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D27.3 Assessment of the potential for city-laboratory based multi-hazards research and a long-term development route map

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Lead	UBRI
Authors	Colin Taylor (UBRI) Neil Carhart (UBRI) Shaofu Huang (UBRI) Jenni Li (UBRI) Georgios Tsionis (JRC) João Pedro Santos (LNEC) Erdal Safak (KOERI) Kuvvet Atakan (UIB), Oreste S. Bursi (UNITN) Patrick Covi (UNITN) Rocco di Filippo (UNITN)
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Summary

The purpose of this report is to explore and assess the potential for city-laboratory based multi-hazard research. This notion of 'city-laboratory' research is approached through the lens of Smart City technologies and Living Laboratories. Smart City technologies provide the means to observe, gather data and model real world urban systems to better inform decision makers and other stakeholders. Living Laboratories allow for experiments to be conducted 'in the wild', working alongside citizens, businesses and local governments to understand problems, design potential solutions and test them within the complexity of their operational environment. Both Smart City technologies and Living Laboratories can be coupled with traditional lab-based research and existing computational approaches to designing and testing. City-laboratory research therefore concerns the conduct of knowledge creation and theory testing in the context of an operational urban environment by harnessing the use of relevant technologies.

The report's overall purpose poses two related questions around the notion of 'potential'. The first relates to potential uses of such research; the second concerns the potential to conduct such research. In other words:

- What value can city-laboratory based multi-hazard research offer in theory?
- To what extent can city-laboratory-based multi-hazard research be conducted in practice?

These questions are used to inform a route map for long term development to ensure that the value is captured through effective application. It reflects on the current situation and what more needs to be done to ensure the necessary capabilities are in place.

Section 1 provides an overview of Smart Cities and Living Laboratories in the context of natural hazards research. Section 2 offers an overview of four case studies looking at the protection of tall buildings in Istanbul, industrial process plants in Sicily, the bridge network in Lisbon and an urban evacuation event scenario in Bristol.

Section 3 elaborates on the Istanbul tall buildings case study with the presentation of a new approach for system identification of multi-story buildings by substructuring. Each story of the building is assumed to be a substructure, and the building is considered as the superposition of substructures, i.e., one-story structures placed one on top of another. System identification is based on the transfer-matrix formulation of the building's response. The dynamic equilibrium equations of each story is expressed in terms of the story mass, stiffness, and damping, and by accounting forces and displacements from the adjacent stories above and below. The relationship between the forces and displacements of two adjacent stories are defined by the story transfer matrices.

It is shown that the transfer matrix of a story is a function mass, stiffness, and damping properties of that story only, and the displacements and forces on that story are influenced by the properties of all the stories above, but not the stories below. This allows the dynamic properties of each story to be identified separately, provided the identification started from the top story. One requirement for the story-based identification is that we need records from every story. Normally, multi-story buildings are instrumented only at a certain number of stories. However, by assuming that the deformations of the building can be approximated as the sum of those of a nonlinear shear and bending beams, we can get a very good estimate of the responses at non-instrumented stories from those of the instrumented stories. The method presented provides a better alternative to commonly used modal identification techniques.

Informed by the case studies, a modular Smart City concept is discussed in **Section 4**. This considers specialised capabilities provided by separated but connected modules that can be triggered by a central executive system as needed. A Smart Earthquake Response Module (SERM) may be one such component. In this context, this Smart City paradigm is more broadly positioned as comprising of three main elements: (i) an observational component gathering data from the real world; (ii) a modelling system interpreting and combining the observed data with existing data to provide an understanding of the real world; and (iii) city inventories of existing infrastructure resources. The Smart City can combine distributed research facilities, observational networks, structural health monitoring, critical infrastructure monitoring, and earthquake early warning systems. In this sense it represents the key underpinning infrastructure of much city-laboratory research.

Section 5 looks in more detail at the Lisbon and Bristol case studies to develop a process for the initial phase of the Smart City workflow that concerns the fundamental design of the city-laboratory research and its supporting infrastructure. It implements a novel canvas that enables key decision makers and other city stakeholders to articulate their perspectives on critical urban infrastructure and capturing their information requirements. This phase can inform the design of sensor deployment, data processing, knowledge sharing, city-based experiments and computational models. The process is extended through the workflow to demonstrate how it could inform the design of an Agent Based Model of pedestrian flow which could in turn be interrogated in a number of multi-hazard scenarios to inform decision makers and the design of additional real-world experiments.

One of the key elements that arises from the case studies in Section 2, the Smart Earthquake Response Module in Section 4 and the service requirement diagnostic process in Section 5 is the need for an aligned process to the integration of disparate forms of data. **Section 6** considers this in more detail in the context of metadata for Structural Health Monitoring.

The report concludes by outlining a future roadmap to ensure that the capabilities for city-laboratory-based multi-hazard research are developed, and the value of such approaches are fully captured.

1 Smart Cities & Living Laboratories in the context of natural hazards

One important component of mitigating cascading effects is the monitoring capacity of the observational systems that are designed for monitoring natural hazards such as earthquakes, tsunamis, etc. as well as anthropogenic hazards associated with the exploitation of natural resources. As such the European Plate Observing System (EPOS) is designed to address these issues with the two main goals of contributing to the understanding of geo-hazards and geo-resources. These understanding will be overlaid upon the understanding of people's use of the natural and manmade infrastructure and the space in built environments, to fully apprehend the value chain that connects these fundamental areas of research all the way through to ultimate outcomes enjoyed by citizens.

This section introduces two related concepts that frame the means by which the built environment is observed and people's use of it is understood.

The Smart City concept general refers to the use of ICT and other technologies in the service of urban planning and management (Lee and Lee 2014). While there are many interpretations of what constitutes a Smart City they commonly involve three themes: technological factors, human factors and institutional/governance factors (Nam and Pardo 2011). Technological factors include instrumentation, observational systems, modelling and analytics. Human factors relate to societal outcomes such as entrepreneurship, creativity and connectivity. Institutional factors concern planning, regulation and legal components. The Smart City concept provides a means to understand people's use of natural and manmade infrastructures, as well as the condition and behaviour of the built environment itself. Data collated and analysed by Smart Cities along with the services they facilitate can help in disaster management (Chaudhuri and Bose 2019; Sakhardande, Hanagal, and Kulkarni 2016). Tangential fields such as Internet of Things research consider applications in earthquake early warning systems (Spalazzi, Taccari, and Bernardini 2014; Zambrano et al. 2017) and other natural hazard contexts (Sood et al. 2018; Shah et al. 2019). This can be extended to the sensing, analysis and management of infrastructure assets and networks (Hoult et al. 2009; Ogie, Perez, and Dignum 2017). Smart Cities or Smart Infrastructures involve a degree of real time monitoring which can be recorded, analysed or used to inform dynamically updated digital models of real-world systems -known as digital twins-.

The following sections consider the interactions of technological and human factors in the creation of city-laboratory resources and experiments.

The Living Laboratory is a similarly nebulous concept with its origins in observing people undertaking their every-day life, particularly following the introduction of novel digital communication technologies and services (Markopoulos and Rauterberg 2000). In addition to undertaking research in a more natural complex setting than a traditional laboratory, the approach also facilitates user-centred design, participatory design, co-design (Markopoulos and Rauterberg 2000) and co-creation practices (Veeckman et al. 2013). Co-creation brings together multiple stakeholders with different perspectives or partial views of the system to create something of mutual value. Thus, diverse stakeholders can be involved in the design of the research and innovations to ensure they have outcomes with impact and value. The concept matured with the foundation of the European Network of Living Labs in 2006 which define the concept as "user-centred, open innovation ecosystems based on systematic user co-creation approach, integrating research and innovation processes in real life communities and settings" (European Network of Living Labs, n.d.). Also reflecting on the European approach, Eriksson et al describe the Living Labs approach "a user-centric research methodology for sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts" (Eriksson, Niitamo, and Kulkki 2005). The notion of putting users at the centre of the research and innovation is clearly a common factor, along with the idea of conducting it in real-world settings (or as close to as possible). The involvement of diverse actors and the ability to cope with multiple dynamic contexts position Living Labs well to deal with multi-hazard research. More generally Dutilleul et al (2010) reviewed the literature to identify five different uses of the term: (1) an innovation system, (2) a means for monitoring social settings normally in relation to the introduction of novel technologies, (3) a way of involving users in product development, (4) organisations maintaining an ICT infrastructure or platform and (5) the movement initiated by the European Network of Living Labs.

Living Labs have been implemented at the domestic scale with purpose built homes such as PlaceLab established at MIT in 2004 and Philips' HomeLab in the Netherlands (Eriksson, Niitamo, and Kulkki 2005) but they have also been implemented at the city scale. Dell'Era and Landoni (Dell'Era and Landoni 2014) identified 70 Living Labs and provided case studies on 14 'mature' examples. These tend to involve establishing an ICT infrastructure upon which new technologies and services can be tested. Examples include the Bristol Living Lab which has a particular focus on citizen-sensing projects to support neighbourhoods in gathering data to contribute to contribute to urban development. This involves participation in REPLICATE, a Horizon 2020 Lighthouse Project (Grant No. 691735). In Bristol this involves the deployment of smart integrated energy, mobility and ICT solutions to allow neighbourhoods to test technologies that could address inequalities[1].

While many Living Labs focus on communication, mobility and energy, there are some examples of their use in the context of natural hazards research. For example the Wellington region of New Zealand has been promoted as a living laboratory for research into community resilience to earthquakes (Doyle et al. 2015). An early reference can be found following the 2002 Molise earthquake in Italy with Maffei and Bazzurro (Maffei and Bazzurro 2004) encouraging research that went beyond "reconnaissance" to utilise the area post disaster as a "living laboratory". The concept was more recently developed by Dobre et al (Dobre, Sorin Dragomir, and Georgescu 2019) who explore "the role of seismic areas as living labs/natural laboratories for studying the behaviour of buildings and of people". They propose an open, user-centred and co-created platform for seismic research that feeds into disaster resilience education. This brings together historic data, temporary instrumentation, permanent structural monitoring, disaster drills, human behavioural observations, data analysis etc.

Collectively these concepts suggest that no single sensor, observational system, database or model is enough to provide a rich enough understanding of urban life in general or in the context of disaster management. Multiple data sets and models are required, but these must be internally consistent and coherent if their full value is to be realised.

Fully exploiting the potential benefits of city-laboratory experimentation requires a robust, integrated framework for operating the necessary technological infrastructure in a way that serves the inhabitants of those cities. This in turn requires an understanding of the how those inhabitants interact with and use the urban built environment in normal and extreme circumstances, and how they make decisions concerning those interactions. The city-laboratory concept offers a means both to improve that understanding and to develop innovations that will improve the safety and quality of life of citizens.

The following sections explore some of the key issues relating to the city-laboratory based multi-hazards research in the context of the 'smart' and 'living laboratory' concepts. In the next section several applications of city-laboratory multi-hazard research are outlined indicating the value they could bring and the extent to which they can be conducted in practice. Section 3 looks in more detail at a novel analytical approach to assessing the damage in high-rise buildings. This is an important

[1] https://replicate-project.eu/actions/bristol/

development in a specific application of smart infrastructure. Section 4 then moves from the asset to the whole city scale. It explores a modular structure of Smart Cities and the development of a Smart Earthquake Response Module in more detail. Section 5 then looks at the early stages of the Smart City module workflow to consider the human factors angle, outlining a new method to establish service requirements and translate these into requirements of the smart city modules. Pilot applications are outlined. Section 5 also looks at how these service requirements can be used to inform scenario-based modelling and simulations of the urban environment, with an example scenario modelled using Agent Based Modelling. Section 6 turns to look at the critical step of integrating data from diverse observational systems and contexts in a useful and meaningful way in the context of the European Plate Observing System (EPOS). The report concludes with suggested next steps in addressing the key issues arising.

2 Potential City-Laboratory Case Studies

This section describes four case studies utilised to explore, develop and evaluate the potential for city-laboratory based multi hazard research. These case studies range from structures and industrial facilities to urban infrastructure systems. Each presents its own challenges and unique perspectives. Collectively they help inform the assessment.

The first case study looks at the instrumentation and development of safety warning algorithms and software to generate a safety warning system within high-rise buildings in Istanbul, Turkey. The early warning can be used to control the operation of buildings facilities and the optimal evacuation of people via smart-phone software application. The second case study looks at monitoring of critical bridge infrastructure in Lisbon, Portugal. Data is gathered in real time from deployed sensors and aggregated within the city's structural health monitoring system. The case study considers the potential use of Artificial Intelligence and information sharing across the city's bridge network. The third and fourth case studies concern industrial processing plants in Sicily, Italy -an oil refinery and a liquid natural gas facility-. These case studies look at the understanding of the hazards and risks associate with these plants. The final case study examines crowd management during a hazard event in Bristol, UK. The case study is used as a means to explore the potential for generating effective scenarios, identifying city management information requirements and modelling of human behaviours in extreme circumstances.

2.1 Case Study #1 – Tall buildings in Istanbul

The goal is to develop building-specific safety warning algorithms and software to generate a safety-warning signal in one of the instrumented tall buildings in Istanbul. This will allow estimation of the reduction in ground shaking as the waves travel from the early warning stations to the building. The tall buildings that we are considering are shown in the figure below (Figure 2.1).

Figure 2.1: Tall buildings in Istanbul.

The first step is to identify the attenuation (i.e., reduction) of ground motions from the early warning stations (those stations closest to the fault) to the building location by using the earthquake records available from the early warning stations and the building monitoring network. This will allow us to estimate the reduction in ground shaking as the waves travel from the early warning stations to the building. We will then identify the threshold shaking levels for damage in the building by investigating the maximum deformations and forces considered during the design of the building. When the ground shaking for the building, which is estimated from the early warning station data and the attenuation relationship, near the threshold shaking level for the building we will issue early warning. We expect that we will be able to give 5 to 7 seconds early warning for the building and the occupants. The early warning signal can be used to control the operation of elevators, shutting down the natural gas lines, and the evacuation of people from the building. A smart-phone application software will be developed to inform the occupants when there is a warning.

2.2 Case Study #2 – Bridge network in Lisbon

The city of Lisbon, in Portugal, is located in a seismic region with significant earthquake and tsunami risk due to its location on the shore, to the fact that most of its buildings and facilities are near sea-level and to the fact that it is close to the most important seismogenic faults located in Portugal mainland and sea. The city and its surrounding region is now equipped with a tsunami early warning system and a part of the Portuguese ground-based accelerometric network, both managed by IPMA (Portuguese Institute for the Sea and Atmosphere).

The city of Lisbon is also undergoing important initiatives in the realm of Smart Cities and is close to becoming one. At the end of 2017, the Lisbon Municipality started implementing an integrated holistic framework capable (Figure 2.2, left) of combining data and managing, in real-time, ten of its services, such as firemen, municipal police, trash services, and over thirty additional external services considered crucial for the city's adequate functioning such as other police forces, public transports, surveillance cameras, civil protection, etc. All services are being aggregated in Lisbon's Cloud City Operations Center (CCOC), which is being implemented along with AI for processing and helping in decision-making. In addition, the Lisbon Municipality is also opening part of the data it owns to the community so as to allow interested citizens and companies to develop tools and strategies for improving the city services and functioning (Figure 2.2, below). The city is also opening calls for research projects with the objective of having the help of scientific community in understanding what are the needs and requirements of a Smart Lisbon as well as the possibilities now offered by technology.

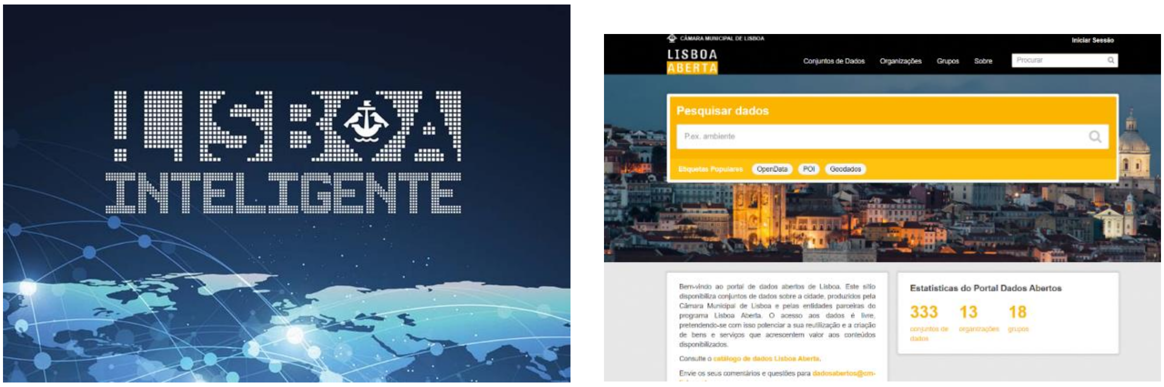


Figure 2.2: Programs "intelligent Lisbon" (on the left) and "Open Lisbon" (on the right).

LNEC (Portuguese National Laboratory for Civil Engineering) is responsible for monitoring the most important critical infrastructures in the country. Large bridges as well as large concrete and earth dams are monitored and have their safety controlled by this institution's staff. Within the city of Lisbon, LNEC is monitoring two distinct structures in real-time, the 25 de Abril suspended bridge (Figure 2.3d) and its North Viaduct (Figure 2.3c) and within its metropolitan area is monitoring three additional ones, two to the north, the Salgueiro Maia Road Bridge (Figure 2.3e) and the Santana do Cartaxo Railway Viaduct (Figure 2.3b), and to the south the Bridge over River Sado (Figure 2.3g). All are instrumented with static (displacements, strain, rotations and forces) and dynamic (accelerations) sensing and the data is being acquired in real-time. In addition, all bridges are connected by high-speed fibre optic networks (Figure 2.4), thus allowing for this set to be considered as a pilot study for smart city environment under hazard situations, with the advantage of enabling an easy connection to the new Lisbon CCOC under implementation.

Figure 2.3: (a) Portuguese mainland and bridges monitored by LNEC, (b) Cartaxo Viaduct, (c) 25 de Abril North Viaduct, (d) 25 de Abril Suspended Bridge, (e) Salgueiro Maia Bridge, (f) Lisbon metropolitan area and bridges monitored by LNEC and (g) Sado Bridge.

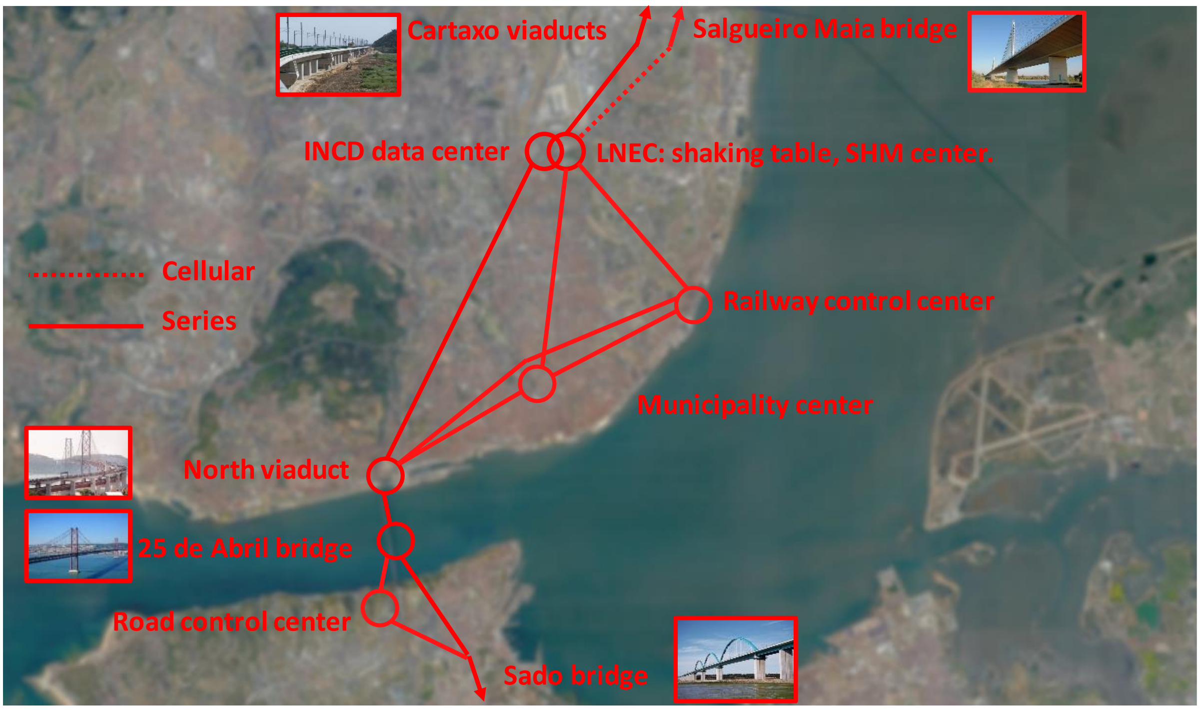


Figure 2.4: Lisbon area with the representation of the bridges monitored by LNEC and the network.

LNEC is currently controlling the safety of these structures using pattern recognition and artificial intelligence applied to the streams of data in real-time, which are aggregated in the SHM (Structural Health Monitoring) system developed, implemented and in operation in this institution. Two PhD theses are under development at the moment addressing these structures and the processing of data being acquired and two more are being started. These research works are being developed not only with the objective of defining new methods for AI-based single structural control but also on how to conduct this control in a multi-structure environment, by taking advantage of the fact that multiple structure are sharing the same loadings (temperature, railway traffic crossing the region, road traffic, etc). In one of the works, the particular aspect of conducting SHM based on monitoring in/on the structures and in/on the crossing vehicles is particularly appealing for smart city environments as is another one, in its beginning, where sensing systems for condition assessment are being studied for optimization considering both a single structure or a set of multiple structures in a multiple-structure fully connected smart city environment.

2.3 Case Study #3 – Process plants in Sicily (I)

Along this line, two probabilistic approaches, devoted to risk quantification of plants and conceived in chemical engineering and nuclear engineering, were summarized. With regard to representative sub-plants, it was decided that the Case Study #1 was a refinery situated in Sicily (Italy), conversely, the Case Study #2 treated a plant with one liquefied natural gas (LNG) - tank with a volume of 150.000 m3, in a small chemical plant with a size of 2 km2. The main aspects of the seismic hazard analysis were highlighted, and the use of a fully probabilistic approach was underlined by analyzing the main source of uncertainty: distance, magnitude, and attenuation law. All these aspects were defined and formalized in the framework of the probabilistic seismic hazard analysis (PSHA). The PSHA was applied to the site of an actual plant, Priolo Gargallo, in Sicily (Italy). This zone was selected for the two Case Studies due to the high seismic hazard. In addition, seismic design categories (SDCs), relevant annual mean probability of failure Pf, Limit States, and relevant Return Periods, used in different standards, were recalled to be able to set proper intensity measure values endowed with importance factors. Finally, a procedure was suggested to check the seismic performance of components/structures in probabilistic terms and based on structural analysis. With regard to the Case Study #3.1, main information and results are reported in the following references: Reza et al., (2014), Bursi et al. (2015), Bursi et al., (2016). Conversely, Nam et al. (2017), Bursi et al, (2018), Caputo et al., (2019) gather main results relevant to Case Study #3.2.

Case Study #3.1

Case Study #3.1 concerns a modern and technologically advanced refinery located in Sicily, Italy. Fig. 2.5 shows a plan view of the refinery.

The plant is built to produce steam and electricity from the gasification of the heavy hydrocarbon residues of refining. The IGCC (integrated gasification combined cycle) plant with electric power of about 280 MW can produce about 2 billion KWh/p.a. The refinery covers an area of over 700,000 m.^{2}; moreover, it has a refining capacity of 3,900,000 tons per annum, equivalent to approximately 85,000 barrels per day, and a storage capacity of over 1,500,000 m.^{3}. The refinery is also equipped with a dispatch facility by land, which has a potential capacity of over 12,000 tons per day. It is connected to the sea through a combination of marine terminals that can accommodate tankers from 1,000 to 400,000 tons.

From the refinery, two different tank classes were selected to be investigated: (i) the slender tank class; and (ii) the broad tank class.

The slender tanks, marked as TK 23-24 in Fig. 2.5, contain flammable 'Category A' liquid. The cylindrical tanks are made of steel, diameter 8 m, height 14 m, and capacity 700 m3. The tanks are provided with floating roof and they are unanchored with respect to the foundations. Since these tanks are filled with dangerous liquid, an excavation capable of containing it, in case of accident, has been achieved.

The broad tanks, indicated as TK 59 and TK 60 in Fig. 2.5, contain crude oil. Tank #59 is made of steel, diameter 85 m, height 22 m and capacity 125721 m3. Tank #60 is made of steel, diameter 55 m, height 15.6 m and capacity 37044 m3. The tanks are provided with floating roofs and they are unanchored with respect to the foundations.

Within broad and slender cylindrical tanks, Case Study #3.1 includes a cathedral type heater. This type of structure is generally used to produce various feedstock that is needed for the petrochemical industry, such as ethylene and propene, by thermal cracking. High temperatures 700-900 °C and pressures up to 70 bar can be reached in the cracking process. The dimension of the heater is 7.61 meters x 19.24 meters at ground level and is divided into a 4 x 7 grid. Deliverable D1.1 contains details of the heater.

In addition, there are piping systems on support structures in surrounding areas, which connect different components including tanks. The piping system contains typical components, such as flange joints, elbow and Tee-joints. A typical example is shown in Fig. 2.6.

Figure 2.5: Plan view of the refinery relevant to Case Study #1 and tanks position.

The main risks identified in the plant are the following:

- Release of Hydrocarbon in atmosphere from safe valves;
- Release of H2S and SO2 from acid column;
- Release of H2S and SO2 from the sulphur container;

- Leakage of GPL in pressure;
- Fire close to a storage floating roof tank with flammable liquid (Category A);
- Loss from a high-pressure unit;
- Release of toxic products from a lead tank (TEL);
- Release of syngas from an oxidation reactor R8001/1;
- Release flammable liquid from sea terminals;
- Generation of a toxic cloud from flammable products fire.

The most critical components in this case study are the floating roof tanks containing flammable liquid. The possible events that could cause a fire close to these tanks are the following three:

- Possible failure of floating roof;
- Possible leakage from pipe system;
- Possible over-filling of the tank.

In addition, a possible event in the piping system is leakage from piping joints, e.g. flanges and Tee-joints.

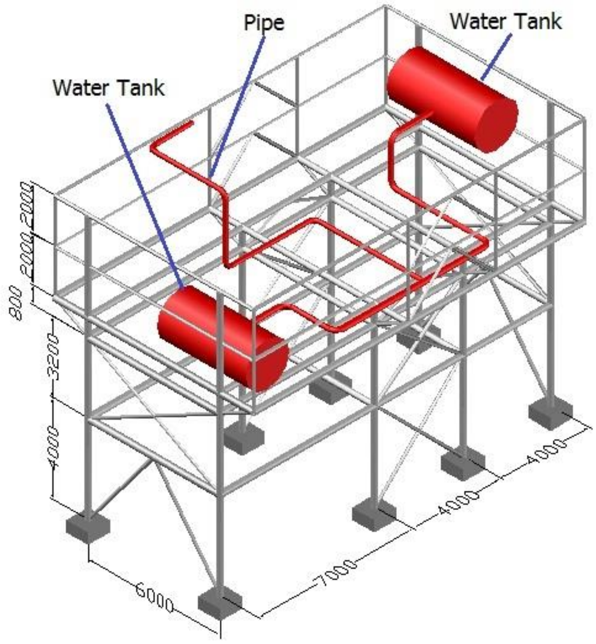


Figure 2.6: Piping system on a support structure.

