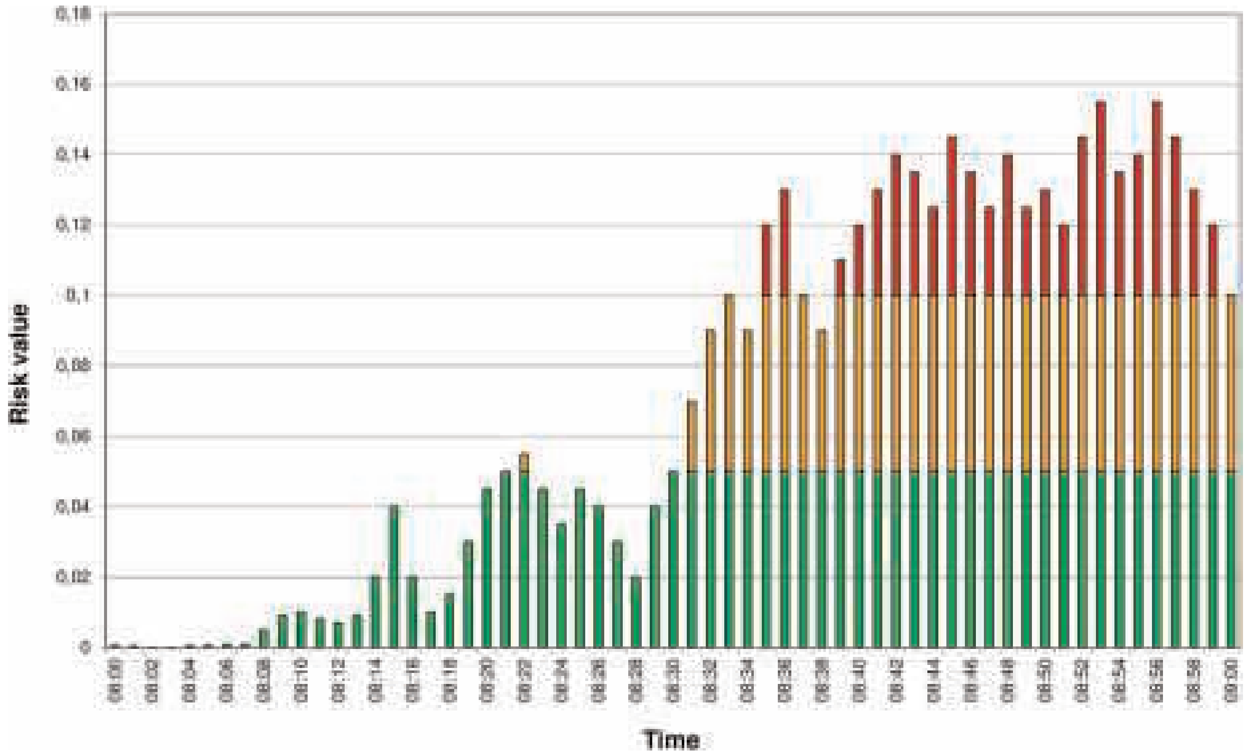

Figure 7 *Example of the visualization of assessed online risks [4]*

Risk assessment is performed online with the help of freely scalable threshold. Figure 7 depicts an example for a possible visualization of a three-level assessment of the online acquired risk values. Following the ALARP principle (As Low As Reasonably Practicable), accepted risks are green; risks which need a higher level of attention are yellow and non-accepted risks are marked red.

2.10 Expert system

In order to process the generated data, an 'expert system' is developed that allows tunnel operating staff to derive suitable measures or strategies from a given catalogue of measures for emergency response. For RETISS, the basic functional principle of this expert system was established whereas ESIMAS for the first time is developing an automated system for generating event-specific measures in real-time. Generally, the expert system is conceived so that measures to prevent events ('preventive' measures) as well as strategies to mitigate the consequences of events ('mitigative' measures) are included. Preventive measures include, for example, situation-dependent speed limits or traffic restrictions; mitigative measures can be, for example, the closing of tunnels and diversions, on the one hand. On the other hand, the possibilities for optimizing operating process flows in case of emergency response are to be examined. As far as incident management is concerned, an early initiation of specific, appropriate measures can reduce the time interval between detection of incident and countermeasures taking effect. With the ESIMAS system, the tunnel operating staff's attention is to be drawn specifically to critical situations in infrastructures they are monitoring. If critical situations arise, videos are automatically displayed and a selection of related measures suggested. The system specifically chooses measures which help to mitigate critical situations during operation. Since the expert system draws on the results of the real-time risk assessment and on the indicators calculated during data fusion, the measures allow a direct reaction to the higher occurrence probabilities of events or an increased potential degree of damage.

2.11 Demonstrator

For the comprehensive demonstration of the RETISS and the ESIMAS overall system demonstrators have been set up, both being in operation. For RETISS, the Rennsteig tunnel in Thuringia, almost 8 km long, was selected (being Germany's longest road tunnel). For ESIMAS, the 1.3-km-long overhead noise barrier Goldbach-Hoesbach in Bavaria was chosen. Here, all modules developed in the course of the projects were/are installed as prototypes and operated and tested under realistic conditions. Additionally to the tunnel equipment required according to the applicable German guidelines, RABT 2006 [3], the sensor systems for infrared detection and additional loops for combination with the WIM sensors will be installed for the ESIMAS demonstrator in particular. Depending on the availability of the various modules both systems are/will be tested and validated at system level.

3 Conclusions

In Germany, the safety and security management of road tunnels is currently based on single data provided by installed information and detection systems and transmitted to the tunnel control centre. Since within the past few years the trend has been to connect more and more tunnels to one single control centre, it has become more and more difficult for tunnel operators and their staff to evaluate and assess the multitude of incoming data with regard to tunnel security and safety to initiate appropriate measures promptly, if necessary.

The innovative approach taken up in RETISS and further developed within the ESIMAS project consists in the holistic consideration of all bits of information provided by the different detection systems in tunnels, the fusion of the available data, their automatic evaluation and prioritization based on an online risk assessment, thus allowing the dynamic assessment of the prevailing situation in real time. The developed expert system is to support tunnel operating staff by automatically generating recommendations which measures to take in order to handle and manage hazardous situations with a particular focus on prevention. Its advantages mainly unfold when a great number of tunnels have to be monitored by one control centre and when it is essential that all information relevant for possible reactions of the control centre is provided consistently and in real time, assessed with regard to the prevailing safety or security level and to initiate appropriate measures. The option of integrating new and innovative detection technologies renders the system scalable in view of the specific characteristics of individual road tunnels. Both projects have contributed to increase the capacity and availability of the traffic infrastructure and thus to enhance the safety and security of road users, too [10].

4 Acknowledgements

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The ESIMAS project is funded by the German Federal Ministry for Economic Affairs and Energy within the framework of the programme "Mobilität und Verkehrstechnologien" (mobility and traffic technologies). Further information on project contents and partners involved can be retrieved from www.esimas.de.

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