Case Study #3.2

Case Study #3.2 contains a typical regasification plant, as shown in Fig. 3.7. It consists of the following main components:

- One full containment ethylene tank with a volume of 50.000 m³ with in-tank-pumps and platforms/piping on top;
- Horizontal and vertical pipe racks with piping;
- Shell and Tube Heat exchangers;
- Ambient Air Heaters;
- Centrifugal Pumps (canned type);
- Reciprocating Compressors;
- Pressure vessels;

- Jetty Structures including Trestle and Loading Arms;
- Elevated Flare.

For the identification of critical components, the hazard potential of each component shall be evaluated; this potential it is mainly defined by:

- The properties of the liquid/gas handled;
- The quantity of the liquid/gas handled;
- The process conditions;
- The vulnerability of the component itself.

The most critical components are pipes and the heat exchanger. Moreover, leakage and LOC are the major risks. The hazard identification study (HAZID) distinguishes between the following different hazards:

- Environmental hazards;
- Environmental impacts;
- Fire and Explosion hazards;
- Toxic hazards;
- Corrosion hazards;
- Thermal hazards;
- Pressure hazards;
- Electricity hazards.

Of course, fire and explosion, as well as, pressure hazards are the most severe ones and their probability of occurrence owing to an earthquake is very high. The highest hazard in this Case Study is obviously posed by the storage tank itself containing the biggest volume of flammable material. The consequences of a failure (gas clouds, fire) can easily reach over 1000m and potentially affect public areas. However, due to the overall design of the tank, e.g. steel and concrete the actual risk of such event is quite low. Nonetheless, the pumps on top could fail due to large floor accelerations.

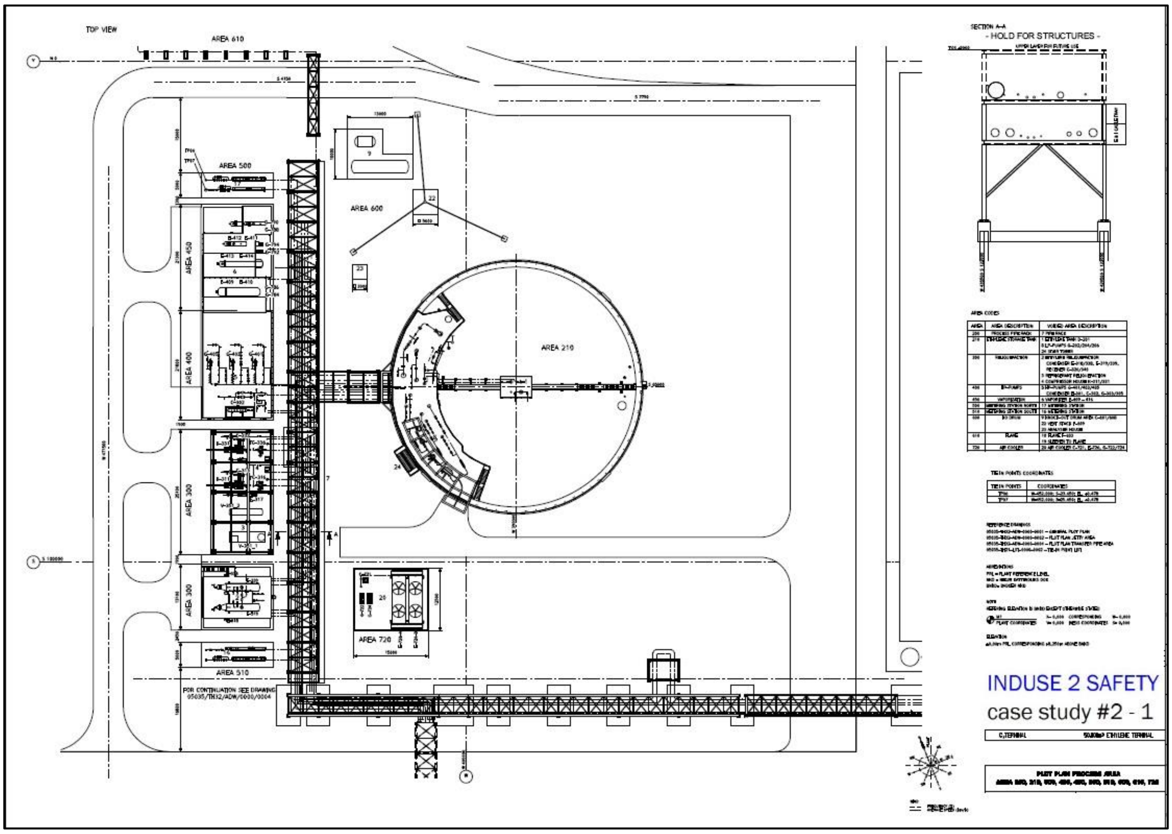


Figure 2.7: Layout of tank and surrounding area considered within the Case Study #3.2.

The second major hazard in the plant is posed generally by equipment handling cryogenic liquid ethylene under high pressures. The biggest potential spill results from leakage from pressure vessels and the main pipe rack. Pressure vessels additionally pose the risk of boiling liquid expanding vapour explosion (BLEVE) in case of firing or collapse of the supporting structure.

For these reasons, the following representative elements were suggested for a detailed modelling:

- The storage tank and some critical component on top of it;
- Parts of the horizontal and vertical pipe rack;
- A pressure vessel containing liquefied gas located in the process area.

2.4 Case Study #4 –Bristol City & Clifton Suspension Bridge

The Bristol case study is focussed at the overall city scale, with a view on the maintenance and operation of legacy mobility infrastructure in a hazard event. While Bristol itself does not experience significant seismic activity, generic hazards, both natural and man-made are of interest and are investigated here in order to identify transferable lessons to the workflows associated with the establishment of Smart Cities and Living Laboratories. In 2017 Bristol was ranked as the UK's top Smart City the UK Smart Cities Index. In 2018 Bristol won the Global Mobile Awards Smart City Award, beating Barcelona, Dubai, New York, Singapore and Yinchuan. These awards were in part based on the unique opportunities Bristol provides to this project from several concurrent activities within the city. Firstly, the University of Bristol houses one of four national Urban Observatories. These are integrated urban infrastructure laboratories, established by the United Kingdom Collaboratory for Research in Infrastructure and Cities (UKCIRC), for the digital capturing, mapping, sensing, monitoring and testing of urban infrastructure.

Secondly, Bristol is Open has brought together the City Council's Operations Centre with the University of Bristol to utilise a private fibre backbone network for city-based experimentation. Finally, Bristol City Council has recently published its latest five-year Smart City Strategy which include initiatives to look at how Smart City technologies can achieve more citizen safety. The West of England Combined Authority (WECA) has worked with 5G Smart Tourism to trial thermal imaging sensors that alerts emergency services should someone fall into the harbour.

Bristol has been forward looking through its investment in Bristol is Open, which is a joint venture between Bristol City Council and the University of Bristol. This has resulted in a Smart City Research and Development network platform of multiple communications technologies installed around the city. Currently three networks are integrated through software controls: fibre in the ground, a wireless het-net along the Brunel Mile area of Bristol with Wi-Fi, 3G, 4G, LTE, and 5G experiments, and a radio frequency mesh network deployed on 2,000 of the city's lampposts.

Through the UKCRIC Urban Observatory and other initiatives, collaborative research with the city's citizens has always been a strong component. This case study builds on previous work in this area to apply a process for understanding the operational needs of service users, and utilise this to inform the design of sensor deployment, smart city modules and scenarios through which the infrastructure can be tested.

The case study focuses on Isambard Kingdom Brunel's Clifton Suspension Bridge (Figure 2.8). The bridge, opened since 1864, provides a key transport route between the city and North Somerset by spanning the Avon Gorge. The bridge has a wooden deck supported by iron girders. The deck is suspended by 162 vertical iron rods from cables recycled from Brunel's Hungerford Suspension Bridge over the Thames when it was demolished in 1860.

Figure 2.8: Clifton Suspension Bridge
(By Gothick - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8263495)

Each year Bristol International Balloon Fiesta is held in Ashton Court on the North Somerset side of the bridge (left side in Figure 2.8), attracting in the region of 100,000 people[2]. The bridge provides a key route to the festival from the Clifton area of the city. On such occasions the bridge is closed to vehicle traffic and, at times, pedestrian traffic.

The Clifton Suspension Bridge (CSB) is owned and operated by a charitable trust. It's sole source of income is the toll charged on vehicles using the bridge. Resources for structural health monitoring and day to day operational decisions must be carefully designed and deployed. Recently this has included consideration for the rapid deployment of a structural health monitoring wireless sensor network (Gunner et al, 2017).

Combining these issues there are key considerations regarding the location and nature of sensors, the analysis of gathered data and the presentation of that analysis to key decision makers and other stakeholders. This must be developed through collaborative deliberation with key stakeholders. Furthermore, for this to be of most value it must be contextualised in larger scale models of its operational environment which, in the case of the Bristol International Balloon Fiesta, includes the movement of people around the city to and from the festival site. The key consideration is to enable those operating the bridge to make informed decisions regarding the maintenance and operation of the bridge, those using the bridge to make informed decisions regarding their interactions with it, and those providing services to the bridge (e.g. maintenance) to have access to the information they require. This is further explored in the following sections.

3 System Identification & Damage Detection via Substructuring

This section looks in more detail at analytics associated with smart infrastructure monitoring, presenting a novel approach for system identification of multi-story buildings by sub-structuring.

3.1 Introduction

The standard approach to system identification of multi-story buildings from their vibration data has been to use the modal identification, in which the characteristics of vibration modes (e.g., modal frequencies, damping ratios, mode shapes, and modal participation factors) are identified by using spectral analysis techniques. Modal identification can give misleading results if the building does not have modes in classical sense, such as buildings with nonlinear behaviour, non-proportional damping, and strong vertical irregularities (e.g., sharp changes in mass, stiffness, and damping along the height).

Transfer-matrix formulation of the dynamic response of multi-story buildings provides an alternative to modal analysis (Thomson 1972; Safak, 1999; Safak and Cakti, 2015). In transfer-matrix formulation, the building is considered as the superposition of one-story structures (i.e., one-story structures placed on top of each another). The dynamic characteristics of the building are defined in terms of the dynamic characteristics of each one-story structure (i.e., the story mass, stiffness, and damping), which gives the

[2] https://www.bristolpost.co.uk/whats-on/whats-on-news/bristol-balloon-fiesta-weather-forecast-3185622

story natural frequency, and the story damping ratio. In transfer-matrix formulation, system identification involves identifying the natural frequencies and damping ratios of each story individually, as if they were all one-story structures.

A critical requirement in transfer-matrix based system identification is that we need vibration records from every floor. This is not typically the case, since only a limited number of floors are installed with sensors. However, it is possible to estimate the motions of non-instrumented floors from those of the instrumented floor.

This Section first outlines the formulation of the transfer-matrix approach to the dynamic response of multi-story structures. Next, a story-based system identification procedure for multi-story structures is introduced, along with a methodology to estimate the vibration time histories at the non-instrumented floors from those of the instrumented floors.

We present examples by using simulated data to confirm the validity of the methodology presented.

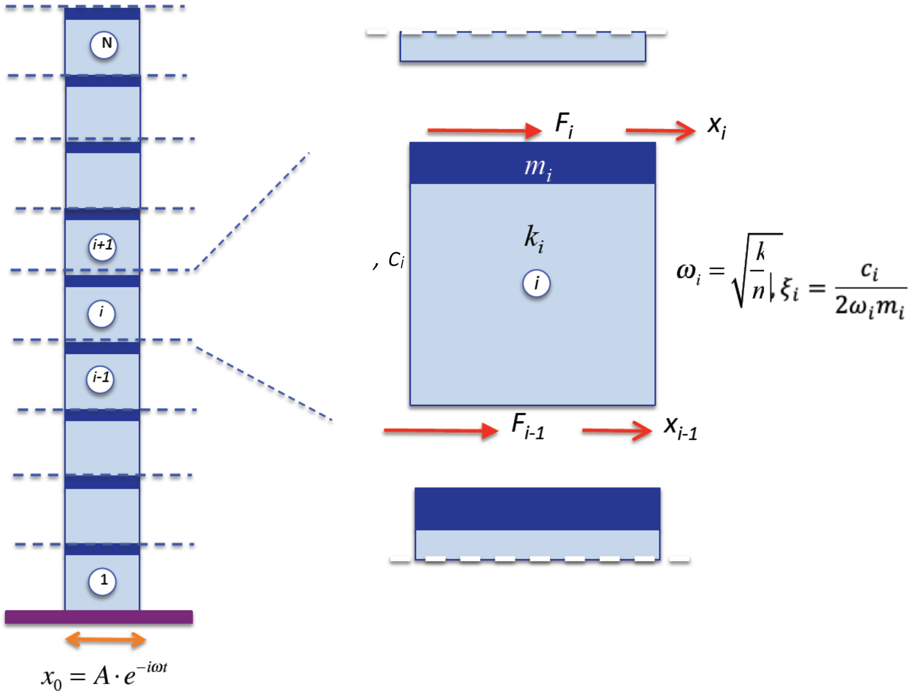
3.2 Transfer-matrix formulation of building vibrations

Consider a multi-story building as shown in Fig. 3.1 on the following page. Assume that the building mainly deforms in shear and subjected to harmonic base accelerations at frequency ω. Let us isolate one of the stories, story *i,* of the building. The free body diagram of the story with forces and displacements above and below the story is shown in Fig. 3.1a. Figure 3.1b shows the forces and displacements, when the one-story segment is further separated into its floor mass and walls/columns, and the equilibrium equations for each component. By inserting the equations for walls/columns in the equations for the floor mass in Fig. 1, we obtain the following set of equations that relates the forces and displacements at floor *i* to the forces and displacements at floor *i-1*:

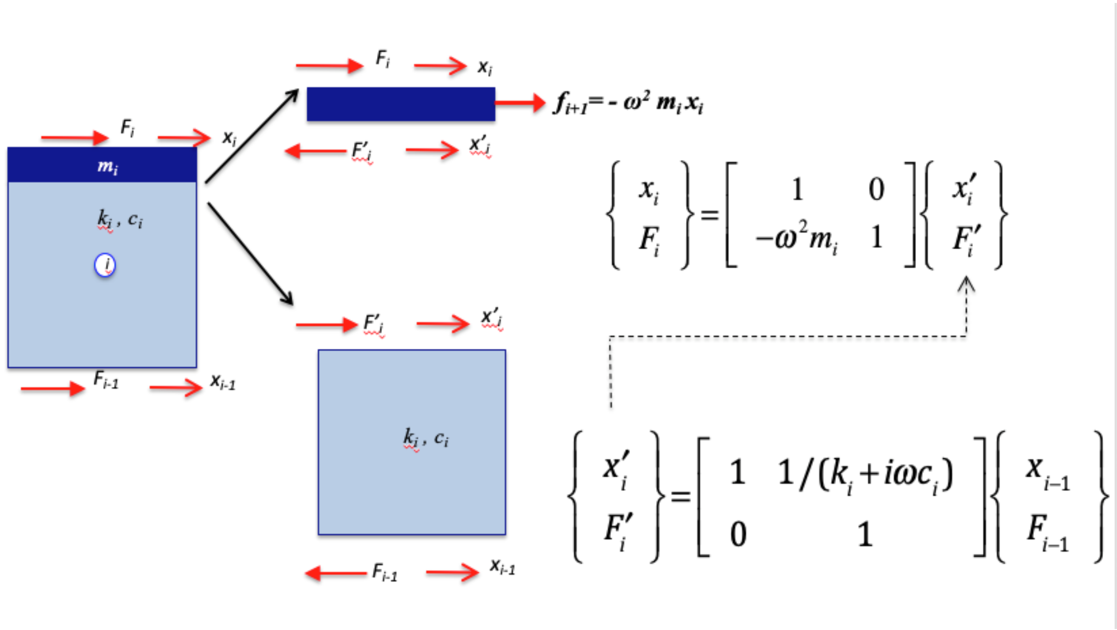
$$\begin{Bmatrix} x_i \\ F_i \end{Bmatrix} = \underbrace{\begin{bmatrix} 1 & 1/(k_i + i\omega c_i) \\ -\omega^2 m_i & 1-\omega^2/\omega_i^2 \end{bmatrix}}_{[T_i]} \cdot \begin{Bmatrix} x_{i-1} \\ F_{i-1} \end{Bmatrix}$$

$$\begin{Bmatrix} x_i \\ F_i \end{Bmatrix} = \left[T_i \right] \cdot \begin{Bmatrix} x_{i-1} \\ F_{i-1} \end{Bmatrix}$$

where m_i and k_i denote the floor mass and the story stiffness of story *i*, ω_i is the natural frequency of the story, and ω is the frequency of the base excitation. $[T_i]$ is know as the transfer matrix for story *i*, as it transfers the forces and displacements from floor *i*-1 to floor *i*.



(a)



(b)

Figure 3.1. Transfer-matrix formulation of the vibrations of multi-story buildings: (a) One-story segment of a building, (b) Equilibrium equations of the one-story segment.

By continuing the formulation for all the stories from the ground floor to the top floor, we can write the following equation for the relationship between the forces and displacements of the ground floor (*Floor* 0) and the forces and displacements of the top floor (*Floor* *N*).

$$\begin{Bmatrix} x \\ F \end{Bmatrix}_N = \left[T_1\right]\cdot\left[T_2\right]\cdots\cdot\left[T_N\right]\cdot\begin{Bmatrix} x \\ F \end{Bmatrix}_0$$

Transfer matrices given above transfers the forces and displacements of the floor below to the floor above. We can write similar equations for the reverse direction, i.e., transferring the forces and displacements of the floor above to the floor below, by simply taking the inverse of the transfer matrices. That is

$$\begin{Bmatrix} x_{i-1} \\ F_{i-1} \end{Bmatrix} = \begin{bmatrix} 1 & 1/(k_i + i\omega c_i) \\ -\omega^2 m_i & 1-\omega^2/\omega_i^2 \end{bmatrix}^{-1} \cdot \begin{Bmatrix} x_i \\ F_i \end{Bmatrix}$$

$$\begin{Bmatrix} x_{i-1} \\ F_{i-1} \end{Bmatrix} = \left[T_i\right]^{-1} \cdot \begin{Bmatrix} x_i \\ F_i \end{Bmatrix}$$

Note that since the equations are all in frequency domain, *x* and *F* represents the Fourier transforms of displacements and forces. The time-domain representation are obtained by taking the inverse Fourier transforms of *x* and *F.*

3.3 System identification and damage location

3.3.1 System identification

For system identification, let us write the transfer matrix equation for the top story, Story *N*, assume for now that the damping is zero:

$$\begin{Bmatrix} x_N \\ F_N \end{Bmatrix} = \begin{bmatrix} 1 & 1/k_N \\ -\omega^2 m_N & 1-\omega^2/\omega_N^2 \end{bmatrix} \begin{Bmatrix} x_{N-1} \\ F_{N-1} \end{Bmatrix}$$

By noting that $F_N=0$ for the top floor, we can write the following equation in the frequency domain:

$$\frac{x_N}{x_{N-1}} = \frac{\omega_N^2}{\omega_N^2 - \omega^2} \quad \Rightarrow \quad SR_N(\omega) = \frac{\left|\ddot{X}_N(\omega)\right|}{\left|\ddot{X}_{N-1}(\omega)\right|} = \frac{\omega_N^2}{\omega_N^2 - \omega^2}$$

where $SR_N(\omega)$ denotes the spectral ratio of the Fourier amplitudes of the accelerations recorded at the *N*'th floor to those recorded at the *N-1*'th floor. It is clear from this equation that $SR_N(\omega)$ has its peak at $\omega=\omega_N$. Therefore, ω_N can easily be identified as the frequency corresponding to the peak of $SR_N(\omega)$.

If we include the story damping in the formulation, the spectral ratio expression would become as follows (Safak, 1995):

$$[SR_N(\omega)]^2 = \frac{\omega_N^4 + (2\xi_N\omega_N\omega)^2}{(\omega_N^2 - \omega^2)^2 + (2\xi_N\omega_N\omega)^2}$$

By making the derivative of $SR_N(\omega)$ with respect to ω equal to zero, it can be shown that the peak of the spectral ratio, including damping, is at the following frequency

$$\omega_{max} = \frac{\left[-1 + \sqrt{1 + 8\xi_N^2}\right]^{\frac{1}{2}}}{2\xi_N}\omega_N$$

For low damping ratios (i.e., ξ_N<0.30), we can show that $\omega_{max} \approx \omega_N$. Therefore, when the damping is included, the peak of top to bottom spectral ratio of the records in a story still gives the natural frequency of that story.

The transfer-matrix equation for the next floor down is:

$$\begin{Bmatrix} x_{N-1} \\ F_{N-1} \end{Bmatrix} = \begin{bmatrix} 1 & 1/k_{N-1} \\ -\omega^2 m_{N-1} & 1 - \omega^2/\omega_{N-1}^2 \end{bmatrix} \begin{Bmatrix} x_{N-2} \\ F_{N-2} \end{Bmatrix}$$

To calculate the spectral ratio x_{N-1}/x_{N-2} for this story, we eliminate F_{N-2} in the equations, and insert F_{N-1} that is calculated from the equations of the story above (Story *N*). By matching the calculated spectral ratio with that calculated from the recorded motions, we can identify the natural frequency ω_{N-1} of the story *N-1*.

By continuing the same procedure downward, we can identify the individual natural frequencies and damping ratios of all stories. If we can approximate the floor masses (e.g., from design drawings or calculations), we can identify the story stiffnesses from the story frequencies.

An alternative procedure for system identification is given below. Consider the (N-1)st floor's response in terms of the N^{th} floor (i.e., by taking the inverse of the transfer matrix):

$$\begin{Bmatrix} x_{N-1} \\ F_{N-1} \end{Bmatrix} = \begin{bmatrix} 1 & 1/(k_N + i\omega c_N) \\ -\omega^2 m_N & 1 - \omega^2/\omega_N^2 \end{bmatrix}^{-1} \cdot \begin{Bmatrix} x_N \\ F_N \end{Bmatrix}$$

Again, starting from the top floor (i.e., F_N=0), we can identify the story natural frequencies and damping ratios by following the steps given below.

1. Assume initially that $\xi_N = 0$ and consider a range of values for ω_N :
2. For each ω_N, calculate $x_{N-1}(\omega)$ and the error $\varepsilon_N = \sum_\omega \left([x_{N-1}(\omega)]_{calculated} - [x_{N-1}(\omega)]_{recorded}\right)^2$
3. Plot ω_N versus ε_N; identify ω_N as the frequency corresponding to minimum ε_N.
4. Fix ω_N and repeat Step 2 for ξ_N; identify ξ_N as the value corresponding to minimum ε_N.
5. Calculate F_{N-1} from the transfer matrix equation by using the identified ω_N and ξ_N.
6. Write the transfer matrix equation for the next story down, and identify ω_{N-1} and ξ_{N-1}.

Performing the identification for natural frequency and damping in two steps does not create an error, since as discussed above, damping does not change the identified natural frequency for low damping values.

The identification procedure outlined above (i.e., starting from the top story and going downward) indicates that the top/bottom spectral ratio of the records at any given story is dependent on the properties of that story and the stories above, but not the stories below. In other words, any changes in the properties of a story would change the spectral ratios for that story and the stories below, but not the stories above. Therefore, when we start the identification from the top story and continue downward, each story can be identified uniquely, because the identification in a story does not change the identified parameters of the stories above.

3.3.2 Damage location

Since the identification procedure outlined above indicates that the top/bottom spectral ratio of the records at any given story is dependent on the properties of that story and the stories above, but not the stories below, any changes in the properties of a story would change the spectral ratios for that story and the stories below, but not the stories above. Therefore, damage in a story would influence the spectral ratios for that story and the stories below, but not the stories above. If we have the records from the damaged and undamaged building, we can locate the damaged floor by comparing the damaged and undamaged spectral ratios. The floor, at which the mismatch of the spectral ratios begins, indicates the damaged story.

We will show this by using the simulated data from a five-story building subjected to same earthquake ground accelerations for the damaged and undamaged condition, as shown in Fig. 3.2. The damage is simulated by reducing the 3rd story stiffness by 50%. As seen in Fig. 5, the spectral ratios for the top two floors are identical for the damaged and undamaged building, whereas for the third floor, where the damage occurred, and the floors below the spectral ratios are different.

It can be shown that the same change in spectral ratios can be observed for any type of excitation, including ambient vibrations.

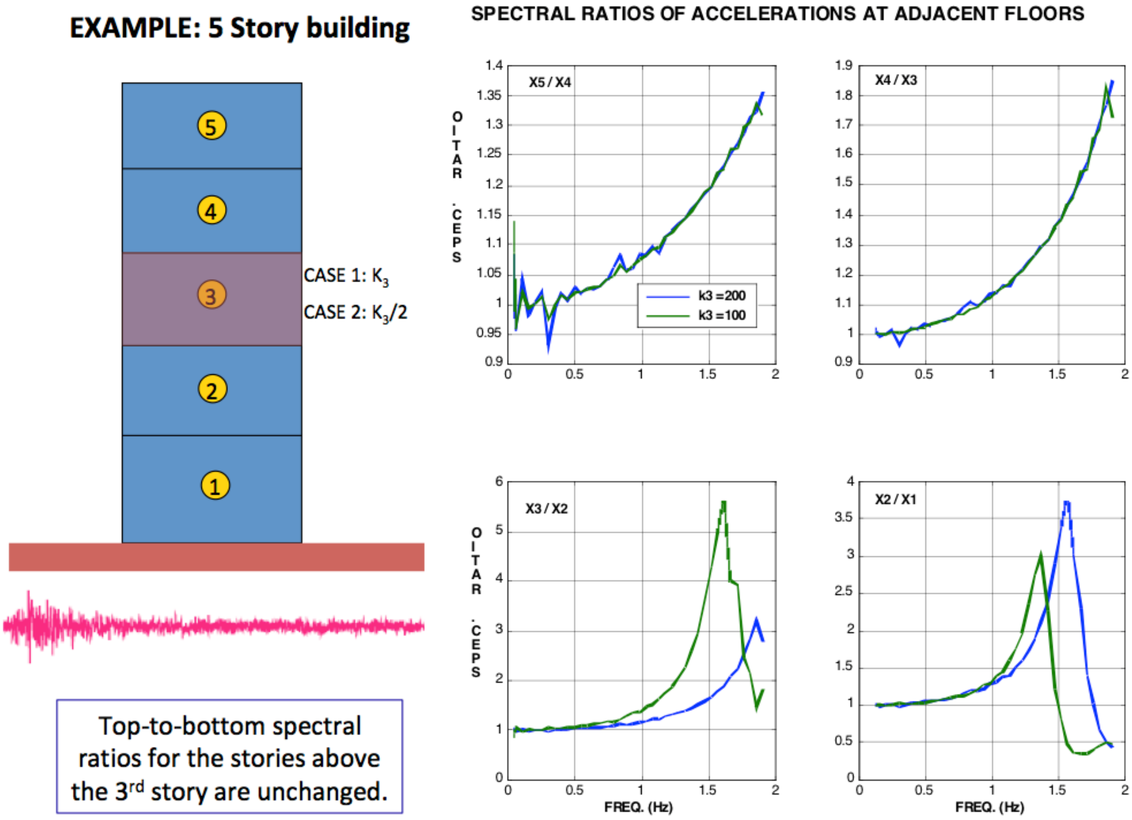
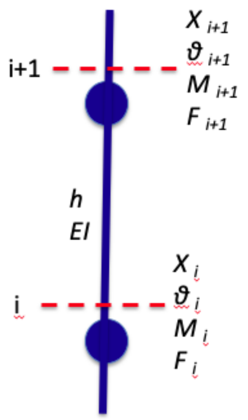


Figure 3.2. Comparison of story spectral ratios of a 5-story building before and after a damage at the 3rd story.

3.4 Transfer matrix formulation including rotational deformations

The formulation given above assumed that the building behaves as a shear beam and deforms mainly in shear. For tall buildings, the rotational deformations are also important and the building's behaviour is a combination of shear and bending beams. Rotational deformations can be included in the transfer matrix formulation by accounting for the rotations and moments at the end of each story. The transfer matrix is now not a 2x2 matrix, but a 4x4 matrix, as shown in Figure 3.3 below.



$$\begin{Bmatrix} x \\ \theta \\ M \\ F \end{Bmatrix}_{i+1} = \begin{bmatrix} 1 & h & \frac{h^2}{2EI} & \frac{h^3}{6EI} \\ 0 & 1 & \frac{h}{EI} & \frac{h^2}{2EI} \\ 0 & 0 & 1 & h \\ \omega^2 m & \omega^2 mh & \frac{\omega^2 mh^2}{2EI} & 1+\frac{\omega^2 mh^3}{6EI} \end{bmatrix}_{i+1} \cdot \begin{Bmatrix} x \\ \theta \\ M \\ F \end{Bmatrix}_{i}$$

For top floor, *N*: $M_N=0$, $F_N=0$

Figure 3.3. Transfer matrix of a story by accounting for displacements and rotations.

3.5 Estimation of motions at non-instrumented floors

As stated earlier, the transfer-matrix approach to system identification of multi-story buildings requires that we have records from every floor. Since this is typically not the case, we developed a methodology to estimate vibration time histories at the non-instrumented floors from those recorded at the instrumented floors.

The methodology assumes that the mode shapes of a building at every time step can be approximated as a linear combination of the mode shapes of a shear beam and a bending beam. The natural frequencies and the mode shapes of a shear beam are given by the following equations, where *n* is the mode number and *h* is the building height.

$$\omega_n = \sqrt{\frac{G}{\rho}} \cdot \frac{(2n-1)\pi}{2h}, \quad n = 1,2,3 \ldots$$

$$\phi_n(u) = sin\frac{(2n-1)\pi \cdot u}{2h}, \quad n = 1,2,3 \ldots$$

Similarly, the natural frequencies and the mode shapes of a bending beam are:

$$\omega_n^2 = \frac{{\beta_n}^4(EI)}{m} \quad \text{wit} \quad 1 + cos\beta L\, cosh\beta L = 0$$

$$\phi_n(x) = C_n\left[cosh\beta_n x - cos\beta_n x - \frac{cos\beta L + cosh\beta L}{sin\beta L + sinh\beta L}(sinh\beta x - sin\beta x)\right]$$

From the records of the instrumented floors, we first identify the modal frequencies, and then band-pass filter the records around each modal frequency to find the modal responses at each instrumented floor. For each mode and at each time step, we approximate the *i*'th mode shape for all the floors by the following equation:

$$f_i(x,t) = C_{si}(t) \times f_{si}(x) + C_{bi}(t) \times f_{bi}(x)$$

where

$f_i(x,t) =$ Amplitude of the i'th mode at location x and time t.

$f_{si}(x) =$ Amplitude of the i'th mode of a shear beam at location x.

$f_{bi}(x) =$ Amplitude of the i'th mode of a shear beam at location x.

$C_{si}(t) =$ A constant; shear beam contribution to modal response i at time t.

$C_{bi}(t) =$ A constant; bending beam contribution to modal response i at time t

To identify the unknown coefficients C_{si} and C_{bi} for each mode and at each time step, we minimize the sum of total error over the instrumented floors between the measured modal response and the approximated modal response. That is:

$$\varepsilon(t) = \sum_{j=1}^{NIF} \left[y_i(x_j,t) - \phi_i(x_j,t) \right]^2$$

where *NIF* is the number of instrumented floors, and $y_i(x_j,t)$ is the *i*'th mode's measured amplitude at the instrumented floor *j*. C_{si} and C_{bi} are determined from the following equations:

$$\frac{\partial \varepsilon(t)}{\partial C_{si}(t)} = 0 \quad \text{and} \quad \frac{\partial \varepsilon(t)}{\partial C_{bi}(t)} = 0$$

Note that since C_{si} and C_{bi} are calculated at each time step and each mode shape, separately. Therefore, the shear and bending beams contributions are time and frequency varying, and they can be considered as nonlinear beams. More detail on the approach, and the examples to confirm its validity can be found in Safak et. al. (2014) and Kaya et. al. (2015).

4 Components of a Smart Earthquake Response Module

Purpose and definition of a smart earthquake response module (SERM)

The purpose of developing a Smart Earthquake Response Module (SERM) is to adopt the existing knowledge base about the relevant aspects of earthquakes into a generic and modular smart-city concept. SERM is considered as one of the components of a modular smart city conceptual model, where individual elements of this module are described following a generic approach. In Figure 4.1 main generic elements of SERM are shown schematically. The concept is based on a three-layer structure, which consists of:

- Modelling systems that are dependent on data provided by various observational systems (e.g. distributed research infrastructures and networks, early warning systems, structural health monitoring systems, and monitoring systems for critical infrastructures) and city inventories (e.g. buildings, infrastructures and resources).
- A Decision Making System based on an integrated diagnostic process using the combined results of a set of relevant scenario-based models and data provided by the real-time automated observational systems.
- Communication/Decision Layers, where technical implementation of automated decision-making systems needs to be combined with clear communication procedures and strategies regarding governance, legal, financial and political aspects.

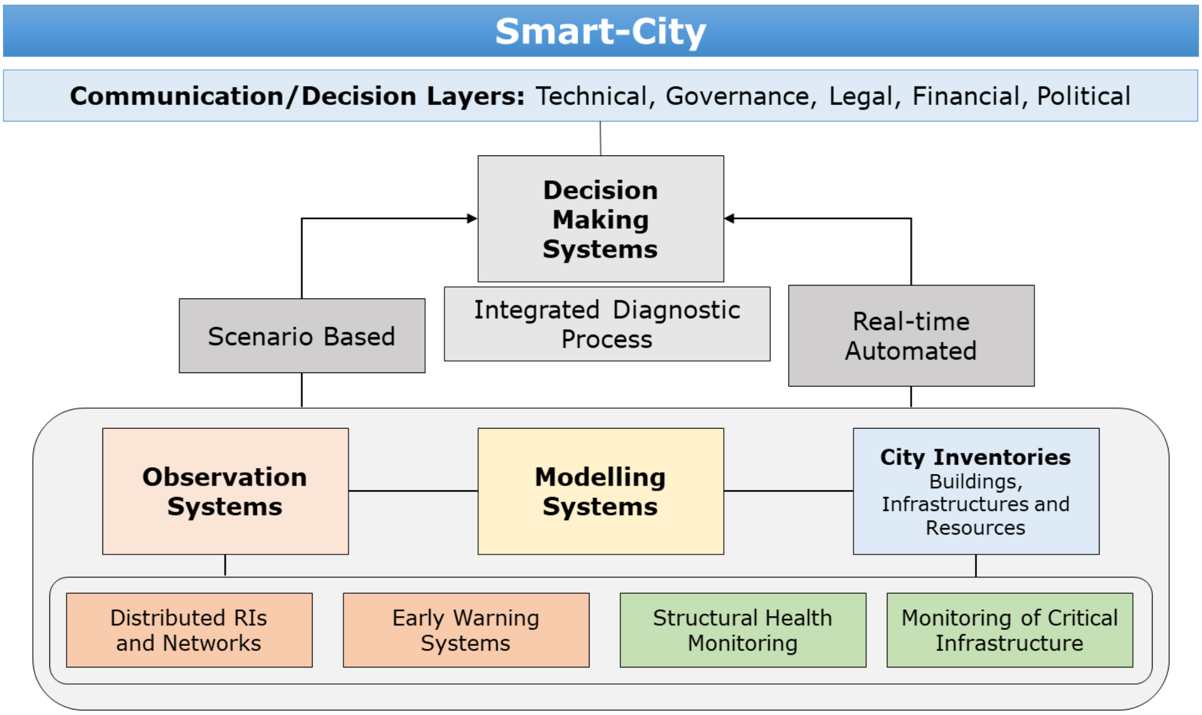


Figure 4.1: Three layers of a generic module as part of a smart city conceptual model.

One important aspect of all these elements involved in the three layers mentioned above, is related to **metadata** describing the properties of these elements in sufficient detail. A rich metadata catalogue is therefore needed to be compiled based on an international standard such as the Common European Research Information Format (CERIF - https://www.eurocris.org/cerif/main-features-cerif), which is adopted in the European Plate Observing System (EPOS – www.epos-euorg).

In order to create an operational **Decision Making System** metadata/data exchange is required between the underlying three main elements of the system:

- Observational Systems
- Modelling Systems
- City Inventories

The **main elements** of the system are dependent upon:

- Distributed Research Infrastructures and Observational Networks
- Earthquake Early Warning (EEW) Systems
- Structural Health Monitoring (SHM) Systems
- Monitoring Networks of Critical Infrastructures

Each one of these **underlying systems** has its own metadata/data standards which require an IT-system that enables interoperability among the metadata/data of the underlying elements. These rely on:

- A common metadata standard and a rich metadata catalogue
- Clear Data Access Policies, and an authentication, authorization and accounting infrastructure (AAAI) system implemented

Unique and persistent identifiers (PIDs/DOIs etc.) for each object in the system

Components of SERM

A generic model of a SERM, consists of two main elements (Figure 4.2). These are:

1. **the real-time monitoring systems, and**
2. **the scenario-based modelling systems.**

The real-time monitoring systems rely on a geographically distributed sensor network to cover the area of concern, where in each node a dedicated sensor package is installed. A typical workflow of a real-time monitoring system starts with choosing a relevant sensor package which may consist of a combination of scientific/technical sensors designed to obtain high-quality measurements of the phenomenon, and lower quality sensors which may be provided by a large number of low-cost smart sensors or citizen science solutions. The decision about sensor package is informed by the understanding of needs and requirements, which will be discussed in detail in Section 4. Each sensor package has usually its own software solution to provide data in an internal equipment/manufacturer specific format, which needs to be harmonized into a single standard format for the entire network. Designing a suitable network of sensors require a careful analysis of the local conditions as well as factors affecting the data collection. Once the data are combined in a centralized unit of the sensor network, it is then possible to conduct additional operations/processing on the data. Resulting processed data is the product of a network data analysis software, which is made available for further use in real-time monitoring operations. The real-time monitoring system needs to be optimized depending on the local conditions through an optimization/training/advisory module. In addition, governance, legal and financial issues need to be coordinated for establishing a system that can be operational for a longer time period. Validation/benchmarking/certification are needed for quality assurance and long-erm sustainability of the system.

The second major element in the system is the scenario-based modelling and simulations, the so-called digital-twins. These are based on various input models that are used in the simulation software which are derived from a knowledge base containing a wide spectrum of multi-disciplinary data and data products from various analyses. Interactions with real-time monitoring systems is required in order to calibrate the simulation results and provide pre-defined scenario-based modelling results for triggering actions in decision making organs and the citizens of the relevant societies. Communicating the results to citizens and other relevant stakeholders to trigger relevant actions in line with the mitigation strategies, is an essential and integrated part of the smart-city concept.

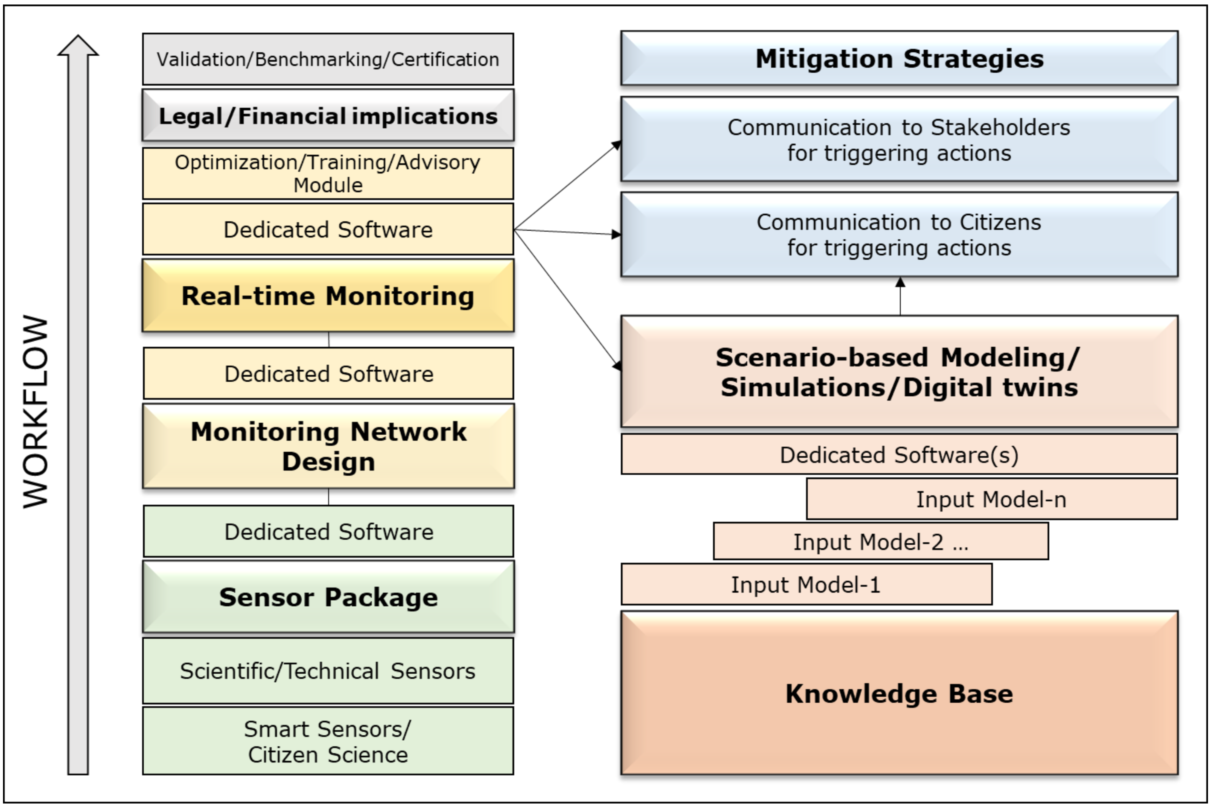


Figure 4.2: Generic components of a SERM.

Central Executive System (CES) of a Smart City

The central executive system (CES) of a smart -city should be capable of activating the relevant modules of the smart-city triggered by an event which has consequences for the society such as earthquakes. The conceptual idea of a modular smart-city and an associated CES is shown in Figure 4.3. Each module of the Smart City may have a different purpose for operations. However, the Central Executive System (CES) needs to be designed to handle in an automated manner the triggering of the various modules relevant to that triggering event. In the case of a large earthquake, a dedicated SERM will be activated and both the real-time monitoring systems and the scenario-based modelling results will be made available for providing appropriate decisions.

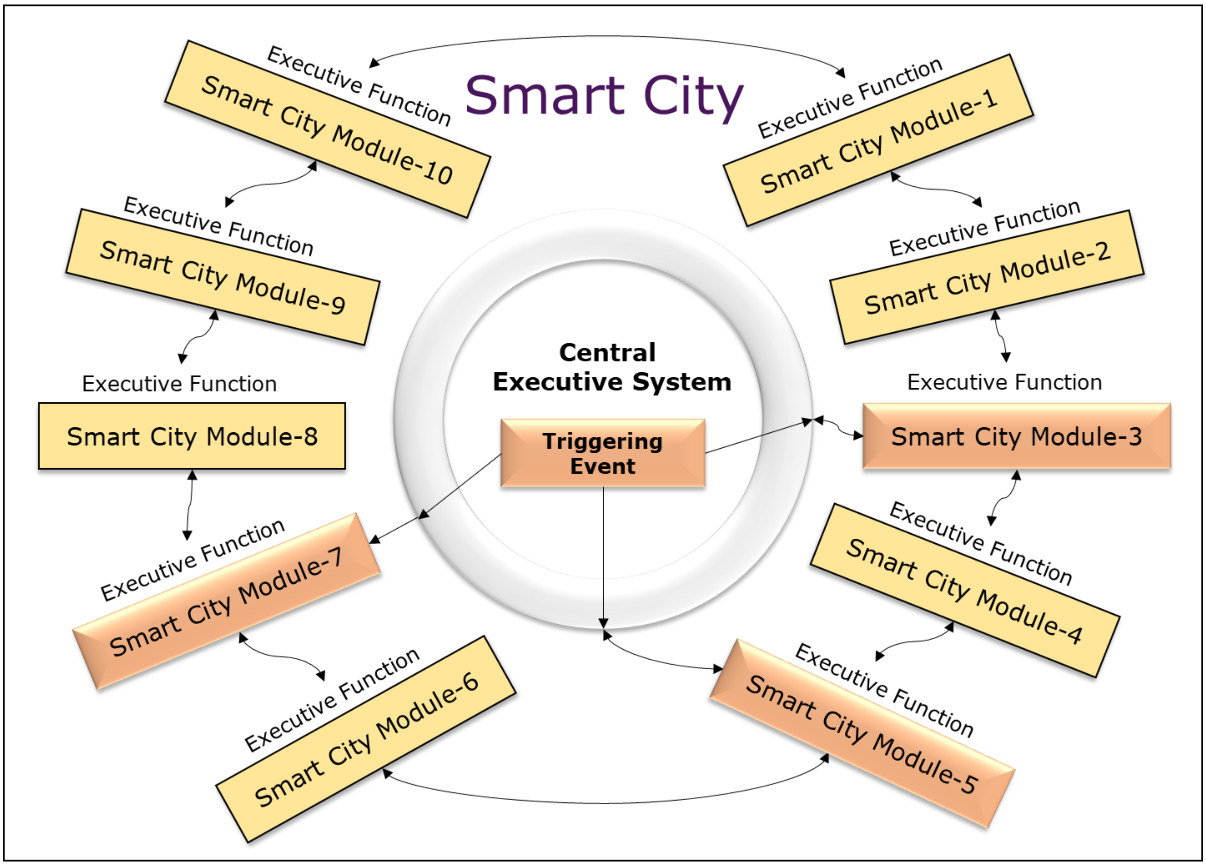


Figure 4.3: Central Executive System (CES) of a smart-city. The SERM can be one of the modules of a smart-city.

5 Service requirement diagnostics

As mentioned in previous sections, identifying the requirements of a Smart City Module (e.g. what data is required and when, what sensors are required, designing the network and real-time monitoring system etc.) can be a significant challenge above and beyond the technical design of those elements in their own right. This section discusses the design and application of a process to illicit those requirements, and illustrates their use in constructing a scenario-based modelling system that can be used for city-laboratory research.

5.1 Methodology of service requirement diagnostics

The Unified Process (Kruchten, 2004) is a widely adopted framework in software development that describe the development life cycle in four phases: Inception, Elaboration, Construction, and Transition (Figure 4.1). This process model applies to the development of a new executive function module, the enhancement of either an existing module or the integration between modules. It highlights the two phases of work to be rigorously completed before the physical construction starts – Inception and Elaboration.

In the Elaboration phase the generic components and workflow model that was discussed in Section 4 (Figure 4.2) can be adapted to develop a detailed system architecture of the module, which enables further examination, de-risking and refinement of the scope, cost, and schedule.

In the Inception phase an integrated set of requirements is generated. The modular design of a Central Executive System reduces functional dependencies between the modules and allows each executive function to take the form that best fit for its purpose and the optimal pace of development according to the resource availability. Despite the modular design, an integrated set of requirements ensure the development of individual modules to work harmoniously as part of a Smart City at the earliest stage as possible.

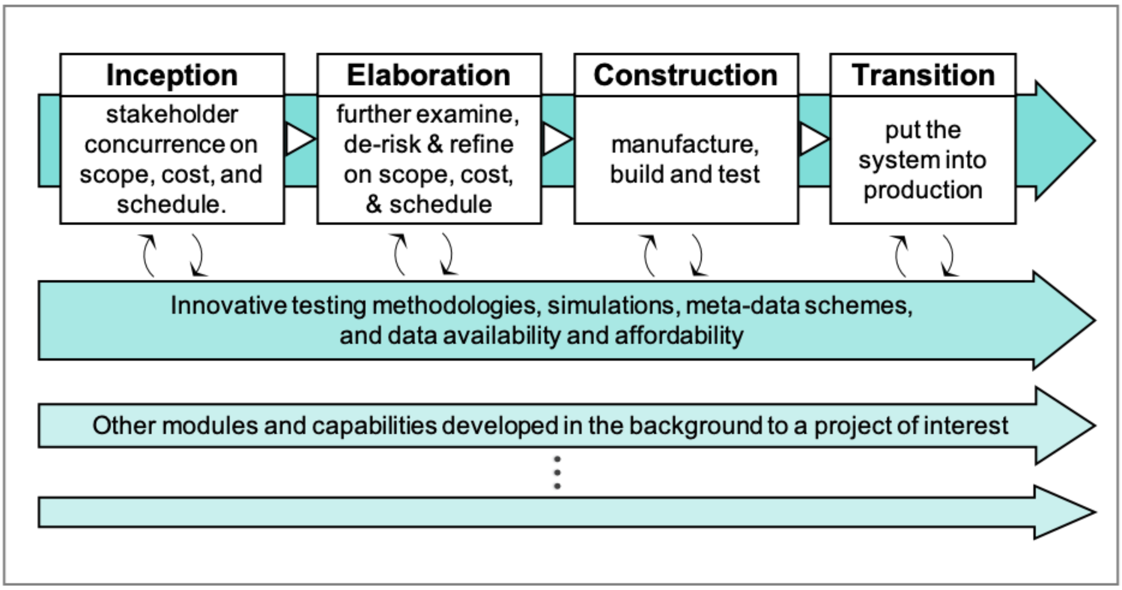


Figure 5.1: A generic process model for developing an executive function module as part of central executive system of a smart city

For the integrated requirement to be effective in guiding the development of individual modules, its generation has to involve stakeholders from all relevant parts of the system including the general public as end users. The requirement generation is a process of collaborative deliberation to structure the problems, consider alternatives, and address difficult decisions on issues such finance and investment, change of regulation, and governance. Similar methodologies have been developed from the domains such as civic innovation and health care (Girouard & Sirianni, 2014; Elwyn, et al., 2014), and are based on principles of collective learning (Priaulx & Weinel, 2018; Daniels & Walker, 1996; Crick, Huang, Godfrey, Taylor, & Carhart, 2017). The *service requirement diagnostics methodology* described in the section is developed to facilitate the collaborative deliberation.

5.2 Framing the system of interest

The service requirement diagnostics methodology starts by identifying the system-of-interest, such as a high-rise building or the road network in a region. Next the stakeholders who have a role in the system and whose decisions and actions are essential to the operation of the system can be identified. Initially, stakeholders will be conceptualised as roles or *personas* that represent generic but distinctive sets of behaviour patterns. The selection of these roles ought to consider:

- People who use the service of the system;
- People who develop and operate the system; and
- People who provide services to the system.

Table 5.1 below illustrates what such a consideration might look like for each of the case studies outlined in Section 2. For example, in the context of Case Studies #2 & #4 service users may include pedestrians and car drivers, system operators may include asset owners and those providing a service might include contracted structural health experts.

Table 5.1: Illustrative sets of stakeholder roles based on the case study scenario

	Case 1: High-Rise Buildings	Case 2 & 4: Urban Road and Bridge Networks	Case 3: Process Plants
People who use the service of the system	– Office workers – Estate service staff – Business visitors – Shop/restaurant customers	– Resident pedestrian – Tourist pedestrian – Resident car driver – Non-resident car driver – Train/Bus passenger	– Production crew – Logistics workers – Office workers
People who develop or operate the system	– Building owner – Estate Manager – Security – First Aider – Health & safety officer – Car parks and traffic management officer	– Bridge owner – Bridge master/operator – Municipality or Council – Maintenance engineer – Police officer – Transport management officer – SHM officer	– Process designer – Maintenance engineer – Security – First Aider – Health & safety officer – Plant owner
People who provide services to the system	– Maintenance engineer for lifts, fire alarm, etc – Water and waste suppliers – Energy suppliers	– SHM developer – Crowd analytics developer – Sat Nav system developer	– Regional transport manager – Water and waste supplier – Energy suppliers – Equipment supplier

5.3 Capturing service user stories

For each role, specific individuals will then be identified and invited to contribute to the exploration of their interactions with the system. The exploration is conducted through facilitated story-telling interviews using the *Service Requirement Canvas* (Appendix 1).

Firstly, the researcher and the stakeholder participant discuss a disruptive event that is meaningful both to the participant and to improving the system of interest. The event can be acute, such as an earthquake, or chronic, such as a delay of an overloaded or ill-managed transport system.

Secondly, they discuss how the event might disrupt a routine of the participant and the participant consider how she might react to the disruption during and after the event. This will then be captured at the top-right quadrant of the Canvas as a brief story of the participant's anticipation, decisions, and actions against the backdrop of the disruptive event.

Thirdly, they discuss the social or infrastructure services the participant will utilise to make those decisions and actions. This is essentially a hierarchical model of a part of the system but built upon the participant's perception of how those things work for her. These services are to be recorded on the bottom left quadrant of the Canvas as a view of the operational dependencies of the system.

Lastly, with the operational dependencies documented, the researcher and the participant are to reflect on how the participant interacts with those services in the past, during the event, and in the future. These interactions are to be recorded at the bottom-right quadrant of the Canvas.

5.4 Generating insights

User stories captured as unstructured data using the Service Requirement Canvas. The data will be parsed and converted into two structured data views:

Hierarchical processes – the services or, otherwise, passive resources a user need to utilise to plan, decide and act. This view reveals one's understanding of the system.

The analysis of hierarchical processes views will reveal differences between individual stakeholders' understanding of the system and how these can be harmonised. Such understanding helps to develop more effective communication between the stakeholders from the earliest stage as possible and to avoid the cost related to miscommunication downstream.

Decision models – a more detailed examination of the decisions one needs to make, including:

Stakeholder role – who makes the decision

Context – situational background conditioning the temporality and scope of the decision

Data - sources of information one draws during the decision-making process

Causal beliefs – pre-existing understanding or assumptions in relation to the decision

Rationale – the criteria or logic underpinning one's decision

The analysis of the decision model dataset will reveal dependencies between the system components and identify data gaps and barriers that stop any of the stakeholders to act effectively.

Insights generated from these analyses will inform the collaborative deliberation on the relevant socio-technological strategies to improve citizen outcome, and to consider whether and where SMART city and infrastructure can become part of a solution.

5.5 Recognising the unknowns

The service requirement diagnostics aims not only to reveal different perspectives among stakeholders and to identify improvement opportunities based on what is known by the stakeholders, it also serves as a process to surface gaps of understanding that were unknown to individual stakeholders or collectively. These areas of 'unknown unknowns' are to be discovered by:

- At the level of individuals, examining the services and resources required for getting one's needs met and comparing with one's own perception before using the tool will reveal the areas that were previously unknown to the individuals.
- Some services and resources might be identified in some user stories as fundamentals to their decisions and actions. If the operation of those services and resources cannot be sufficiently

described by the selected stakeholders, it reveals a gap of understanding in the system as it is currently conceptualised.

Although it is often unrealistic to expect a project to exhaustively explore all it extended dependencies, as that list will be endless, it is important to recognise what the areas of unknown are, assess the significance and potential impact of the gaps of understanding, and determine the boundaries of the system on a conscious decision.

5.6 Pilot applications of Service Requirements Diagnostic

The service requirement diagnostics method is trialled during this project on two cases: the bridge network in Lisbon and the Clifton Suspension Bridge in Bristol. Both methodological case studies are based on a hypothetical scenario that is plausible to the system of interest with an aim to understand the process of applying the diagnostics method.

5.6.1 Pilot Application (1) – Lisbon Bridge Network

The first pilot application of the service requirement diagnostics was constructed around the 25 de Abril Bridge, sitting upon the context of the Lisbon bridges and road network that people use to travel across Tagus river. Many people who work in Lisbon live at the south side of the river, and as there are few bridge connections into Lisbon from the south, the bridges carry heavy traffic every day. The application of the service requirement diagnostics is explored using a scenario where concerns of the structural safety of the bridge arise during peak hours after the impact of a hypothetical disruption.

Data collection

The service user stories were constructed by a researcher engineer from LNEC who is specialised in structural health monitoring and simulation and is regularly consulted by owners of the Lisbon bridges. The author received an exemplar set of service requirement canvas and a brief introduction to the diagnostics methodology before starting to construct these stories. The author was also facilitated by the Bristol team regarding the choice of the disruptive scenario. The perspectives of the following stakeholder roles were explored:

- Resident car driver
- Regular urban train user
- Non-resident car driver
- Police officer
- Bridge operation officer
- Bridge management officer
- Inspection and maintenance officer
- SHM officer

A selection of these stories captured using service requirement canvas are attached in Appendix 1 for reference. Although this set of canvas includes multiple stakeholder roles, it is worth noting that the researcher has more comprehensive understanding of some stakeholder roles and is understandably less familiar with some other roles.

Insights about the use of the diagnostics tool

The purpose of this pilot is to gain insights about the usefulness of the diagnostics tool. The canvases were sent to the Bristol team for analysis, and the findings were played back to and discussed with the author in a virtual meeting for member check. The analysis and the collective reflection session that followed reveal some insights about the usefulness of the diagnostics tool:

1. The service requirement canvas is intuitive to read once populated, but it works better through a facilitated process, as we did in this pilot, as opposed to being used as a self-helped tool.
2. The choice of disruptive event has an important effect on the depth of insights obtainable from the user story.
3. It also takes experience to unpacking a service user's experience and identify the necessary system components, especially to consider it from both hard and soft systems perspectives. Nevertheless, it is a useful way to widen and deepen the understanding of the system.
4. The process of considering and recording the interaction between the service user and each of the service component can feel trivial at time when there are a lot of repetitions.
5. The author felt challenged in constructing the stories of those stakeholders who work in a department the author has not engaged with depth before; this flagged up an area of unknown which led to a subsequent conversation the author had with someone in that role.

Points 3 and 4 indicate an area of improvement for making this tool more accessible, which is to be explored in future research. The observation from the last point is a positive proof of the design purpose of the canvas, which is in helping each of the stakeholders to have a purposeful and focused conversation and to develop a more comprehensive understanding of a system together.

5.6.2 Pilot Application (2) – City of Bristol

The pilot application of the service requirement diagnostics in Bristol took a focus on the Clifton Suspension Bridge and the surrounding road and transport network. The suspension bridge is a cultural icon of the city, but it also provides a safe and convenient passage for people to cross the Avon Gorge. In this pilot, the initial diagnostics was followed by prototyping a scenario-based simulation model to learn about the processes through which the initial insights from the service requirement diagnostics are translated into technical specifications of a computerised simulation model.

Due to its cultural significance, the bridge attracts large number of visitors. In the summer, when the Bristol International Balloon Fiesta takes place just one mile away at the west side of the Avon Gorge, the bridge is also the crossing preferred by many residents and visitors. The volume of crowds it attracts during the festival season poses challenges to those tasked with its operation, and as a result of those challenges the bridge has needed to be temporarily closed during the event. While it doesn't consider a hazard pe se, it was considered a useful disruptive event to be used to conduct the service requirement diagnostics because it involves not only a single piece of infrastructure but also large number of people moving across the road and transport network across the city.

Data collection

The service user stories for the Clifton Suspension Bridge (CSB) was constructed based on understanding about the stakeholders that had been developed through a series of conversations with professionals who have the experience of overseeing the operation of the bridge, structural health inspection, sensor technology development or user decision modelling. The perspectives of the following stakeholder roles were explored:

- Tourist Pedestrians
- Resident Car Users
- Clifton Suspension Bridge Master
- CSB Trustees
- CSB Maintenance Engineers
- Transport Management Officers
- Structural Health Monitoring system developers
- Sat Nav system developers
- Traffic and crowd analytics developers

A selection of these stories captured using service requirement canvas are attached in Appendix 1 for reference. When the method is used to inform an actual project, these stories will have been played back to the representative individual in each stakeholder roles identified for verification and further adjustments. However, this is out of the scope of the current research project.

For the purpose of this case study, which is to understand the process of conducting the diagnostics, these stories were parsed and converted into a hierarchical processes model and a decision models data table. Selected sections of these table are attached as Appendix 2 for illustration.

Insights from the analysis

The analysis of the hierarchical processes and decision models reveals, from a service-centric point of view, the potential contributions of conventional laboratory and city-laboratory to enhance the capabilities of people and technical systems in responding to disruptions caused by natural or human-made hazards.

Ultimately, to reduce the negative impact of hazardous on people's health and wellbeing, it requires those people who are affected to make right decisions and take effective actions. Their abilities to make right decisions and take effective actions in the context of a hazardous disruption depend on their understanding of the situation and possible options. Few people have sufficient knowledge ready in hand because, by definition, the disruption is not part of their usual lives. They need to be supported by technical systems or those trained professionals. It also becomes apparent from exploring the users' decision-making process that there is inevitably a time lag for any message communicated to propagate through technical and social networks then to attract an individual user's attention.

This echoes the workflow described in Section 4 Components of a Smart Earthquake Response Module. It further identifies the need for a more elaborated exploration of social behaviour modelling processes as an underpinning capability of scenario-based simulation, to fully appreciate the range of data required to develop smart multi-hazards response capabilities.

Through the analysis of the decision models data, a potential opportunity for improvement was chosen to be further explore. This opportunity arises from a set of interconnected data needs:

– Pedestrians and drivers who either are joining the Fiesta or have other business to care in the surrounding area can take advantage of a digital route recommendation service that incorporate the near real-time traffic and crowd information so the user can adapt their trip schedule accordingly.

– The bridge operator and traffic management officer of other road sections can make better decision regarding any traffic control measure if they are assisted by a traffic and crowd forecasting model that gives 30 to 60 minutes early warning when the volume is likely to go beyond the service capacity

– The developer of digital route recommendation service can improve their service if their software is connected to real-time monitoring of people movements in the wider area of the city as well as receiving prompt update for any traffic control decisions when they are made.

– Likewise, people in each of these stakeholder roles possess some information that can help others:

– The digital route recommendation service has a record of user queries, which is potentially a powerful indicator of people's intention to travel. Such data can help improve traffic and crowd forecast modelling.

– The bridge operator and traffic management officer can take just one extra step to register their control decisions into a data base and make it available to the developers of route recommendation engine.

– Those pedestrians and drivers can keep themselves up to date with the traffic information and adapt their trip accordingly, which will enact all this information to achieve a more effective transport coordination for all users.

It appears a traffic and crowd forecast model is a critical gap to be filled to connect these data with data needs, and to trigger a virtuous cycle of improvement as illustrated in the figure below. Forecast models that involve people's behaviour are known to be complex to develop, and for this reason, it was selected to be further explored.

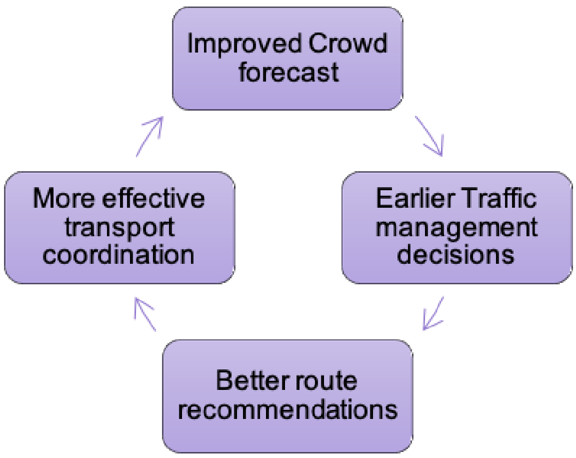


Figure 5.2: A reinforcing cycle of data driven improvement as identified through the decision model analysis from the case study of Bristol Clifton Suspension Bridge

5.7 Scenario Based Modelling/Simulation/Digital Twin: Developing the scope of an Agent Based Model of the Clifton Suspension Bridge

A city is a complex system (Batty, 2009) that is consist of a large urban population and a range of infrastructures. An extreme event, for example, an earthquake or a flood, can be a significant disruption to the city. Simulation based modelling and simulations in smart city applications integrate data collected from real-time monitoring systems and other data sources to aid stakeholders' decision-making processes for better preparation and risk mitigation.

It has already been established in Section 4 (Figure 4.2) that a Smart City module may require scenario-based modelling/simulation/digital twin capabilities to provide additional insights into an observed phenomenon, inform key decision makers, calibrate real-world observation and monitoring systems and plan mitigation actions for anticipated or emerging disruptions.

Computer modelling and simulations are well-understood to be an economical tool to investigate system behaviours and optimise the design and operations of a system. Modelling and simulations are widely applied in different fields. For example, finite element modelling is used to model the behaviour of structures in engineering research. For operational and socio-behavioural research three modelling approaches are commonly used: discrete event simulation, system dynamics modelling, and agent-based modelling.

Discrete event simulation simulates a system that is composed of a series of events. Entities in such simulations go through the events in the system at the event clock time and change states under the impact of the events. A typical application of discrete event simulation is modelling queuing systems. System dynamics modelling is a top-down approach that simulates a system by modelling system entities interact with each other through feedback loops, which is usually based on causal influences identified at the macro level. Compared to system dynamics, agent-based modelling is a bottom-up approach to model micro-level entities (so called autonomous agents) and their interactions in order to study emerging behaviours of the system at macro level. Agent-based modelling is particularly useful in testing the effect of an intervention on a large group of actors, offering a virtual testbed city-laboratory research and the investigations of complex real-world problems and possible solutions. Agents can be built with learning capabilities and decision-making mechanism to simulate people's interactions with the city infrastructure. The relationships among agents can be developed to simulate the social relationships among people and organisations.

Crowd analytics, as identified from the requirement insights as an opportunity for improvement, is a social-behavioural matter and, therefore, places the focus of investigations on socio-behavioural simulations. However, it is worth noting that the same generic method of applying and interpreting the service requirement canvas process is equally applicable to structural behaviour simulation.

Citizens collectively play a vital role in smart city infrastructure development and maintenance, and at the same time, an individual citizen interacts with the city in his/her own way. Therefore, developing an Agent-Based Model (ABM) to carry out crowd analytics is an appropriate approach for the City of Bristol use case.

5.8 The dialogue between model development and service requirement insights

A fundamental design aspect of a simulation model is defining what we know and can provide as the inputs to the model, and what we would like to observe as emergent behaviours through the simulations; this will determine the design of experiments that the model is used to perform. To answer this design question, the insights from the service requirement diagnostics need further deliberations to formulate the core concept to be proved or key questions to be answered using the model and simulations .

The improvement opportunity identified above is the potential of using crowd simulation to bridge the missing link in the virtuous development cycle illustrated in Fig. 4.2. And the key questions to be explored include:

- Is this achievable
- What is the value this improvement can add?
- What kinds of data and complimentary models are required to implement the crowd simulation model?

Two scenarios below are designed to investigate the key questions discussed above

Scenario A - The bridge is closed for the entire time during the simulation

Scenario B - The bridge is operated dynamically based on the information provided by a structural health monitoring system and a crowd prediction model. Pedestrian agents are informed about the bridge closure beforehand thanks to the crowd prediction model in place.

During the simulation, numbers of pedestrian agents present on each section of the road or bridge are to be recorded a timeseries data, as well as visualised on the screen as a heat map. The visualisation can help the observation of the patterns of the behaviour.

5.9 Architecture of the model

Once the scenarios have been captured, relevant actors are picked to populate the model. It is important to identify information gaps and possible solutions to meet the gaps in this stage. For example, whether the information of an actor's behaviours is biased and whether more data needs to be collected to and whether there is available data to support an agent of the actor.

To perform the experiment as set out by the two simulation scenarios, two key actors were chosen from the *service requirement canvas*: tourist pedestrians and Clifton Suspension Bridge and its operators. The ABM models hundreds of people walking to Ashton Court for the annual International Balloon Fiesta through the designed routes. In this model visitors arrive at the city through three locations: Bristol Temple Meads station, the coach station and Whiteladdies Road. These are highlighted with in Figure 4.3 below. Each visitor has his/her preferred stops on the route: Clifton Suspension Bridge, Brunel's SS Great Britain, or no stop.

<u>Pedestrians</u>

Pedestrians are implemented with a built-in decision mechanism to simulate people making decisions when the circumstances change around them. In this model, pedestrians' objectives are set to reach the destination via their preferred route. When the transport system is modified due to heavy crowd flows, the pedestrians in the model will make decision to choose an alternative route to reach their destination. The 'best' route for a pedestrian is decided by two factors: distance and preference.

Clifton Suspension Bridge and its operators

Clifton Suspension Bridge (CSB) and its management team are merged into one single agent that represents a dynamically operated bridge. The bridge is shut down at times during big events like the International Balloon Fiesta. However, using the ABM it is possible to explore the possibility of keeping the bridge open with a real-time structural health monitoring system in place to guard the bridge and benefit citizens and crowds flowing across the city.

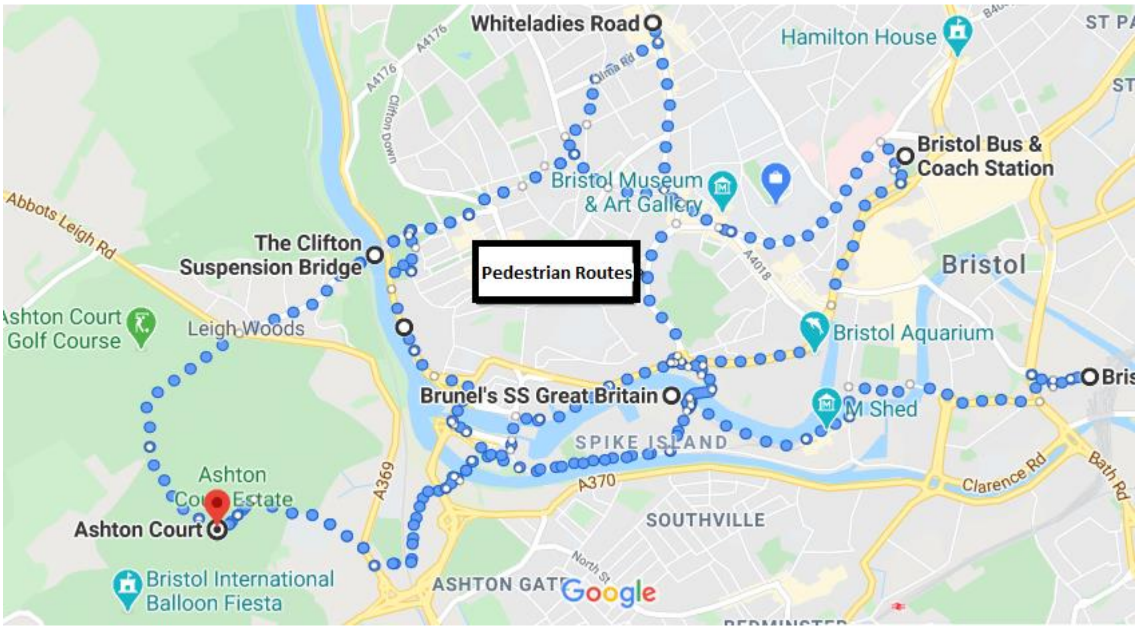


Figure 5.3: Pedestrian routes across Bristol city

The pedestrian agents move across the city with different choices of route and speed. A simplified city map is generated according to the distances based on Google maps and recommended walking routes by Bristol Tourist Office (Figure 5.4). The map includes the aforementioned places of interest for tourists, which are Clifton Suspension Bridge and Brunel's SS Great Britain and Brunel Way, which is an important road to reach Ashton Court from Bristol City area. The destination for all the pedestrians is set to be Ashton Court.

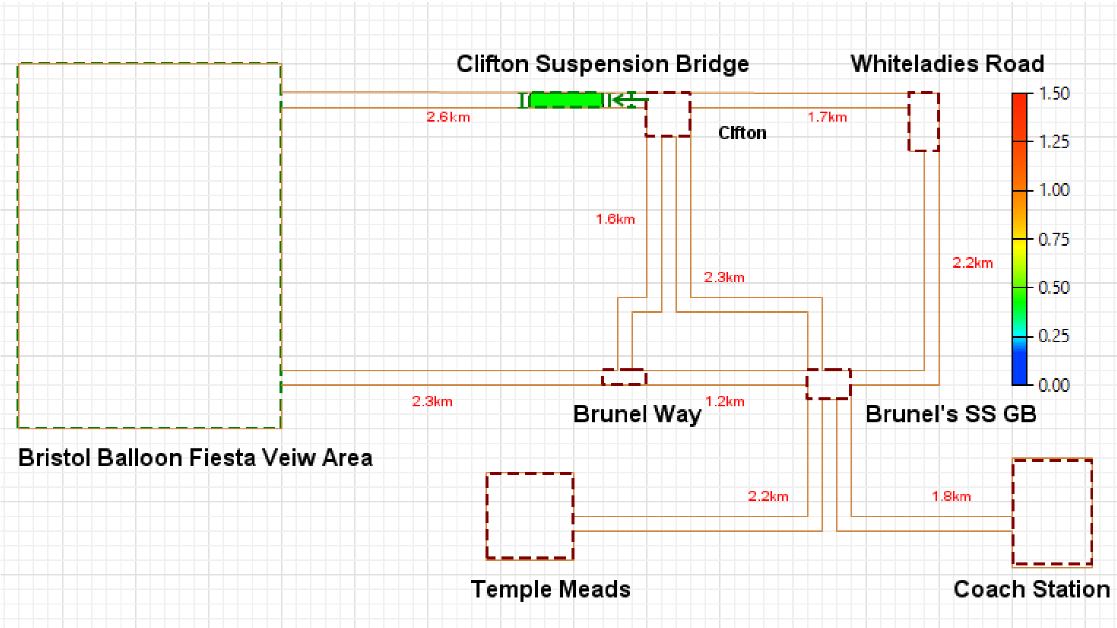


Figure 5.4: A simplified city map in ABM

5.10 Outputs from ABM simulations

During the simulation, researchers can record agents' behaviour as individual or in aggregation, just as they would with agents in the life world. These data can be used broadly in two ways:

1) Real-time data analytics

Most of software used to build agent-based models have the capability to perform real-time data analysis to show the information as the simulation is running. In the Bristol ABM, crowd flows at different locations are displayed in time plots, as well as a real-time heat map (see Figure 5.5 and 5.6). This information can be used to identify critical locations in a city's road networks, which will be the key points to deploy sensors for crowd flow monitoring and prediction. They can be calibrated against real time monitoring using deployed sensors. Combining the monitoring with the models can allow for predictive assessment based on current trends and data. This can inform the knowledge base and decision-making system.

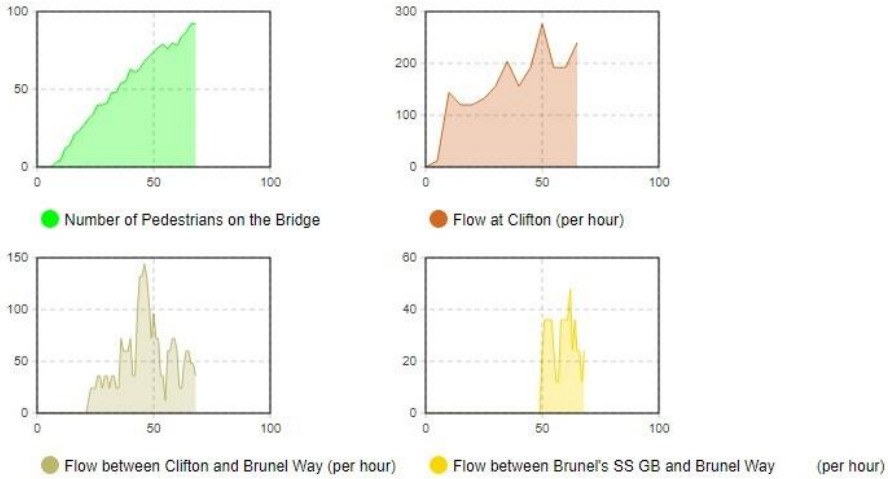


Figure 5.5: Crowd flow at different sections of the road network

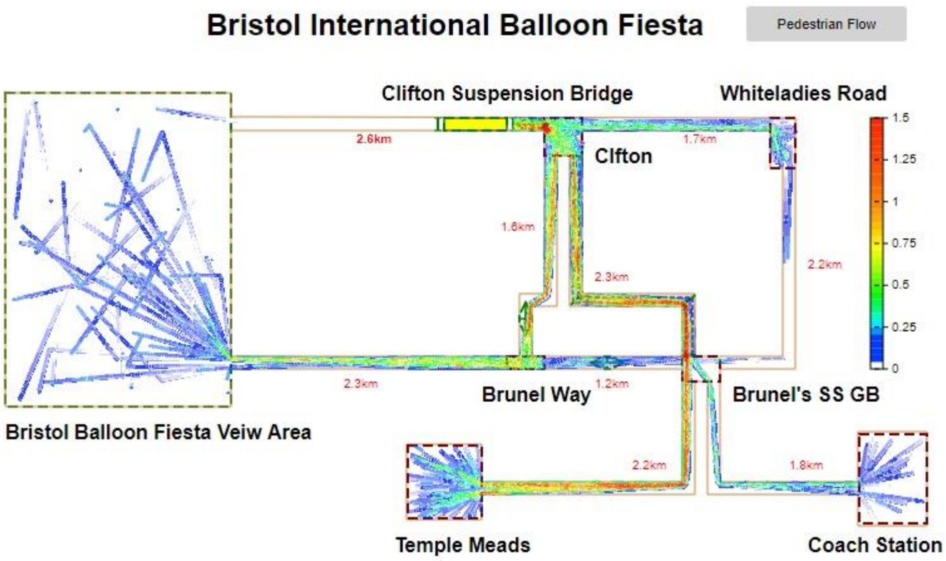


Figure 4.6 Real-time data analytics: Heatmap of the crowd movement

2) Post-simulation data analytics

Data can also be stored and collected after the simulation has finished, to be processed for the metrics researchers intend to observe. In our city of Bristol model, the metrics were chosen as the outcome measures include:

- average travelling time from arrival location to the event site
- average travelling distance in total
- whether a pedestrian visited his/her preferred place during his/her journey

The metrics are useful in comparing the simulated system performance with different configurations to answer research questions such as "does the ability dynamically control the open and closure of the bridge based on SHM output increase the overall service capacity?" Or "does increasing the service capacity of the bridge in this dynamical manner improve the travel experience of the pedestrians?"

5.11 Insights from service requirement diagnostics & simulation model prototyping

The service requirement canvas and the diagnostics methodology are developed to scaffold the engagement with stakeholders in the inception phase of a project. The success criteria for the inception phase is to have achieve stakeholder concurrence on scope, cost and schedule of the development. Although the service requirement canvas has demonstrated its usefulness in the pilot application on the case of Lisbon bridges, it may, as demonstrated in the pilot application on the case of Clifton suspension bridge and the city, fall short in generating sufficient understanding of the technical requirement and achieve a well-informed stakeholder concurrence. Prototyping a potential solution using simulation tool appears to be a complementary approach to service requirement diagnostics.

For example, even though the service requirement diagnostics identified crowd analytics as one of the opportunities of improvement, it, very helpfully, defines a problem space but lacks the specifications of the potential solution to inform the scope, cost, and schedule. The necessary detailed understanding was developed through the dialogue between the perspectives of requirement and outcomes, and the technology and design, or "solution-stimulated problem space exploration."

Through the explorative dialogue, we revealed the gaps in our understanding of some stakeholders, such as:

- How people actually make transport related decision when they are in a tourist mode as compared to a commuter mode

We also advanced our understanding of the technological scope of the potential project, such as:

- Choosing a suitable modelling approach and software platform that are fit for the purpose: there are several software platforms offer the development environment for multiple modelling approaches. It is essential to pick the platform accordingly in consideration of functionality, the length of development cycle (short or long term) and license permissions.

Most importantly, and with greatest relevance to the current investigation, it reveals some critical data-related gaps and challenges in the development of smart city applications, including:

- There are barriers in data collection facility (collection, storage and analysis), regulations on data protection, data ownerships (this part can connect to the metadata)
- There are different models and systems developed for various purposes with different software by practitioners in different sectors.
- Simulation-based models often need to acquire data from other existing models and systems and have the potential to output data to feed into other models and systems. It is essential to develop interfaces between the new model and the existing models.

The lack of good quality data and the cooperability between different data sources is a costly barrier to developing a validated model that can be used dependably in solving a real-world problem.

6 Metadata SHM

As established previously, exploiting the full value of city-laboratory smart city research requires methods which overcome the natural silos of different data, models and services. This section discusses their integration in relation to the Structural Health Monitoring.

6.1 Metadata for SHM

Monitoring capacities of observational systems related to natural hazards such as earthquakes and tsunamis, are an important part of the smart city design regarding risk mitigation. Different case studies from different real time monitored systems from different countries are therefore discussed in SERA milestone 27.1. One of the goals of the European Plate Observing System (EPOS) is to increase our understanding of geo-hazard through sharing of knowledge and data. It is therefore relevant to discuss integration of data, data products, services and software (DDSS) from such real time monitoring systems into EPOS.

In this section, we discuss how multi-hazard research related to Structural Health Monitoring (SHM) systems on critical infrastructure can be integrated into EPOS and what issues that need to be settled before the integration process can start.

Current Status

In milestone 27.1, different case studies from the different WP27 groups were discussed including Structural Health Monitoring Systems (SHM) in Portugal and Turkey and monitoring of process plant in Italy. In addition to this, a generic Smart City design was proposed with potential integration of a smart earthquake response module.

The Kandilli Observatory (KOERI) of the Bogazici University is the responsible institution for SHM of critical infrastructures in Istanbul. The list of critical infrastructures includes historical buildings, bridges, high rise buildings and tunnels under the Bosporus Strait.

For the data management, KOERI has adopted a software based on the COSMOS (Consortium of Organizations for Strong Ground Motion Observation Systems - https://strongmotion.org/) system developed for strong motion observation systems from the US. The software is easy to use and includes extensive search parameters like earthquakes, structural system, soil type and foundation type. The records are made available in two files: One data file (csv-file) and one metadata text or pdf file. KOERI plans to make event data and sample ambient vibration data taken at periodic intervals (e.g 3 months) available for search and download through the new system, but not continuous data from the real-time monitoring systems. The data file will include the time series from an array of relevant sensors and their channel information. A separate software has also been made for inserting new data. Example screenshots are shown in Figure 6.1 and Figure 6.2.

Figure 6.1: Screenshot of KOERI Building Strong Ground Motion Database.

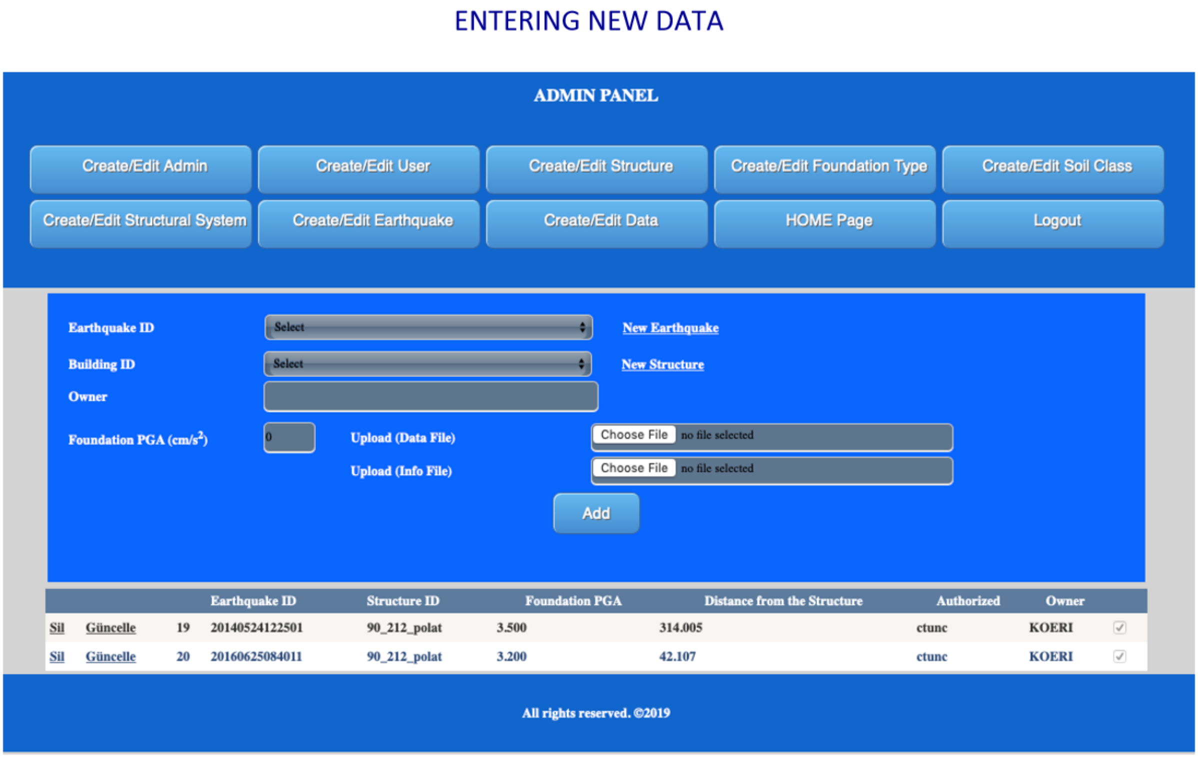


Figure 6.2: Screenshot of KOERI software for entering new data.

The Portuguese National Laboratory for Civil Engineering (LNEC) is the responsible institution for the SHM of critical infrastructures in Lisbon. Structures include bridges and concrete dams. They use a different database and data processing system than KOERI. The system has a hierarchy starting from data acquisition to more and more advanced processing and analysis, as can be seen in Figure 6.3, with the raw data at the bottom and other higher-level data on top. LNEC intends to play a role in Lisbon's goal in becoming a smart city.

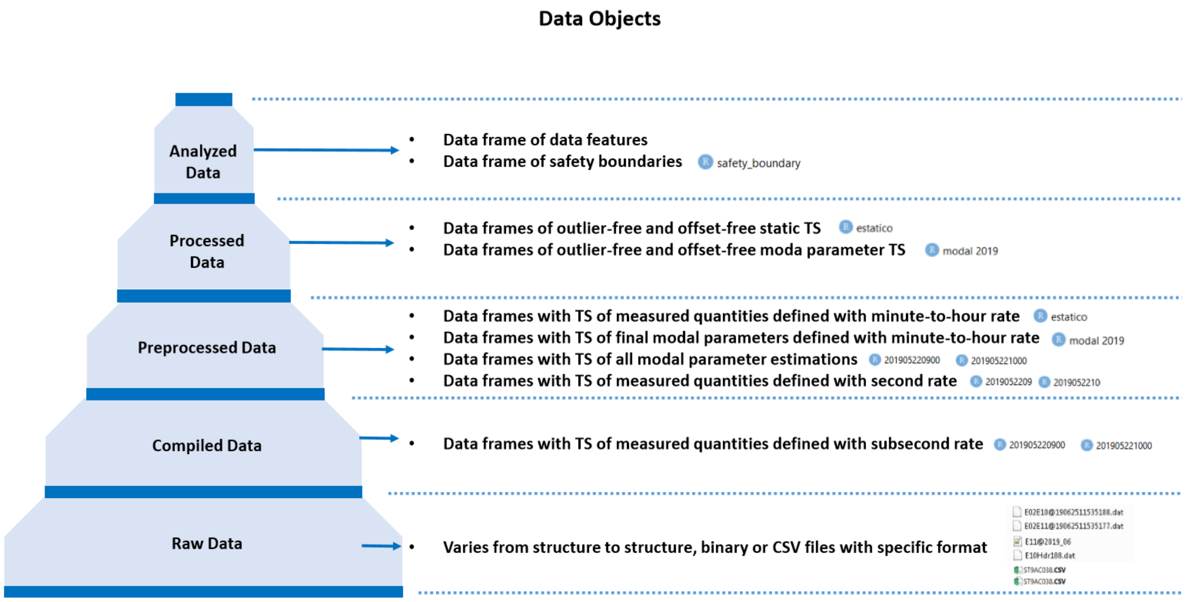


Figure 6.3: LNEC data handling software.

Even though different software and standards are used for LNEC and KOERI, there are obvious similarities because both systems handle similar SHM systems and similar data processing procedures. In addition to this, they both discuss future goals of implementing early warning systems linked to the already existing real time monitoring systems.

6.2 Possible integration of Smart-City concept to EPOS

The smart city concept proposed in SERA milestone 27.1 consists of three different layers; **communication and decision layer**, the **CExS layer** with the decision-making system and the underlying **smart-city modules** consisting of modelling and observational systems with linked information on associated city inventories.

Each of the smart city modules may have different purposes for operation. Examples could be from automated systems fire warning systems, early warning systems for earthquakes, traffic flow monitoring systems, weather monitoring systems and others. An event, such as an earthquake, may trigger one or several of the smart city modules which serve the CExS. Then it is up to the CExS to identify the triggering event and communicate appropriate information and suggested mitigation actions to the decision-making layers. Such a system will require a rich metadata structure at the central system accommodating the complexity and the diversity of critical information from the various the smart-city modules. A standardized internal metadata structure at CExS needs to be decided upon that can communicate with different smart-city modules in an automated manner to query for critical information for harvesting into a centralized metadata catalog.

The workflow between and within each layer is illustrated in Figure 6.4. First, at the smart city module level, we have the high-level data products. These high-level data products can include both real-time monitoring systems, like the local and regional seismic networks and building and structural health monitoring systems, and static data like seismic hazard and risk analysis. The real time monitoring systems may also serve an automated early warning system.

The generic model of a smart-city module consists of two main elements: the real-time monitoring systems and scenario-based modelling systems or the so-called digital twins. The scenario-based modelling is based on various input models that are used in the simulation software which are derived from a knowledge base containing a wide spectrum of multi-disciplinary data and data products from various analyses. Interactions with real-time monitoring systems is required in order to calibrate the simulation results and provide pre-defined scenario-based modelling results for triggering actions in decision-making organs and the citizens of the relevant societies. Communicating the results to citizens and other relevant stakeholders to trigger relevant actions in line with the mitigation strategies, is an essential and integrated part of the smart-city concept.

Before the information from the different smart city modules are communicated to the different stakeholders, the CExS does a search and prioritize the information to decide on the main triggering event. When the triggering event has been decided, external communication is made to different stakeholders. At the decision-making layer, further actions can be in an automated manner or require human interaction.

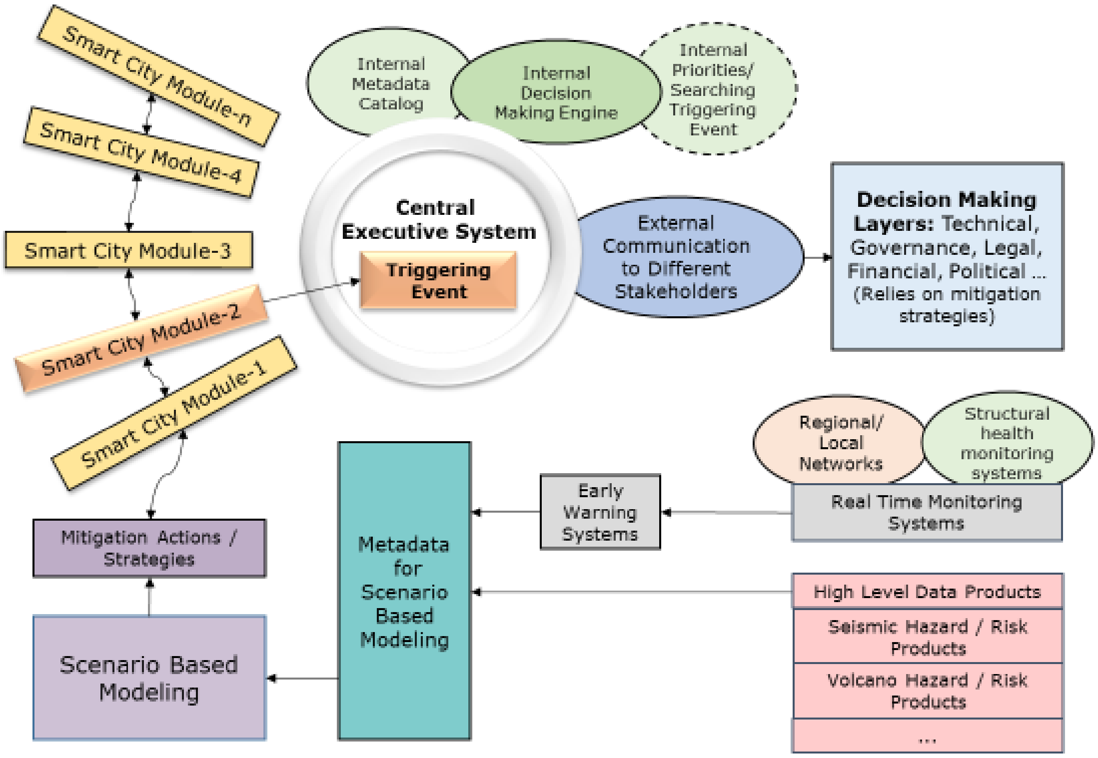


Figure 6.4: Smart City concept, linear illustration.

The different Smart City Modules are run by different data providing institutions. So far, we have discussed a system in which each of these institutions deliver data to the CExS individually. Many of these institutions are already a part of EPOS as different TCS groups. The data and data products from these institutions could, rather than be treated individually, be integrated into the smart city concept through EPOS. Data, data-products, software and services (DDSS) provided by various individual research infrastructures (more than 250) through the relevant Thematic Core Services (TCS), constitute the total EPOS Delivery Framework. As such, EPOS could be one (or several) smart city module(s) and hence be integrated into the smart city concept.

For EPOS to be integrated into the smart city concept (see Figure 6.5), there would need to be a web-service operated at EPOS Integrated Core Service (EPOS-ICS) that would allow for automated and query-based harvesting. EPOS can then provide access to both real time monitoring data and other relevant high-level products needed for scenario-based modelling and mitigation strategies as well as the following mitigation/rapid response actions.

The benefit of integrating EPOS into the smart city concept is that multidisciplinary data are being integrated through EPOS already. This can then potentially save a lot of work.

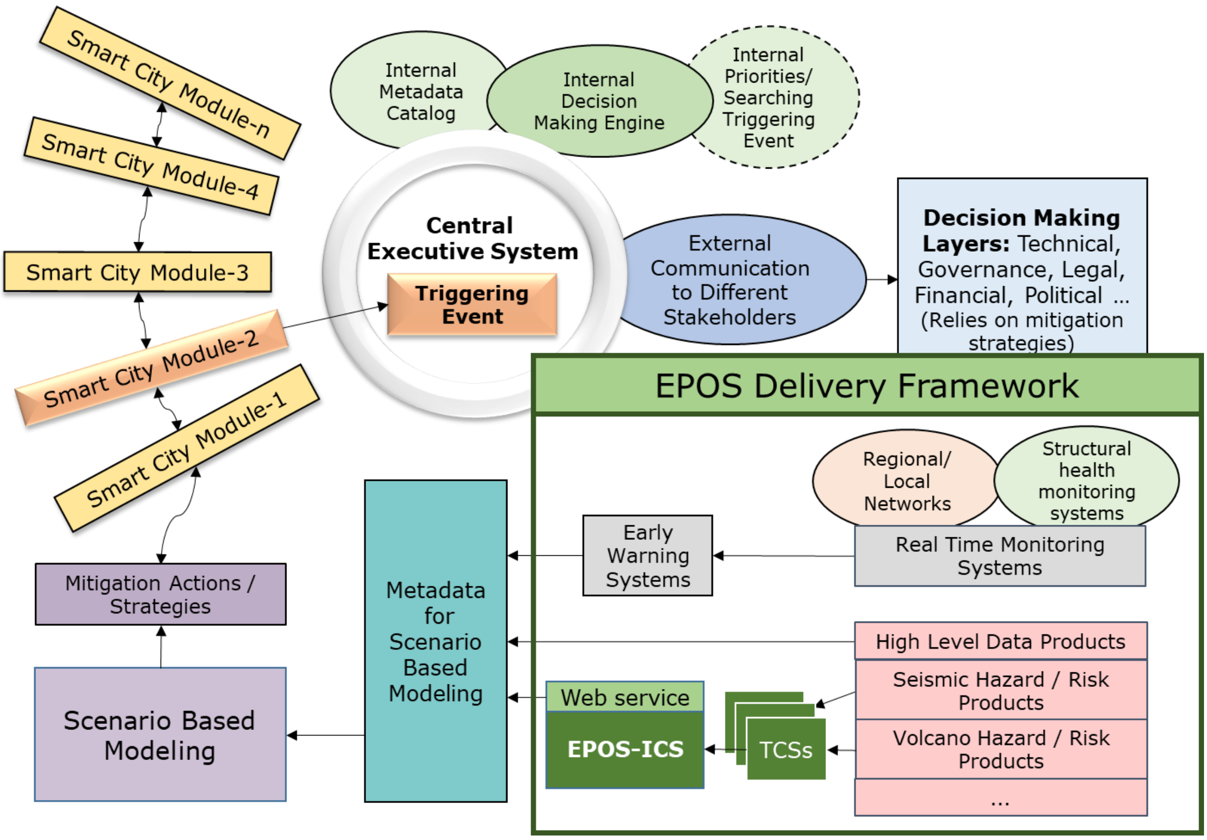


Figure 6.5: Possible integration of EPOS into the smart city concept.

6.3 Possible integration of SHM data products to EPOS

In Figure 6.5, we present a schematic version of an envisaged roadmap for future integration of SHM data into EPOS. In the following we describe this possible roadmap that consists of three parts discussing what is required at the data providing institutions and the centralized service, and a short description of the EPOS ICS and he required additional functionalities (see Figure 6.6).

The first two steps in the entire workflow concerning the raw data and the high-level data products, need to be a part of a system (ideally a standardized database) operated at the data-providing institutions. A "web-service" can then serve as the link to a centralized service. This is a passive service at a local site, which enables machine to machine communication and provide information according to a given set of query parameters. With such a web-service, the "active" side may automatically query and select specific datasets.

The centralized service may include a database of different high level SHM products useful both for domain scientists as well as cross-disciplinary analysis. To achieve a centralized service, a standardized and homogenized metadata structure needs to be decided upon by the SHM community. When a common metadata structure is agreed, then a web-service can be made. The web-service requires that query parameters are defined so that the desired data can be searched, found and accessed. A standardized metadata structure is both needed at the data providing institutions and the Centralized Service. The centralized system may also serve the SHM community.

As discussed, a web-service needs to be operated between the centralized system and EPOS. The first step to integrate the DSS data into EPOS, is to map DSS metadata into the EPOS-DCAT-AP format. From here, EPOS provides automated harvesting from the EPOS-DCAT-AP to the EPOS metadata based on CERIF standard, and the DSS data can be searched, found, accessed and made interoperable with other datasets through the EPOS portal.

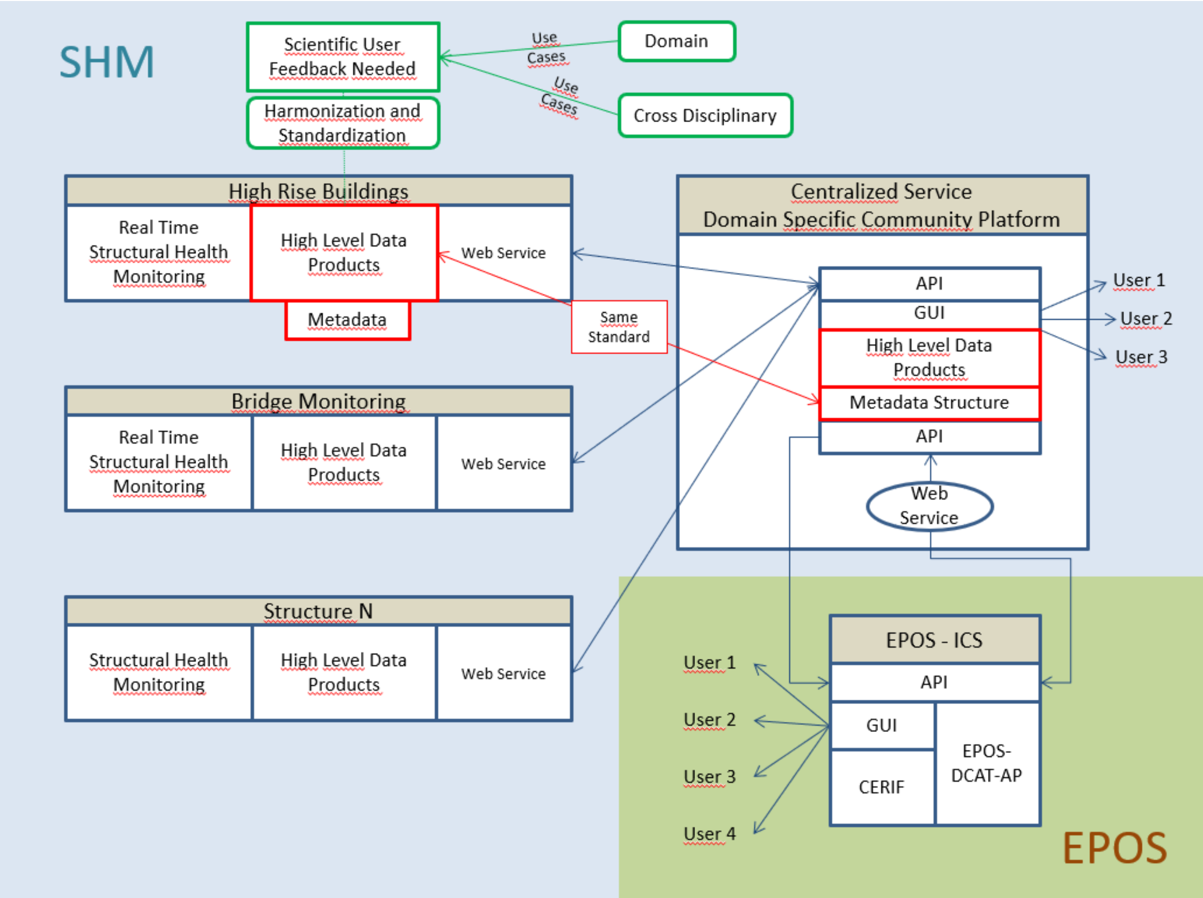


Figure 6.6: Possible roadmap for integration of high-level SHM data products into EPOS.

Harmonizing high-level data products from SHM infrastructures

As a first step towards a harmonization of high-level data products from SHM infrastructures, a list is prepared after discussions among the partners during the WP27 meeting held in Trento (26-27 November 2019). These are summarized below:

In order to develop a roadmap for integration of Structural Health Monitoring (SHM) data to EPOS, collection of various types of SHM data, as practiced among the three groups LNEC (Portugal), KOERI (Turkey) and UNITN (Italy) have been presented and discussed during the meeting. It became clear that there are some commonalities in the high-level data products whereas differences exist in data collection procedures, data formats, processing routines as well as archiving and curation among three institutions gathering SHM data. In the context of further integration of SHM data to EPOS, the critical point is to identify the possible users of the SHM data or data products. In the following we present a short summary of user groups with relevant use cases, list of high-level data products of common interest, details of the data and data products as well as their relevant metadata elements.

User groups:

- Domain scientists/researchers in earthquake engineering and SHM
- Researchers from other relevant domains such as seismology (e.g. seismologists working with earthquake hazard and risk, engineering seismologists working with strong ground motion), structural engineering, geotechnical engineering, etc.
    - Ground Motion (GM) modellers (kinematic/dynamic) (using finite fault models, fault rupture initiation and propagation for seismic waves generation, including further seismic wave propagation in a crustal velocity structure and complex 3-D near-surface geological structures) for calibration and comparison of their synthetic seismograms with recorded strong GM data from large earthquakes.
    - Shake-map developers for calibrating automated shake-maps with recorded strong GM data from large earthquakes.
    - External structural designers
    - Seismic design code developers for checking the underlying assumptions.
    - Geotechnical engineers for assessing local site characteristics
- Public authorities such as:
    - Municipalities
    - Emergency response units
    - Infrastructure managers/owners

High-level data products:

- Response spectrum
- Design spectrum
- Fragility curves for a complete system or system components
- Period vs building height/type
- Damping vs building height/type

In the following, details for *response spectrum* is given as an example. All other high-level data products and their metadata descriptions need to be prepared.

High-level data product: Response spectrum – details of data

- Ground motion time series from earthquake records
- Data presented as ground motion values at different periods
- Ground Motion (GM) (as pre-processed data where instrument response and baseline corrections are applied) represented as spectral accelerations/velocities/displacement
- GM can be represented by up to 15 different ways such as:
    - Peak ground accelerations (PGA)
    - Peak ground velocities (PGV)
    - Arias intensity
    - Spectral intensities at different periods
    - Top displacements
    - Displacements at different levels (e.g. storeys of the building)
    - etc.

High-level data product: Response spectrum – Metadata

- Functional elements
    - Metadata for GM time series from earthquakes
    - Metadata for acceleration vs period
    - Location of the structure
    - Location of sensors
    - Soil conditions
    - Foundation properties for soil structure interaction
    - Maps showing GM distribution (e.g. PGA maps)
    - etc.
- Non-functional elements
    - Persons
    - Organizations
    - Access rules
    - Legal issues
    - etc.

Additional work is needed in order to define the details of the high-level data products from the SHM infrastructures and how these can be further translated into a common metadata structure. As such the above list is a good start for this.

Discussion

Regarding the roadmap for integration into EPOS, we recognize a need for the SHM community to discuss and agree on critical decisions. The first issue is regarding community standardization. For the integration of SHM data into EPOS, a community standard is crucial. One choice might be to decide on one of the already used systems, like KOERIs COSMOS. Alternatively, any other standard the community may decide upon can also be adopted. Included in this is the decision regarding a common metadata standard for the SHM community. If such a common community standard is not decided upon, integration into EPOS would require that each separate system needs to adopt the EPOS internal metadata standards individually. This will create substantial additional work for the individual data providing institutions

The community also needs to decide upon what high level data products that they would like to share. This will require user feedback from domain specific scientist, but also cross-disciplinary user feedback is beneficial, as once these systems are accessible through an open system, then the external user requirements may differ. The raw data is mainly of use to the domain specific scientist and the domain specific scientist do in general already have access to this data. It is therefore natural to focus on what high level data from the SHM community that could be useful for other scientists from other domains. In this regard, in the section above a first attempt for defining the user groups and high-level data products from SHM infrastructures are given.

A discussion should also be held about data availability and possible data restrictions especially regarding real time monitoring data. If the real time monitoring data and information related to early warning systems are restricted or need to be kept confidential due to ownerships, legal implications etc., then this type of data may be in conflict with the open-access policy of EPOS. In this regard, it is worth discussing the possible role of EPOS role in the smart city design. In this report, EPOS is suggested as a smart city module, and real time monitoring data do not necessarily need to be channelled through EPOS.

Even if the EE community decides not to implement real time monitoring data to be integrated into EPOS, the integration of retrospect event data and sample ambient vibration data taken at periodic intervals can be done, nevertheless. Including other high-level data that might be of interest to a broader range of the scientific community.

6.4 Integration of the proposed framework to SERIES-EPOS

The roadmap for the integration of databanks and access services from the EPOS and SERIES platforms (see Deliverable WP6:D6.5) follows the most immediate approach in realizing the integration, namely to consider the SERIES database as the first service of a new Earthquake Engineering Thematic Core Service within the EPOS architecture. By following this approach, SERIES targets as a first step at providing, through EPOS, integrated access to key data and experimental results produced at the most advanced European experimental facilities for earthquake engineering. In its mature phase the integration process will provide advanced interoperability within the earthquake engineering community in total, with the sibling TCS seismology and other TCSs, and with international partners.

For the scope of the pre-operational access service of SERIES-EPOS integration, access to selected SERIES datasets has been provided via EPOS, in order to allow validation of identified access technologies for further implementation in EPOS. Surpassing technical details, the steps taken in realizing interoperability between EPOS and SERIES comprise:

1. Identification of specific datasets to be selected for the validation of EPOS-SERA interoperability.
2. Development, deployment and evaluation of the pilot TCS metadata retrieval web service, hosted in the SERIES Central Site.
3. Development, deployment and evaluation of the TCS data publication service.
4. Production of the TTL-description (Turtle files) for the TCS metadata retrieval web service (as per EPOS-DCAT-AP model). The TTL-description that was developed can be found at https://github.com/seriescentralnode/EPOS-DCAT-AP.

The TCS Metadata Retrieval web service is completed and operational (Figure 6.7). Within the TCS, the chain of data publication, i.e. description of data through the appropriate metadata format, discovery and dissemination via the ICS-C, is fully supported.

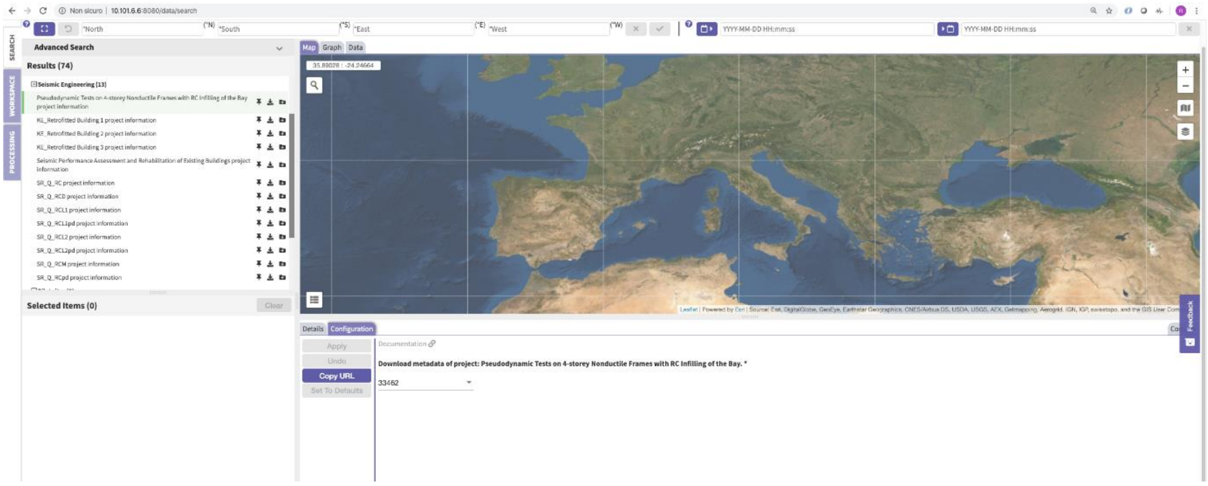


Figure 6.7: View of the ingested SERIES metadata in the EPOS-ICS development portal.

SHM data is not much different than structural testing data and, in that respect, could be easily described by SERIES EDF format. The technical work for providing a new, versatile way of storing and visualizing data at local nodes (individual labs) and importing it in SERIES Data Access Portal led to the development of Celestina Data Viewer, **CDV**, a Web-based application to interact with distributed data sources from the Celestina Data network. It comprises a graphical user interface to manage and interact with data as well as an Application Programming Interface (API). CDV replaces the older version of the local databases at collaborating laboratories. To make the CDV nodes compatible with the SERIES Database, ***SERIESConnector*** was developed as a software component of a CDV node to convert data hosted in a CDV node into SERIES Exchange Data Format (EDF), thus allowing the uploading of metadata from a CDV node to the SERIES Database. Using the SERIESConnector, a CDV node can participate as a partner laboratory in the SERIES database. The SERIES Central Site web service connects to a CDV node's SERIESConnector to retrieve data from the node.

One can upload data to CDV via a Matlab script (provided) and then ***SERIESConnector*** informs SERIES DAP on the availability of new data and, as shown above, makes it visible to EPOS as well. The process is straight-forward and does not require heavy operations. The real-time nature of SHM data is a characteristic that is not supported by SERIES DAP. On the other hand, it is not actually real-time raw data that a user is seeking (as acknowledged in the previous section, these interest more the domain specific scientists), but rather high-level data from the SHM community. As such type of data is a result of intense elaboration, SHM high-level data are not produced and made available in real-time. On the contrary, confidentiality, ownership and legal implications may, as also identified in the previous section, pose restrictions in data availability: as the time at which data is made available to SERIES DAP is decided by the local node level, data owners have complete control over the release of data to external users (despite that data may have already been stored in their local database).

Due to the affinity of SHM data to structural testing data, it seems that the most straight-forward and economic approach is to step on what has already been developed, avoiding creation of many overlapping systems and taking advantage of the achievements realized so far regarding SERIES-EPOS integration. In doing so, a better integration of the Earthquake Engineering community itself will be attained and its eventual evolution to a EPOS TCS made easier.

The picture regarding smart city data and services appears completely different and, as concluded in the previous section, it would be EPOS to be seen a smart city module rather than the opposite. However, this not only requires a different approach, but also might have to be pursued after a critical mass of such smart-city-systems are made available and operational and relevant experience is gained.

7 Conclusions

City-laboratory research can be approached through the lenses of Smart Cities and Living Laboratories. Smart City and allied approaches provide the means to observe, measure and analyse real world urban systems. Living Laboratories allow for experiments to be conducted in real operational settings with the participation of their actors and beneficiaries. This report assesses the potential of city-laboratory multi-hazard research in terms of the value it could offer and the challenges to full exploitation.

Section 3 presented a substructuring methodology for system identification and damage detection in multi-story building. The methodology is based on the transfer matrix formulation of the response, where each story is assumed to be a substructure. It shows that the top/bottom spectral ratio of the records at any given story is dependent on the properties of that story and the stories above, but not the stories below. In other words, any changes in the properties of a story would change the spectral ratios for that story and the stories below, but not the stories above. This provides a simple means to identify the damaged story. The approach requires that records from every floor are available. Since this is not typically the case, a methodology to estimate vibration time histories at the non-instrumented floors from those of the instrumented floors was presented. Thus, the critical role and value of analytics is demonstrated in the context of hazard management for infrastructure assets.

A modular Smart City concept is outlined in Section 4, where each module consists of three layers: modelling systems, decision making systems and communication/decision making. The modelling systems are themselves dependent on observational systems. A Smart Earthquake Response Module is conceptualised, comprising a real-time monitoring system and a scenario-based modelling system.

General challenges to exploitation, and therefore the potential to undertake city-laboratory based multi-hazard research, include understanding the human-factors and service requirements of critical infrastructure systems, modelling complex urban scenarios and integrating diverse data, data products, services and software.

To address the first of these challenges Section 5 proposed a Service Requirement diagnostic tool to assist in the early phases of a typical Smart City module design workflow. This tool involves the identification of key stakeholders and suitable disruptive events though which to frame discussions about the interactions and use with the urban systems of interest. The tool facilitates collaborative deliberation to arrive at an understanding of how the stakeholders interact with the built environment under several scenarios, the decisions they make, and the information that informs those decisions. This can be used to inform observation systems, modelling systems, analysis, decision making and communication to ensure they are of value. The analysis of users' decision-making processes broadly agrees with the workflow and the modular design described in Section 4 but further identifies the need for a more elaborated exploration of social behaviour modelling processes as an underpinning capability of scenario-based simulation, to fully appreciate the range of data required to develop smart multi-hazards response capabilities.

The diagnostic tool also facilitates the development of the scenario-based modelling component of a Smart City module like a SERM. Section 5 demonstrated this though the development of an Agent Based Model which shows the potential value of such approaches to understand the behaviours of actors when interacting with the built environment.

Finally, different data, data products, services and systems exist within and between Smart City modules. To fully exploit the value of the city-laboratory research it is necessary to overcome the barriers established by the various formats these take and integrate them in a coherent and meaningful way. This can lead to new insights and facilitate learning across different communities of research and practice.

What value can city-laboratory based multi-hazard research offer in theory?

- Better informed investment decisions by systemic understanding of the urban infrastructure and as a result the money is used in places that need those improvements most in order to achieve the desirable citizen outcomes.
- Better understanding of the resilience of the city against risks posed by natural hazards and climate changes
- Develop mitigation strategies and improving safety outcomes for citizens
- Understanding what data is available and what additional data is required for developing a Smart City
- Harvesting and curating existing and new data and making it available to professional communities to accelerate innovation
- Developing novel methods to realise the potential of big-data created by joining up diverse sources of data across the city

To what extent can city-laboratory based multi-hazard research be conducted in practice?

- There are some mature observation systems available that can be connected
- There is some mature real-time monitoring software and services available
- There are decision making process which utilise the outputs of these to provide information to stakeholders
- Multi-hazard research can be conducted in areas where a matured observation system exists, and the decision model is well articulated
- It is less clear what data is required by the stakeholders to make decisions and take actions effectively
- Capability to model complexity at city scale is still to be developed
- Combining the above three points about needs, data and modelling, respectively, the overall challenge appears to be developing methods to meaningfully condense large amount of data into a manageable set of insights to inform stakeholders' decisions

Future Roadmap

Looking to the future, there are several outstanding challenges and areas requiring further development in order to fully benefit from the potential of city-laboratory based multi-hazards research. There are numerous technical challenges within specific domains, but the significant general barriers emerging from the discussions in this report can be grouped into two themes:

1. Understanding complex city-scale systems and the requirements of their inhabitants
2. Integrating diverse data, data products, services and software.

The first suggests that robust mechanisms for engaging with infrastructure end-users and other city stakeholders should be developed along the lines of the proposed service requirement diagnostic tool. Once established this can be used to identify decision making processes and data requirements, which can in turn inform the collection of meaningful data where it is currently overlooked. There are challenges in collection and storage of data relating to regulation and ownership that will need to be addressed. While Agent Based Modelling provides a powerful way to simulate city-scenarios, but further work is required on the validation of such models. It is also true that they will only ever paint a partial picture of the complexity of the urban environment. Finite Element models and other quantitative approaches can provide insights into infrastructure asset condition and behaviour, but other modelling techniques will need to be developed and implemented in this context. This leads on to the second point relating to the interface between models, data products and services.

Turning specifically to EPOS, there is a need to develop a service that would allow for automated and query-based harvesting of data. Additionally, raw-data and data products need to be part of a standardized database. If centralized this could offer high-level data products to distributed domain scientists and cross-disciplinary analysis. In the long term there may be scope to provide additional harmonisation to the diverse data collection procedures, data formats, processing routines and archiving methods. Practicalities, legacy systems and local policies may render this impossible. The same outcome can be achieved through the development of a common metadata structure. In practical terms this would mean integrating the data, data products, software and services into EPOS, by mapping the metadata into the EPOS-DCAT-AP format. The critical point is to identify possible users of the data and data products. This can be facilitated by something akin to the service requirement diagnostic tool proposed above, while a summer of uses cases if provided in Section 6. Additional work is needed to define the details of relevant high-level data products.

There is a need for engagement and collaboration across the community to agree critical standardization questions. If common data standard cannot be agreed, then each separate system would need to adopt the EPOS internal metadata standards individually, creating additional work for individual providers.

An understanding of service user requirements will be necessary to inform decisions about why high-level data products should be shared. It will be equally necessary to establish any data restrictions from the community, particularly those regarding real-time monitoring.

The simplest and most economic approach is to take advantage of the achievements realized so far regarding SERIES-EPOS integration (e.g. SERIESConnector). In doing so, a better integration of the Earthquake Engineering community itself will be attained and its eventual evolution to a EPOS TCS made easier.

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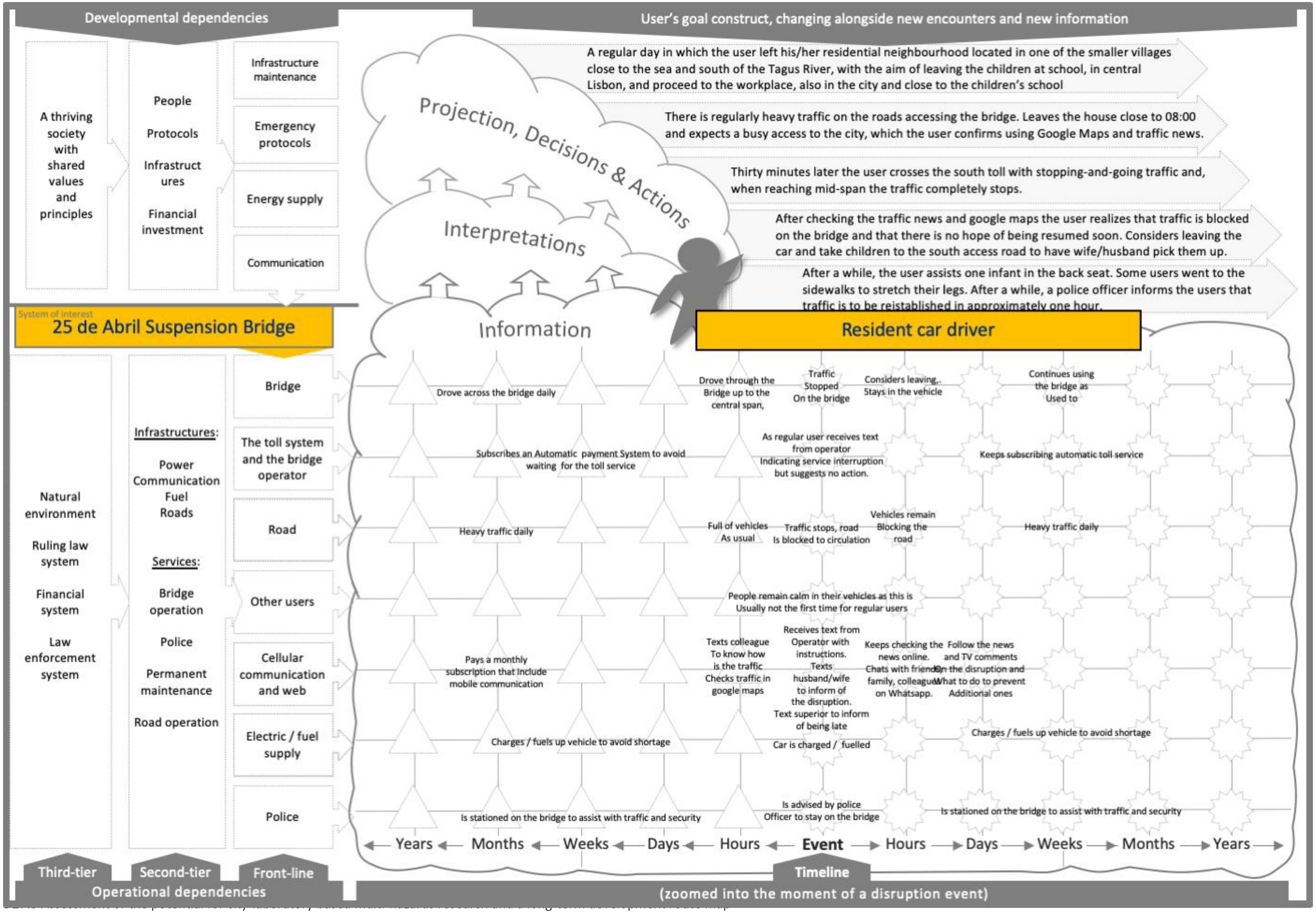
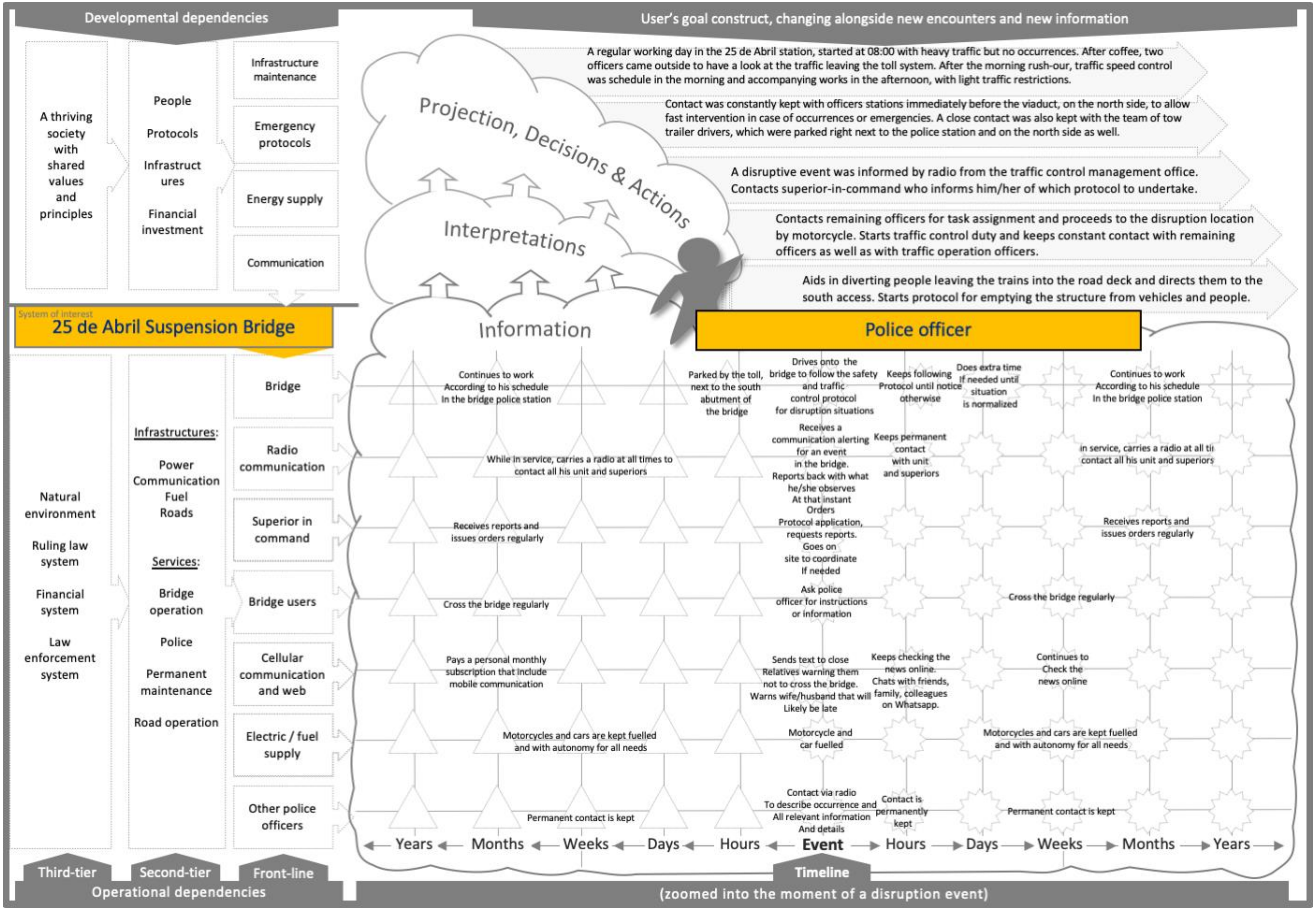
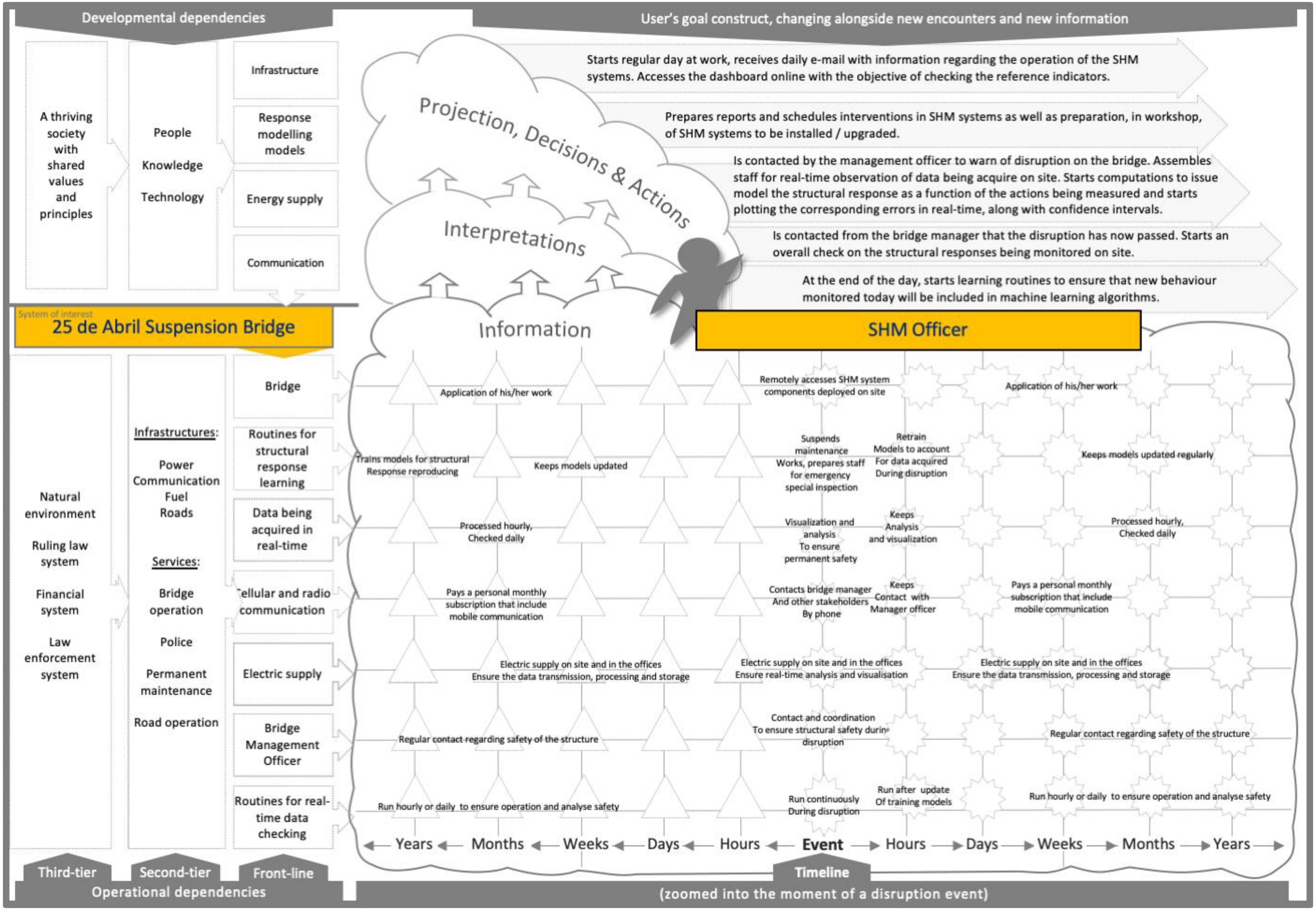
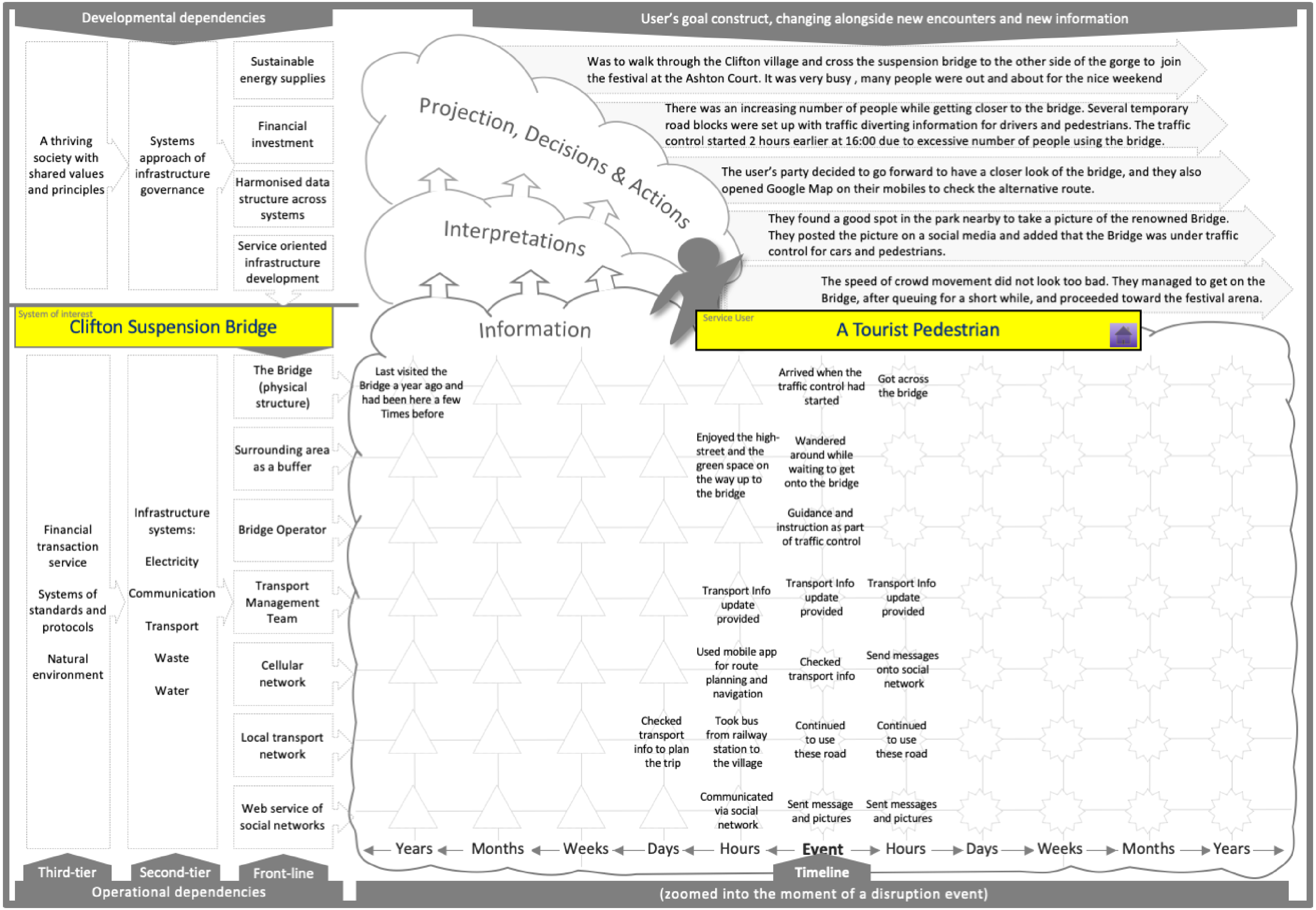
Appendix 1: Illustrative Service Requirement Canvas from pilot applications

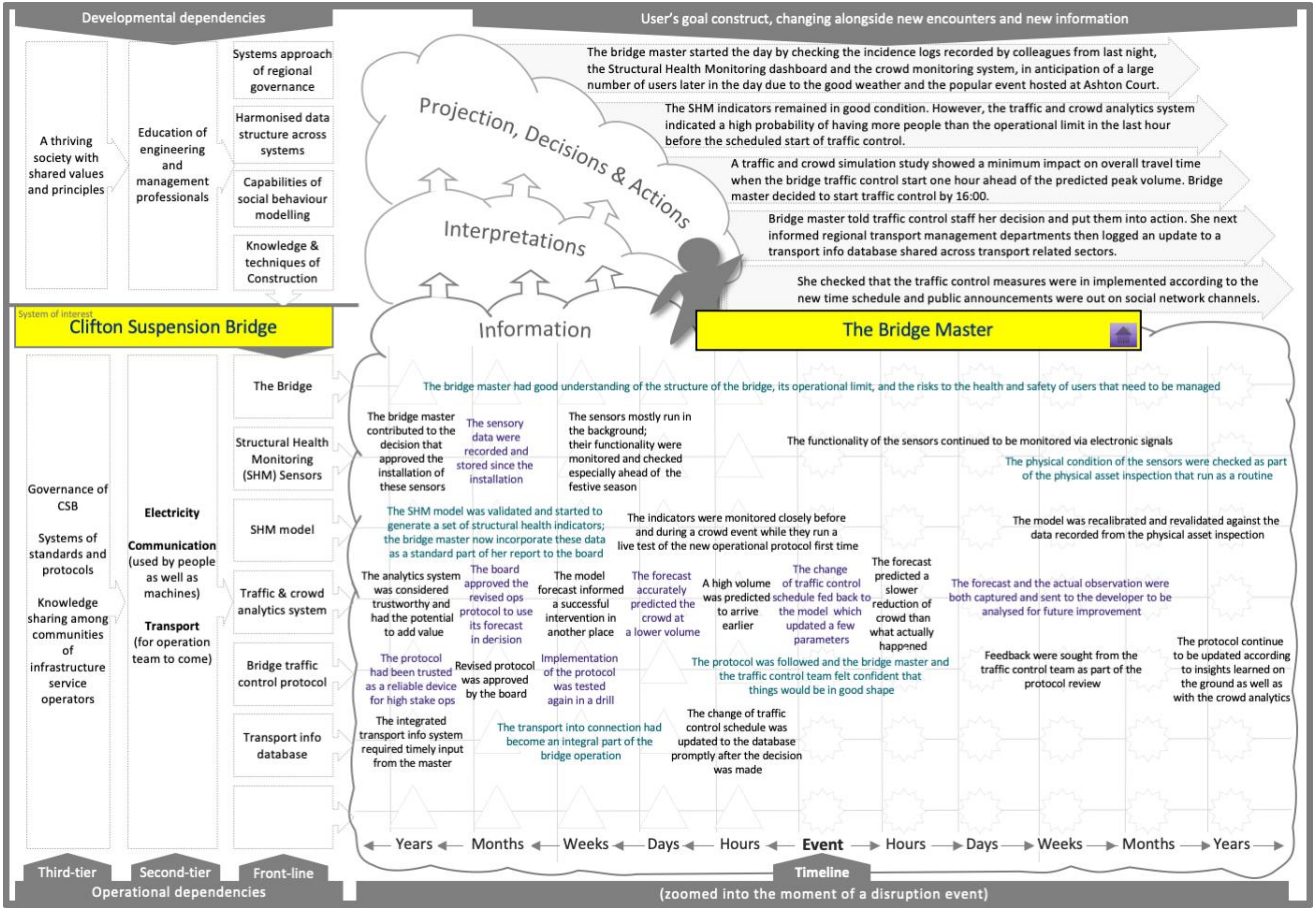
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

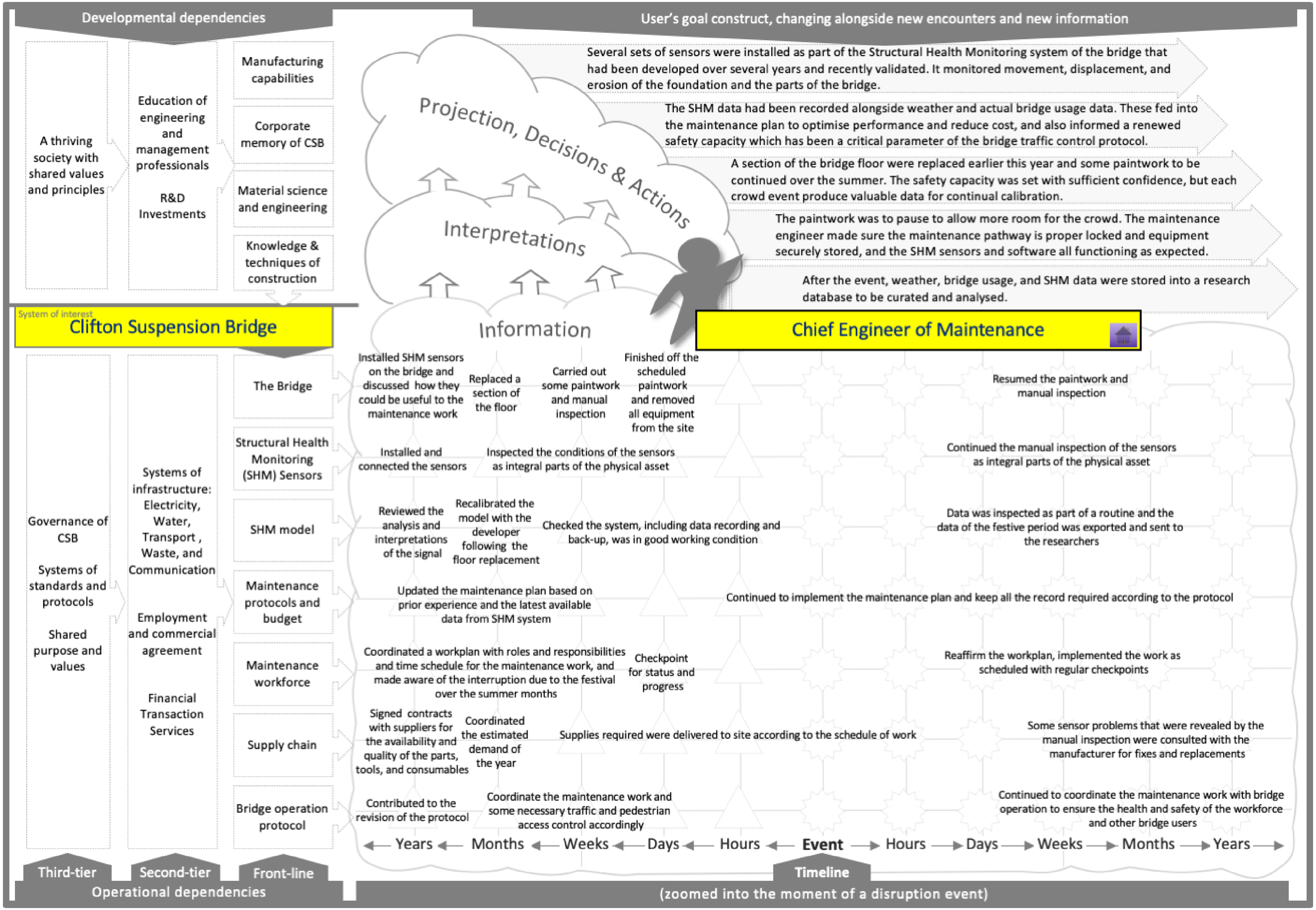

Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
People
Protocols
Infrastructures
Financial investment
Infrastructure maintenance
Emergency protocols
Energy supply
Communication
A regular day in which the user left his/her residential neighbourhood located in one of the smaller villages close to the sea and south of the Tagus River, with the aim of leaving the children at school, in central Lisbon, and proceed to the workplace, also in the city and close to the children's school
There is regularly heavy traffic on the roads accessing the bridge. Leaves the house close to 08:00 and expects a busy access to the city, which the user confirms using Google Maps and traffic news.
Thirty minutes later the user crosses the south toll with stopping-and-going traffic and, when reaching mid-span the traffic completely stops.
After checking the traffic news and google maps the user realizes that traffic is blocked on the bridge and that there is no hope of being resumed soon. Considers leaving the car and take children to the south access road to have wife/husband pick them up.
After a while, the user assists one infant in the back seat. Some users went to the sidewalks to stretch their legs. After a while, a police officer informs the users that traffic is to be reistablished in approximately one hour.
Projection, Decisions & Actions
Interpretations
Information
System of interest
25 de Abril Suspension Bridge
Resident car driver
Natural environment
Ruling law system
Financial system
Law enforcement system
Infrastructures:
Power
Communication
Fuel
Roads
Services:
Bridge operation
Police
Permanent maintenance
Road operation
Bridge
The toll system and the bridge operator
Road
Other users
Cellular communication and web
Electric / fuel supply
Police
Drove across the bridge daily
Drove through the Bridge up to the central span,
Traffic Stopped On the bridge
Considers leaving,. Stays in the vehicle
Continues using the bridge as Used to
Subscribes an Automatic payment System to avoid waiting for the toll service
As regular user receives text from operator Indicating service interruption but suggests no action.
Keeps subscribing automatic toll service
Heavy traffic daily
Full of vehicles As usual
Traffic stops, road Is blocked to circulation
Vehicles remain Blocking the road
Heavy traffic daily
People remain calm in their vehicles as this is Usually not the first time for regular users
Pays a monthly subscription that include mobile communication
Texts colleague To know how is the traffic Checks traffic in google maps
Receives text from Operator with instructions. Texts husband/wife to inform of the disruption. Text superior to inform of being late
Keeps checking the news online. Chats with friends, family, colleagues on Whatsapp.
Follow the news and TV comments On the disruption and What to do to prevent Additional ones
Charges / fuels up vehicle to avoid shortage
Car is charged / fuelled
Charges / fuels up vehicle to avoid shortage
Is stationed on the bridge to assist with traffic and security
Is advised by police Officer to stay on the bridge
Is stationed on the bridge to assist with traffic and security
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)

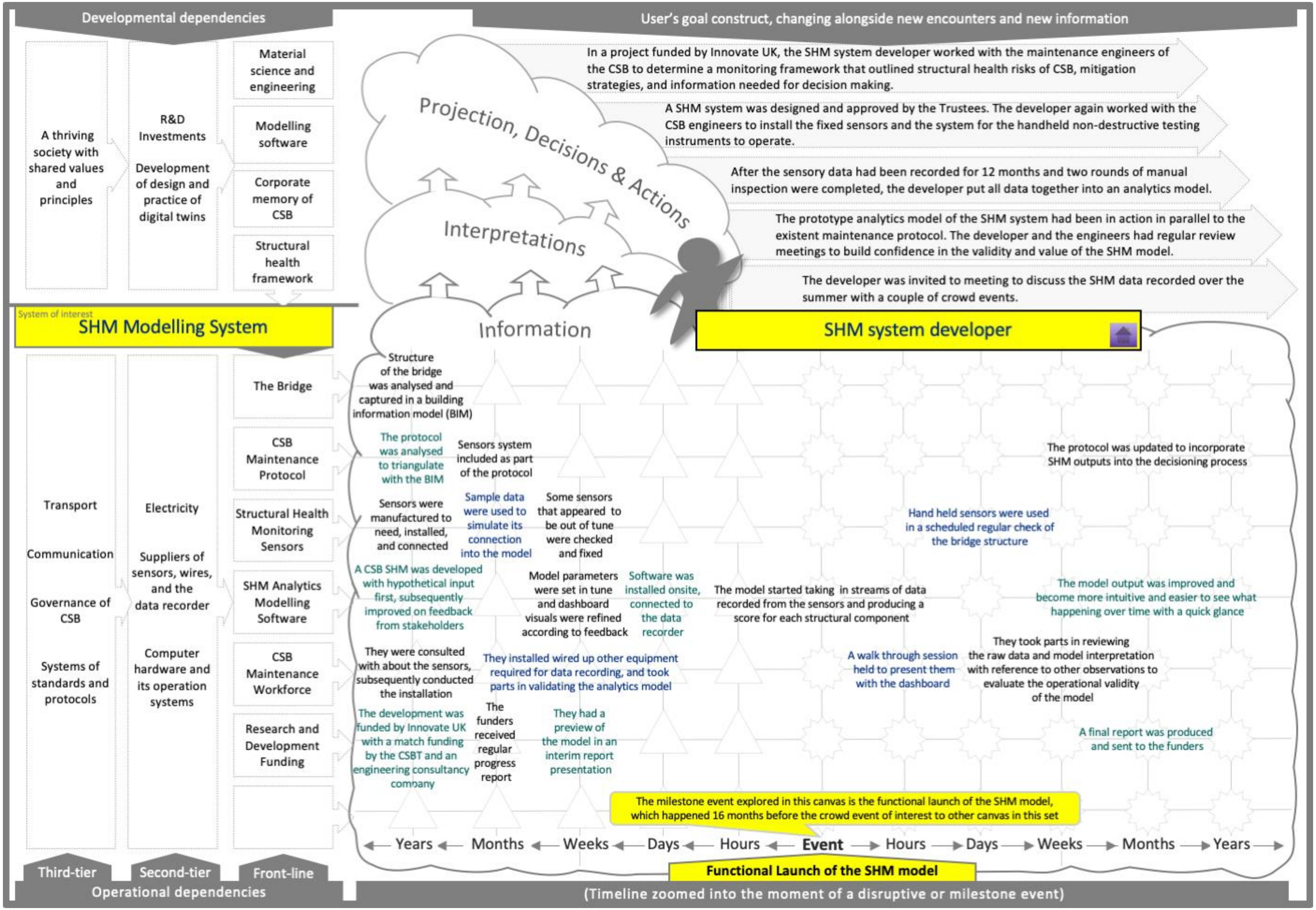

Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
People
Protocols
Infrastructures
Financial investment
Infrastructure maintenance
Emergency protocols
Energy supply
Communication
Projection, Decisions & Actions
Interpretations
Information
A regular working day in the 25 de Abril station, started at 08:00 with heavy traffic but no occurrences. After coffee, two officers came outside to have a look at the traffic leaving the toll system. After the morning rush-our, traffic speed control was schedule in the morning and accompanying works in the afternoon, with light traffic restrictions.
Contact was constantly kept with officers stations immediately before the viaduct, on the north side, to allow fast intervention in case of occurrences or emergencies. A close contact was also kept with the team of tow trailer drivers, which were parked right next to the police station and on the north side as well.
A disruptive event was informed by radio from the traffic control management office. Contacts superior-in-command who informs him/her of which protocol to undertake.
Contacts remaining officers for task assignment and proceeds to the disruption location by motorcycle. Starts traffic control duty and keeps constant contact with remaining officers as well as with traffic operation officers.
Aids in diverting people leaving the trains into the road deck and directs them to the south access. Starts protocol for emptying the structure from vehicles and people.
System of interest
25 de Abril Suspension Bridge
Police officer
Natural environment
Ruling law system
Financial system
Law enforcement system
Infrastructures:
Power
Communication
Fuel
Roads
Services:
Bridge operation
Police
Permanent maintenance
Road operation
Bridge
Radio communication
Superior in command
Bridge users
Cellular communication and web
Electric / fuel supply
Other police officers
Continues to work According to his schedule In the bridge police station
Parked by the toll, next to the south abutment of the bridge
Drives onto the bridge to follow the safety and traffic control protocol for disruption situations
Keeps following Protocol until notice otherwise
Does extra time If needed until situation is normalized
Continues to work According to his schedule In the bridge police station
While in service, carries a radio at all times to contact all his unit and superiors
Receives a communication alerting for an event in the bridge. Reports back with what he/she observes At that instant
Keeps permanent contact with unit and superiors
in service, carries a radio at all ti contact all his unit and superiors
Receives reports and issues orders regularly
Orders Protocol application, requests reports. Goes on site to coordinate If needed
Receives reports and issues orders regularly
Cross the bridge regularly
Ask police officer for instructions or information
Cross the bridge regularly
Pays a personal monthly subscription that include mobile communication
Sends text to close Relatives warning them not to cross the bridge. Warns wife/husband that will Likely be late
Keeps checking the news online. Chats with friends, family, colleagues on Whatsapp.
Continues to Check the news online
Motorcycles and cars are kept fuelled and with autonomy for all needs
Motorcycle and car fuelled
Motorcycles and cars are kept fuelled and with autonomy for all needs
Permanent contact is kept
Contact via radio To describe occurrence and All relevant information And details
Contact is permanently kept
Permanent contact is kept
Years
Months
Weeks
Days
Hours
Event
Hours
Days
Weeks
Months
Years
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)

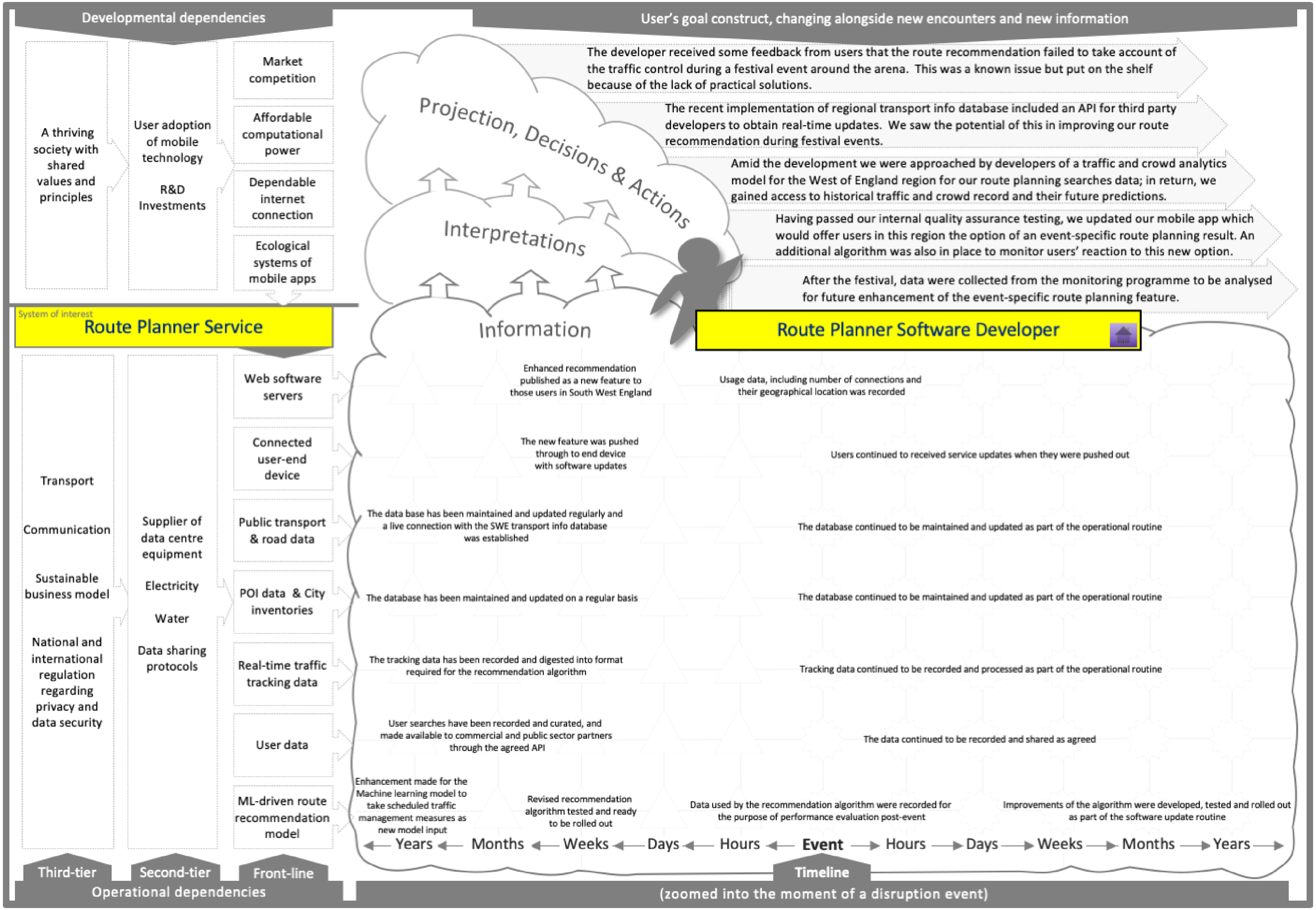

Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
People
Knowledge
Technology
Infrastructure
Response modelling models
Energy supply
Communication
Projection, Decisions & Actions
Interpretations
Information
Starts regular day at work, receives daily e-mail with information regarding the operation of the SHM systems. Accesses the dashboard online with the objective of checking the reference indicators.
Prepares reports and schedules interventions in SHM systems as well as preparation, in workshop, of SHM systems to be installed / upgraded.
Is contacted by the management officer to warn of disruption on the bridge. Assembles staff for real-time observation of data being acquire on site. Starts computations to issue model the structural response as a function of the actions being measured and starts plotting the corresponding errors in real-time, along with confidence intervals.
Is contacted from the bridge manager that the disruption has now passed. Starts an overall check on the structural responses being monitored on site.
At the end of the day, starts learning routines to ensure that new behaviour monitored today will be included in machine learning algorithms.
System of interest
25 de Abril Suspension Bridge
SHM Officer
Natural environment
Ruling law system
Financial system
Law enforcement system
Infrastructures:
Power
Communication
Fuel
Roads
Services:
Bridge operation
Police
Permanent maintenance
Road operation
Bridge
Routines for structural response learning
Data being acquired in real-time
Cellular and radio communication
Electric supply
Bridge Management Officer
Routines for real-time data checking
Application of his/her work
Remotely accesses SHM system components deployed on site
Application of his/her work
Trains models for structural Response reproducing
Keeps models updated
Suspends maintenance Works, prepares staff for emergency special inspection
Retrain Models to account For data acquired During disruption
Keeps models updated regularly
Processed hourly, Checked daily
Visualization and analysis To ensure permanent safety
Keeps Analysis and visualization
Processed hourly, Checked daily
Pays a personal monthly subscription that include mobile communication
Contacts bridge manager And other stakeholders By phone
Keeps Contact with Manager officer
Pays a personal monthly subscription that include mobile communication
Electric supply on site and in the offices Ensure the data transmission, processing and storage
Electric supply on site and in the offices Ensure real-time analysis and visualisation
Electric supply on site and in the offices Ensure the data transmission, processing and storage
Regular contact regarding safety of the structure
Contact and coordination To ensure structural safety during disruption
Regular contact regarding safety of the structure
Run hourly or daily to ensure operation and analyse safety
Run continuously During disruption
Run after update Of training models
Run hourly or daily to ensure operation and analyse safety
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)

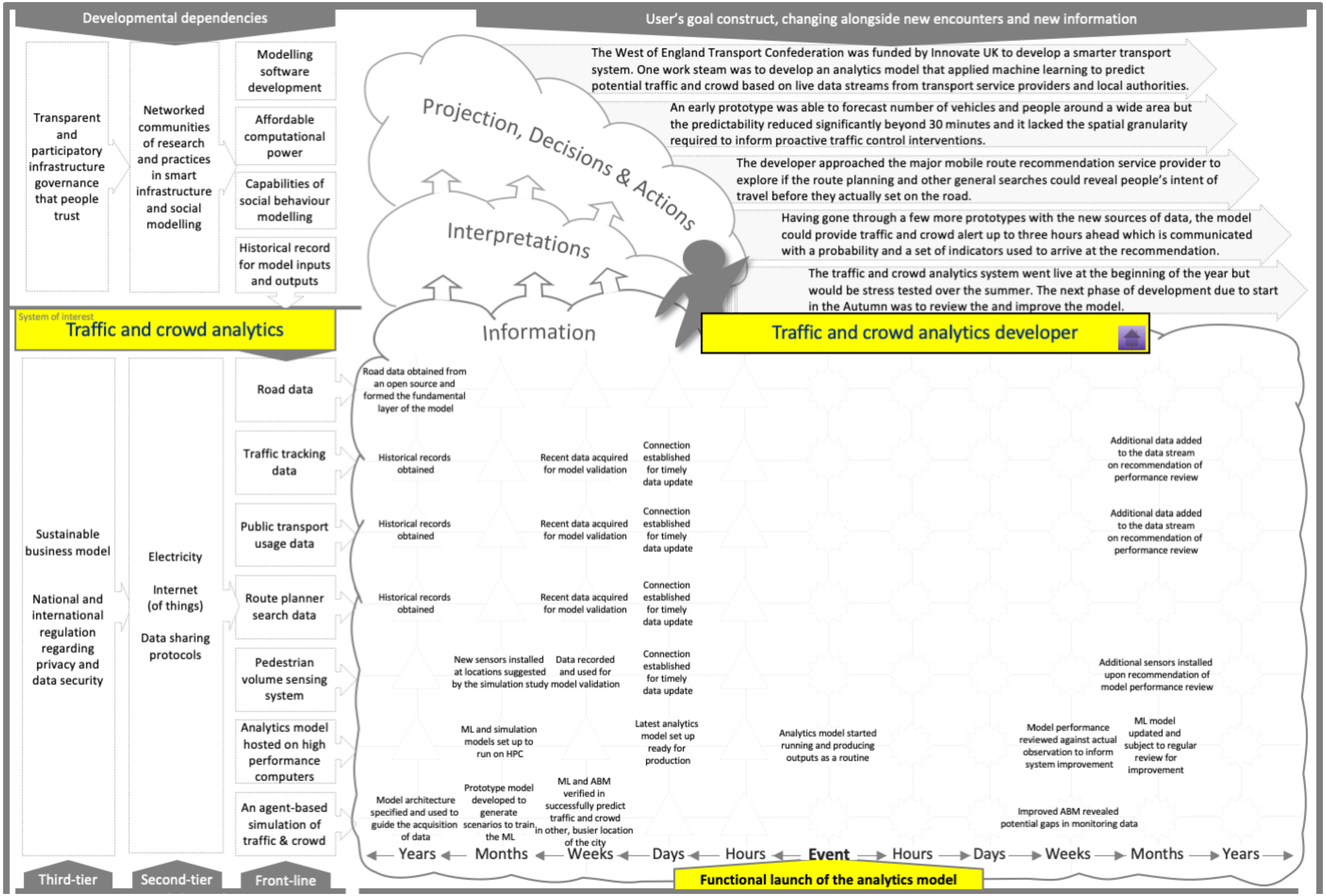

Developmental dependencies
User's goal construct, changing alongside new encounters and new information
Was to walk through the Clifton village and cross the suspension bridge to the other side of the gorge to join the festival at the Ashton Court. It was very busy , many people were out and about for the nice weekend
There was an increasing number of people while getting closer to the bridge. Several temporary road blocks were set up with traffic diverting information for drivers and pedestrians. The traffic control started 2 hours earlier at 16:00 due to excessive number of people using the bridge.
The user's party decided to go forward to have a closer look of the bridge, and they also opened Google Map on their mobiles to check the alternative route.
They found a good spot in the park nearby to take a picture of the renowned Bridge. They posted the picture on a social media and added that the Bridge was under traffic control for cars and pedestrians.
The speed of crowd movement did not look too bad. They managed to get on the Bridge, after queuing for a short while, and proceeded toward the festival arena.
A thriving society with shared values and principles
Systems approach of infrastructure governance
Sustainable energy supplies
Financial investment
Harmonised data structure across systems
Service oriented infrastructure development
Projection, Decisions & Actions
Interpretations
Information
System of interest
Clifton Suspension Bridge
Service User
A Tourist Pedestrian
Financial transaction service
Systems of standards and protocols
Natural environment
Infrastructure systems:
Electricity
Communication
Transport
Waste
Water
The Bridge (physical structure)
Surrounding area as a buffer
Bridge Operator
Transport Management Team
Cellular network
Local transport network
Web service of social networks
Last visited the Bridge a year ago and had been here a few Times before
Arrived when the traffic control had started
Got across the bridge
Enjoyed the high-street and the green space on the way up to the bridge
Wandered around while waiting to get onto the bridge
Guidance and instruction as part of traffic control
Transport Info update provided
Transport Info update provided
Transport Info update provided
Used mobile app for route planning and navigation
Checked transport info
Send messages onto social network
Checked transport info to plan the trip
Took bus from railway station to the village
Continued to use these road
Continued to use these road
Communicated via social network
Sent message and pictures
Sent messages and pictures
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)


Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
Education of engineering and management professionals
Systems approach of regional governance
Harmonised data structure across systems
Capabilities of social behaviour modelling
Knowledge & techniques of Construction
Projection, Decisions & Actions
Interpretations
Information
The bridge master started the day by checking the incidence logs recorded by colleagues from last night, the Structural Health Monitoring dashboard and the crowd monitoring system, in anticipation of a large number of users later in the day due to the good weather and the popular event hosted at Ashton Court.
The SHM indicators remained in good condition. However, the traffic and crowd analytics system indicated a high probability of having more people than the operational limit in the last hour before the scheduled start of traffic control.
A traffic and crowd simulation study showed a minimum impact on overall travel time when the bridge traffic control start one hour ahead of the predicted peak volume. Bridge master decided to start traffic control by 16:00.
Bridge master told traffic control staff her decision and put them into action. She next informed regional transport management departments then logged an update to a transport info database shared across transport related sectors.
She checked that the traffic control measures were in implemented according to the new time schedule and public announcements were out on social network channels.
System of interest
Clifton Suspension Bridge
The Bridge Master
Governance of CSB
Systems of standards and protocols
Knowledge sharing among communities of infrastructure service operators
Electricity
Communication (used by people as well as machines)
Transport (for operation team to come)
The Bridge
Structural Health Monitoring (SHM) Sensors
SHM model
Traffic & crowd analytics system
Bridge traffic control protocol
Transport info database
The bridge master had good understanding of the structure of the bridge, its operational limit, and the risks to the health and safety of users that need to be managed
The bridge master contributed to the decision that approved the installation of these sensors
The sensory data were recorded and stored since the installation
The sensors mostly run in the background; their functionality were monitored and checked especially ahead of the festive season
The functionality of the sensors continued to be monitored via electronic signals
The physical condition of the sensors were checked as part of the physical asset inspection that run as a routine
The SHM model was validated and started to generate a set of structural health indicators; the bridge master now incorporate these data as a standard part of her report to the board
The indicators were monitored closely before and during a crowd event while they run a live test of the new operational protocol first time
The model was recalibrated and revalidated against the data recorded from the physical asset inspection
The analytics system was considered trustworthy and had the potential to add value
The board approved the revised ops protocol to use its forecast in decision
The model forecast informed a successful intervention in another place
The forecast accurately predicted the crowd at a lower volume
A high volume was predicted to arrive earlier
The change of traffic control schedule fed back to the model which updated a few parameters
The forecast predicted a slower reduction of crowd than what actually happened
The forecast and the actual observation were both captured and sent to the developer to be analysed for future improvement
The protocol had been trusted as a reliable device for high stake ops
Revised protocol was approved by the board
Implementation of the protocol was tested again in a drill
The protocol was followed and the bridge master and the traffic control team felt confident that things would be in good shape
Feedback were sought from the traffic control team as part of the protocol review
The protocol continue to be updated according to insights learned on the ground as well as with the crowd analytics
The integrated transport info system required timely input from the master
The transport into connection had become an integral part of the bridge operation
The change of traffic control schedule was updated to the database promptly after the decision was made
Years ← Months ← Weeks ← Days ← Hours ← Event → Hours → Days → Weeks → Months → Years →
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)


Developmental dependencies
A thriving society with shared values and principles
Education of engineering and management professionals
R&D Investments
Manufacturing capabilities
Corporate memory of CSB
Material science and engineering
Knowledge & techniques of construction
System of interest
Clifton Suspension Bridge
Governance of CSB
Systems of standards and protocols
Shared purpose and values
Systems of infrastructure: Electricity, Water, Transport , Waste, and Communication
Employment and commercial agreement
Financial Transaction Services
The Bridge
Structural Health Monitoring (SHM) Sensors
SHM model
Maintenance protocols and budget
Maintenance workforce
Supply chain
Bridge operation protocol
Third-tier
Second-tier
Front-line
Operational dependencies
User's goal construct, changing alongside new encounters and new information
Projection, Decisions & Actions
Interpretations
Information
Several sets of sensors were installed as part of the Structural Health Monitoring system of the bridge that had been developed over several years and recently validated. It monitored movement, displacement, and erosion of the foundation and the parts of the bridge.
The SHM data had been recorded alongside weather and actual bridge usage data. These fed into the maintenance plan to optimise performance and reduce cost, and also informed a renewed safety capacity which has been a critical parameter of the bridge traffic control protocol.
A section of the bridge floor were replaced earlier this year and some paintwork to be continued over the summer. The safety capacity was set with sufficient confidence, but each crowd event produce valuable data for continual calibration.
The paintwork was to pause to allow more room for the crowd. The maintenance engineer made sure the maintenance pathway is proper locked and equipment securely stored, and the SHM sensors and software all functioning as expected.
After the event, weather, bridge usage, and SHM data were stored into a research database to be curated and analysed.
Chief Engineer of Maintenance
Installed SHM sensors on the bridge and discussed how they could be useful to the maintenance work
Replaced a section of the floor
Carried out some paintwork and manual inspection
Finished off the scheduled paintwork and removed all equipment from the site
Resumed the paintwork and manual inspection
Installed and connected the sensors
Inspected the conditions of the sensors as integral parts of the physical asset
Continued the manual inspection of the sensors as integral parts of the physical asset
Reviewed the analysis and interpretations of the signal
Recalibrated the model with the developer following the floor replacement
Checked the system, including data recording and back-up, was in good working condition
Data was inspected as part of a routine and the data of the festive period was exported and sent to the researchers
Updated the maintenance plan based on prior experience and the latest available data from SHM system
Continued to implement the maintenance plan and keep all the record required according to the protocol
Coordinated a workplan with roles and responsibilities and time schedule for the maintenance work, and made aware of the interruption due to the festival over the summer months
Checkpoint for status and progress
Reaffirm the workplan, implemented the work as scheduled with regular checkpoints
Signed contracts with suppliers for the availability and quality of the parts, tools, and consumables
Coordinated the estimated demand of the year
Supplies required were delivered to site according to the schedule of work
Some sensor problems that were revealed by the manual inspection were consulted with the manufacturer for fixes and replacements
Contributed to the revision of the protocol
Coordinate the maintenance work and some necessary traffic and pedestrian access control accordingly
Continued to coordinate the maintenance work with bridge operation to ensure the health and safety of the workforce and other bridge users
Years
Months
Weeks
Days
Hours
Event
Hours
Days
Weeks
Months
Years
Timeline
(zoomed into the moment of a disruption event)


Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
R&D Investments
Development of design and practice of digital twins
Material science and engineering
Modelling software
Corporate memory of CSB
Structural health framework
Projection, Decisions & Actions
Interpretations
Information
In a project funded by Innovate UK, the SHM system developer worked with the maintenance engineers of the CSB to determine a monitoring framework that outlined structural health risks of CSB, mitigation strategies, and information needed for decision making.
A SHM system was designed and approved by the Trustees. The developer again worked with the CSB engineers to install the fixed sensors and the system for the handheld non-destructive testing instruments to operate.
After the sensory data had been recorded for 12 months and two rounds of manual inspection were completed, the developer put all data together into an analytics model.
The prototype analytics model of the SHM system had been in action in parallel to the existent maintenance protocol. The developer and the engineers had regular review meetings to build confidence in the validity and value of the SHM model.
The developer was invited to meeting to discuss the SHM data recorded over the summer with a couple of crowd events.
System of interest
SHM Modelling System
SHM system developer
Transport
Communication
Governance of CSB
Systems of standards and protocols
Electricity
Suppliers of sensors, wires, and the data recorder
Computer hardware and its operation systems
The Bridge
CSB Maintenance Protocol
Structural Health Monitoring Sensors
SHM Analytics Modelling Software
CSB Maintenance Workforce
Research and Development Funding
Structure of the bridge was analysed and captured in a building information model (BIM)
The protocol was analysed to triangulate with the BIM
Sensors system included as part of the protocol
The protocol was updated to incorporate SHM outputs into the decisioning process
Sensors were manufactured to need, installed, and connected
Sample data were used to simulate its connection into the model
Some sensors that appeared to be out of tune were checked and fixed
Hand held sensors were used in a scheduled regular check of the bridge structure
A CSB SHM was developed with hypothetical input first, subsequently improved on feedback from stakeholders
Model parameters were set in tune and dashboard visuals were refined according to feedback
Software was installed onsite, connected to the data recorder
The model started taking in streams of data recorded from the sensors and producing a score for each structural component
The model output was improved and become more intuitive and easier to see what happening over time with a quick glance
They were consulted with about the sensors, subsequently conducted the installation
They installed wired up other equipment required for data recording, and took parts in validating the analytics model
A walk through session held to present them with the dashboard
They took parts in reviewing the raw data and model interpretation with reference to other observations to evaluate the operational validity of the model
The development was funded by Innovate UK with a match funding by the CSBT and an engineering consultancy company
The funders received regular progress report
They had a preview of the model in an interim report presentation
A final report was produced and sent to the funders
The milestone event explored in this canvas is the functional launch of the SHM model, which happened 16 months before the crowd event of interest to other canvas in this set
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Functional Launch of the SHM model
Third-tier
Second-tier
Front-line
Operational dependencies
(Timeline zoomed into the moment of a disruptive or milestone event)


Developmental dependencies
User's goal construct, changing alongside new encounters and new information
A thriving society with shared values and principles
User adoption of mobile technology
R&D Investments
Market competition
Affordable computational power
Dependable internet connection
Ecological systems of mobile apps
Projection, Decisions & Actions
Interpretations
Information
The developer received some feedback from users that the route recommendation failed to take account of the traffic control during a festival event around the arena. This was a known issue but put on the shelf because of the lack of practical solutions.
The recent implementation of regional transport info database included an API for third party developers to obtain real-time updates. We saw the potential of this in improving our route recommendation during festival events.
Amid the development we were approached by developers of a traffic and crowd analytics model for the West of England region for our route planning searches data; in return, we gained access to historical traffic and crowd record and their future predictions.
Having passed our internal quality assurance testing, we updated our mobile app which would offer users in this region the option of an event-specific route planning result. An additional algorithm was also in place to monitor users' reaction to this new option.
After the festival, data were collected from the monitoring programme to be analysed for future enhancement of the event-specific route planning feature.
System of interest
Route Planner Service
Route Planner Software Developer
Transport
Communication
Sustainable business model
National and international regulation regarding privacy and data security
Supplier of data centre equipment
Electricity
Water
Data sharing protocols
Web software servers
Connected user-end device
Public transport & road data
POI data & City inventories
Real-time traffic tracking data
User data
ML-driven route recommendation model
Enhanced recommendation published as a new feature to those users in South West England
Usage data, including number of connections and their geographical location was recorded
The new feature was pushed through to end device with software updates
Users continued to received service updates when they were pushed out
The data base has been maintained and updated regularly and a live connection with the SWE transport info database was established
The database continued to be maintained and updated as part of the operational routine
The database has been maintained and updated on a regular basis
The database continued to be maintained and updated as part of the operational routine
The tracking data has been recorded and digested into format required for the recommendation algorithm
Tracking data continued to be recorded and processed as part of the operational routine
User searches have been recorded and curated, and made available to commercial and public sector partners through the agreed API
The data continued to be recorded and shared as agreed
Enhancement made for the Machine learning model to take scheduled traffic management measures as new model input
Revised recommendation algorithm tested and ready to be rolled out
Data used by the recommendation algorithm were recorded for the purpose of performance evaluation post-event
Improvements of the algorithm were developed, tested and rolled out as part of the software update routine
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Third-tier
Second-tier
Front-line
Operational dependencies
Timeline
(zoomed into the moment of a disruption event)


Developmental dependencies
User's goal construct, changing alongside new encounters and new information
Transparent and participatory infrastructure governance that people trust
Networked communities of research and practices in smart infrastructure and social modelling
Modelling software development
Affordable computational power
Capabilities of social behaviour modelling
Historical record for model inputs and outputs
Projection, Decisions & Actions
Interpretations
Information
The West of England Transport Confederation was funded by Innovate UK to develop a smarter transport system. One work steam was to develop an analytics model that applied machine learning to predict potential traffic and crowd based on live data streams from transport service providers and local authorities.
An early prototype was able to forecast number of vehicles and people around a wide area but the predictability reduced significantly beyond 30 minutes and it lacked the spatial granularity required to inform proactive traffic control interventions.
The developer approached the major mobile route recommendation service provider to explore if the route planning and other general searches could reveal people's intent of travel before they actually set on the road.
Having gone through a few more prototypes with the new sources of data, the model could provide traffic and crowd alert up to three hours ahead which is communicated with a probability and a set of indicators used to arrive at the recommendation.
The traffic and crowd analytics system went live at the beginning of the year but would be stress tested over the summer. The next phase of development due to start in the Autumn was to review the and improve the model.
System of interest
Traffic and crowd analytics
Traffic and crowd analytics developer
Sustainable business model
National and international regulation regarding privacy and data security
Electricity
Internet (of things)
Data sharing protocols
Road data
Traffic tracking data
Public transport usage data
Route planner search data
Pedestrian volume sensing system
Analytics model hosted on high performance computers
An agent-based simulation of traffic & crowd
Road data obtained from an open source and formed the fundamental layer of the model
Historical records obtained
Recent data acquired for model validation
Connection established for timely data update
Additional data added to the data stream on recommendation of performance review
Historical records obtained
Recent data acquired for model validation
Connection established for timely data update
Additional data added to the data stream on recommendation of performance review
Historical records obtained
Recent data acquired for model validation
Connection established for timely data update
New sensors installed at locations suggested by the simulation study
Data recorded and used for model validation
Connection established for timely data update
Additional sensors installed upon recommendation of model performance review
ML and simulation models set up to run on HPC
Latest analytics model set up ready for production
Analytics model started running and producing outputs as a routine
Model performance reviewed against actual observation to inform system improvement
ML model updated and subject to regular review for improvement
Model architecture specified and used to guide the acquisition of data
Prototype model developed to generate scenarios to train the ML
ML and ABM verified in successfully predict traffic and crowd in other, busier location of the city
Improved ABM revealed potential gaps in monitoring data
Years Months Weeks Days Hours Event Hours Days Weeks Months Years
Functional launch of the analytics model
Third-tier
Second-tier
Front-line

Appendix 2: Design a model using service requirement canvas – the city of Bristol case study

A service requirement canvas can not only be used as a tool to explore information gaps among different actors in a complex system, but also offers a collection of data for modelling a complex system. Each service requirement sheet illustrates a perspective of an actor in the system by capturing the behaviours and connections of actors.

In this section, we showcase the design of an ABM for the city of Bristol case study using the service requirement canvas.

The design of agents using service requirement canvas

Following the service requirement canvas in Section 5.1, Table A.1 summarises agent design that is transformed from the canvas data. A model of Bristol city could have these agents: Pedestrians, bridge management team, Clifton Suspension Bridge (CSB) Trust, the bridge engineer team, CSB, city transport management system and the officer, and the Structure Health Monitoring (SHM) System for CSB. Each figure in this section contains a Unified Model Language (UML) diagrams to illustrate agent's construction and a flowchart to illustrate agents' behaviours.

*Pedestrian (A Tourist Pedestrian) (**See** Figure A.1)*

Pedestrian agents in the model are designed based on the service requirement canvas of a tourist pedestrian. In a pedestrian's journey across the city, he/she can choose a route and walk from where he/she arrives at Bristol to Ashton Court, which is the destination for all visitors, send messages to and receive messages from other Pedestrian agents, make decisions when the planned route is closed down or other disruptive events happen in the city that affect their journey.

***Bridge Management Team (The Bridge Master)** (See Figure A.2)*

Bridge management team is responsible for daily operations of the bridge. The bridge management team agent operates according to the designed protocols daily. The agent has the knowledge of the bridge and the surrounded area. It also has first-hand information from all the real-time monitoring systems in the bridge.

***Clifton Suspension Bridge (CSB) Trust** (See Figure A.3)*

CSB Trust is a non-for-profit charity that is responsible for the management and the maintenance of the bridge. The trust makes medium- to long- term decisions for managing the bridge. The CBS agent in an agent-based model would be able to decide what types of real-time monitoring systems the bridge is equipped with, which is an important type of agent in a simulation for medium- and long-term management strategies and policy making.

Bridge Engineer Team (See Figure A.4)

Bridge engineers are working on the daily maintenance of the bridge. They monitor the bridge condition by inspecting the bridge in person and using real-time monitoring systems. They carry out necessary repairing work instructed by the management team and CSB Trust when a defect is spotted.

***Clifton Suspension Bridge (CSB)** (See Figure A.5)*

The Clifton Suspension Bridge is a historic infrastructure in Bristol, which attract many visitors every year. The bridge is often closed when there is a big public event, such as Bristol International Balloon fiesta. A structure health monitoring system is deployed to provide real-time monitoring information of the bridge.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

Transport Management System and the Officer (See Figure A.6)

The officer who is in charge of the city's transport management system monitors the city's transport network and make decisions to modify the traffic lights in order to reduce traffic jams across the city. The officer has access to real-time traffic information and analytics. He gets informed by critical infrastructure's management staff for any unexpected changes of their operation, and makes changes in the transport system accordingly, report the changes to his manager, and announces the new arrangements to the public and other transport assets management team. In a longer time span simulation, the officer can initiate and commission new projects to improve the transport management system, which impacts on the whole region's traffic flow.

Structure Health Monitoring (SHM) System and the developers (See Figure A.7)

The SHM system generates real-time data streams and can be fed into other analytic tools to assist bridge management team in both daily operations and an emergency. SHM system can generate warning messages when the structural changes of the bridge are detected. The warning messages are sent to the bridge master dashboard and other simulation-based decision aiding models.

Table A.1: Agent Design

Agent Type	Agent Properties	Agent Behaviours	Data Source
Pedestrian (Figure A.1)	Location, speed, group size, destination, preferred stops on the way, whether he/she has mobility difficulties, whether he/she has local knowledge; whether connect to the official account on social media; a contact list; a list of received messages, a list of sent messages.	Walk; choose alternative a route; send messages; receive messages; spend time at a location.	The number of people who attend the event in the past; the arrival rate; the percentage of event attendances with special needs;
Bridge manage-ment team (Figure A.2)	Name; a list of received messages (information) from other connected agents; a list of messages sent to other agents; a contact list	Open the bridge; Close the bridge; Monitor/watch the bridge; Guide bridge users to evacuate (send messages to all pedestrians on the bridge and near the bridge); contact emergency services (send messages to contact emergency services) Figure 2	Clifton suspension bridge monitoring data, including traffic flow on the bridge and structure health data; maximum load of the bridge; bridge operation protocols
CSB Trust (Figure A.3)	Frequency of meeting; a list of decision to make; a list of messages received from other connected agents; a list of messages that are sent to other connected agents; a contact list.	Review bridge reports from bridge management team and engineers; in contact with transport manage-ment system; decide and instruct new system installation or upgrade.	CSB Trust work schedule and protocols
Bridge Engineer Team (Figure A.4)	A list of messages received from other connected agents; a list of messages sent to other connected agents; a contact list.	Inspect the bridge daily; repair defects; contact management team; update related databases.	Bridge engineer work schedule and protocols
Clifton Suspension Bridge (Figure A.5)	Bridge engineer team; CBS trust; bridge management team; SHM system and its developers; location; length; width; is open or not; maximum load; a list of messages received from other connected agents; a list of	Open the bridge; close the bridge.	Knowledge and studies about the CSB; research projects on CSB

	messages sent to other connected agents.		
Transport Manage-ment System and the Officer (Figure A.6)	A list of messages received from other connected agents; a list of messages sent to other connected agents; a contact list; dashboard of traffic information.	Check real-time traffic and crowd information; spot problems and generate warning; notify line managers and other transport infrastructure managers; make adaptions of the transport system; report back to the system developers for improvement.	Transport management system officer work schedule and protocols; transport management system and its output information.
Structure Health Monitoring (SHM) System	A list of messages received from other connected agents; a list of messages sent to other connected agents.	Send warning messages.	SHM system output information.

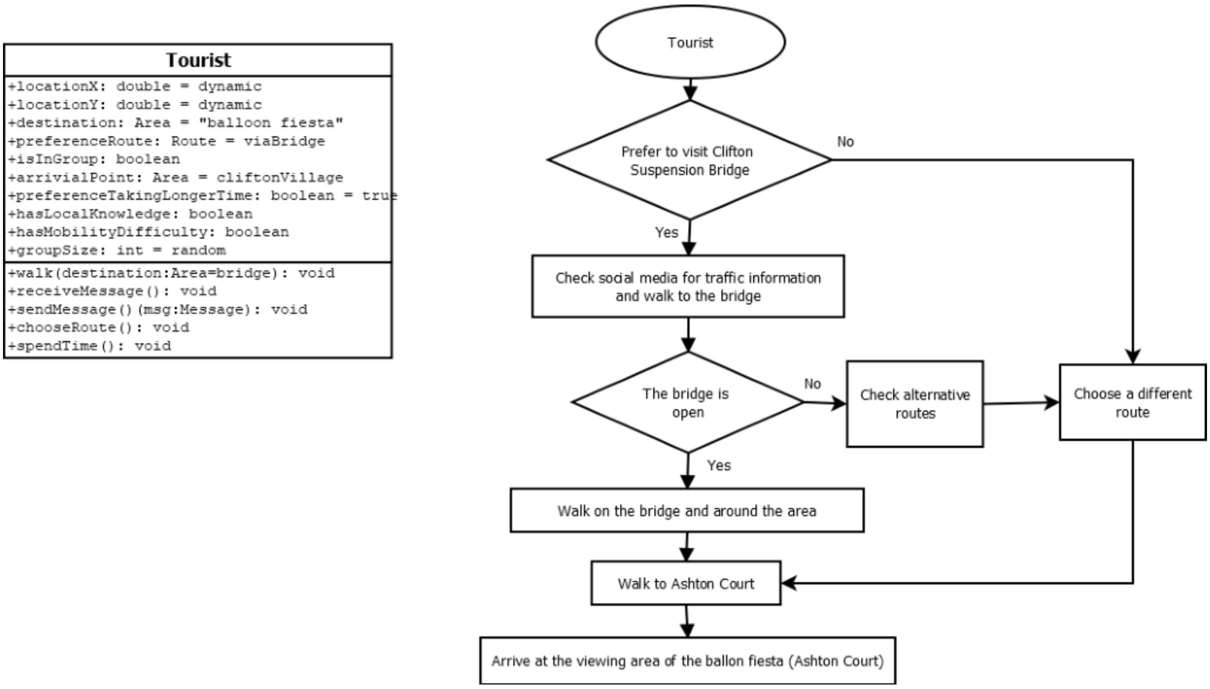


Figure A.1: A pedestrian agent

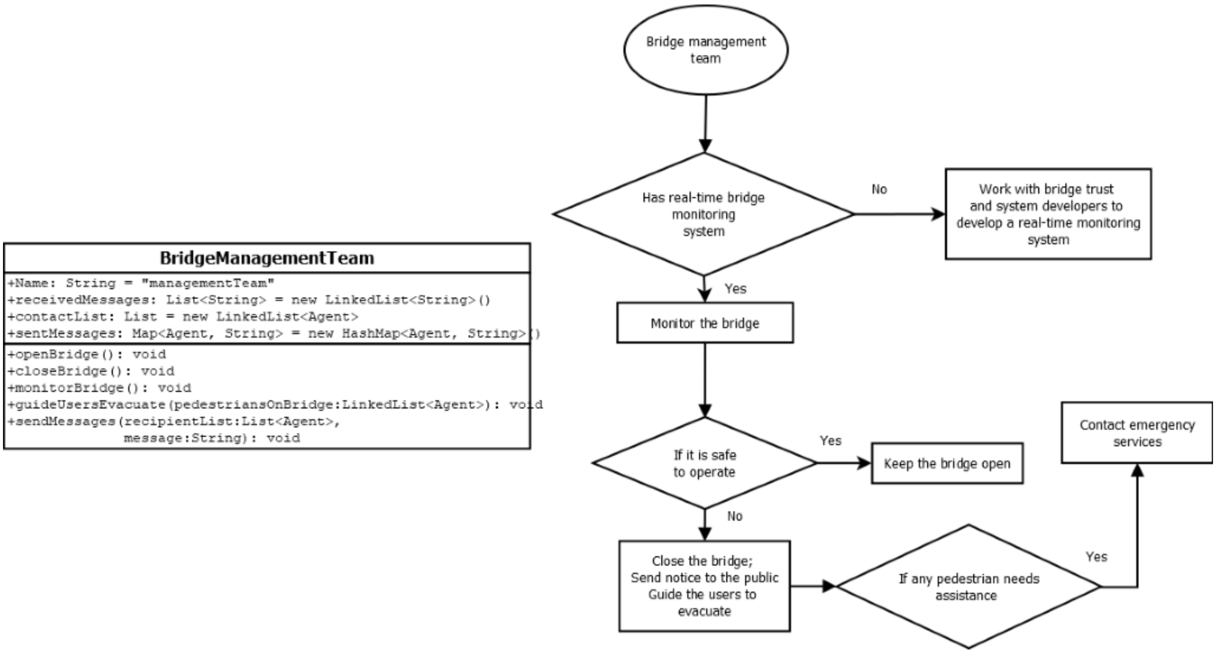


Figure A.2 The bridge management team agent

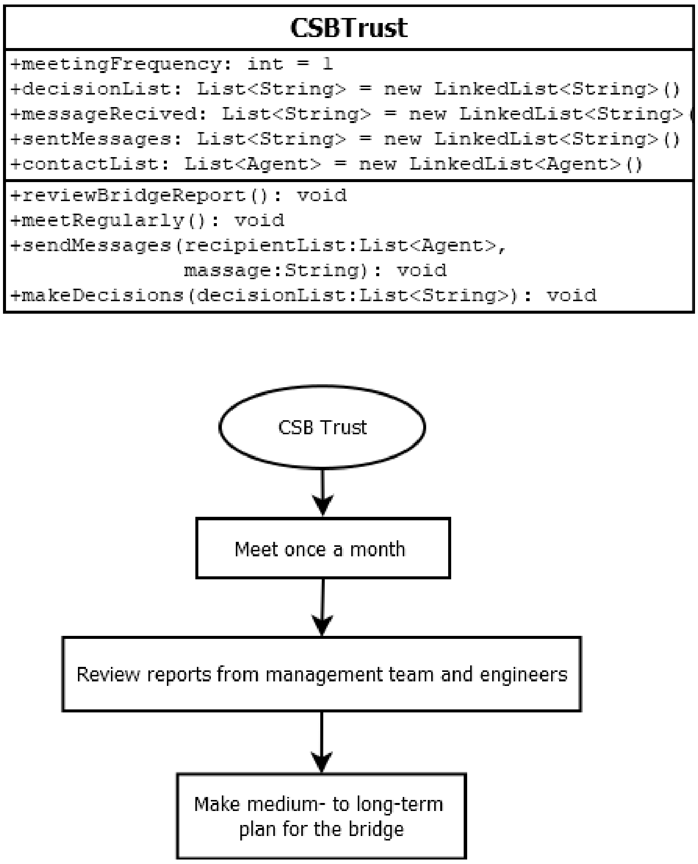


Figure A.3 The CSB Trust agent

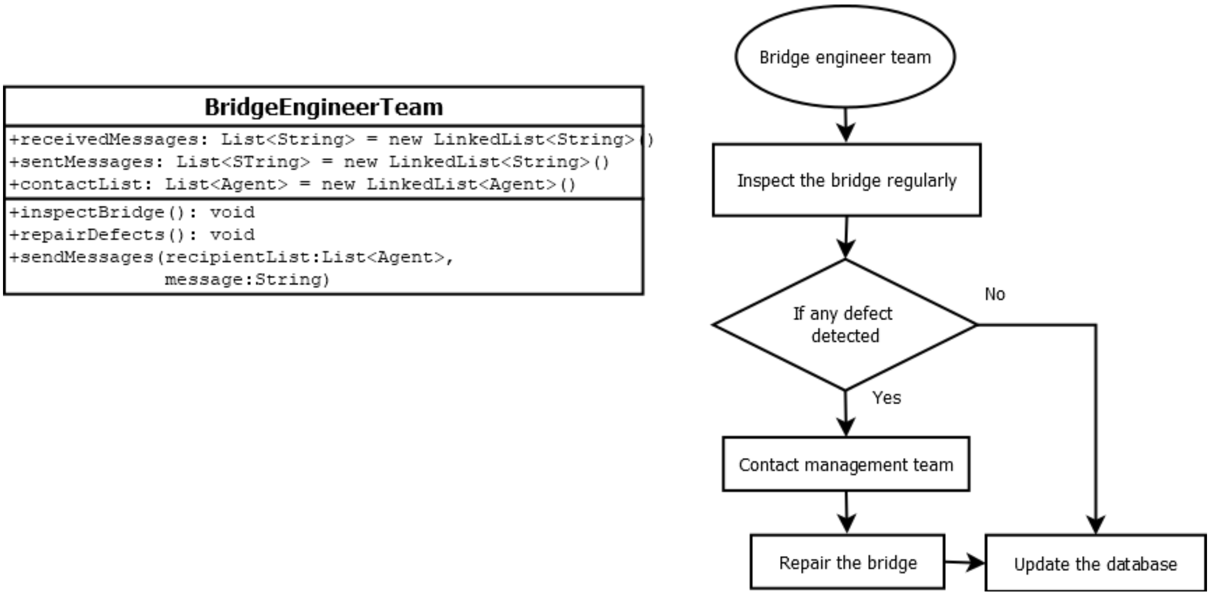


Figure A.4: The bridge engineer team agent

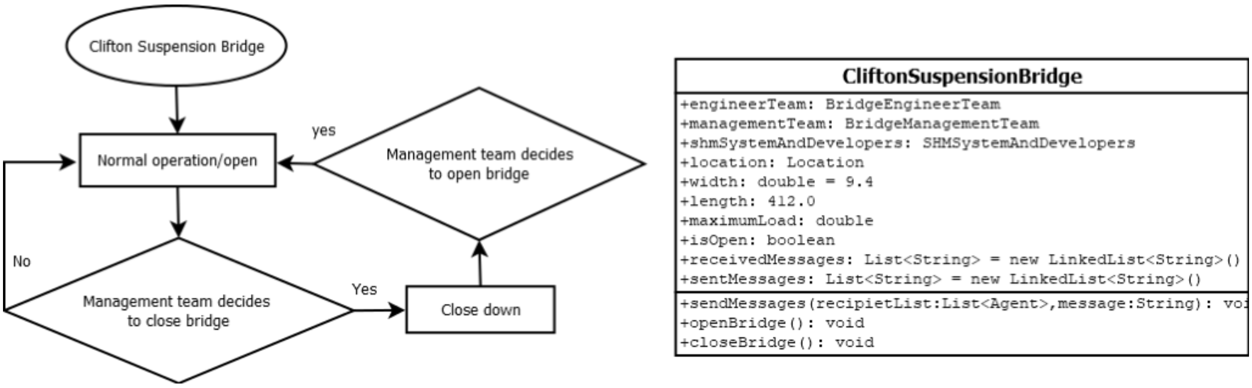


Figure A.5: The CSB agent

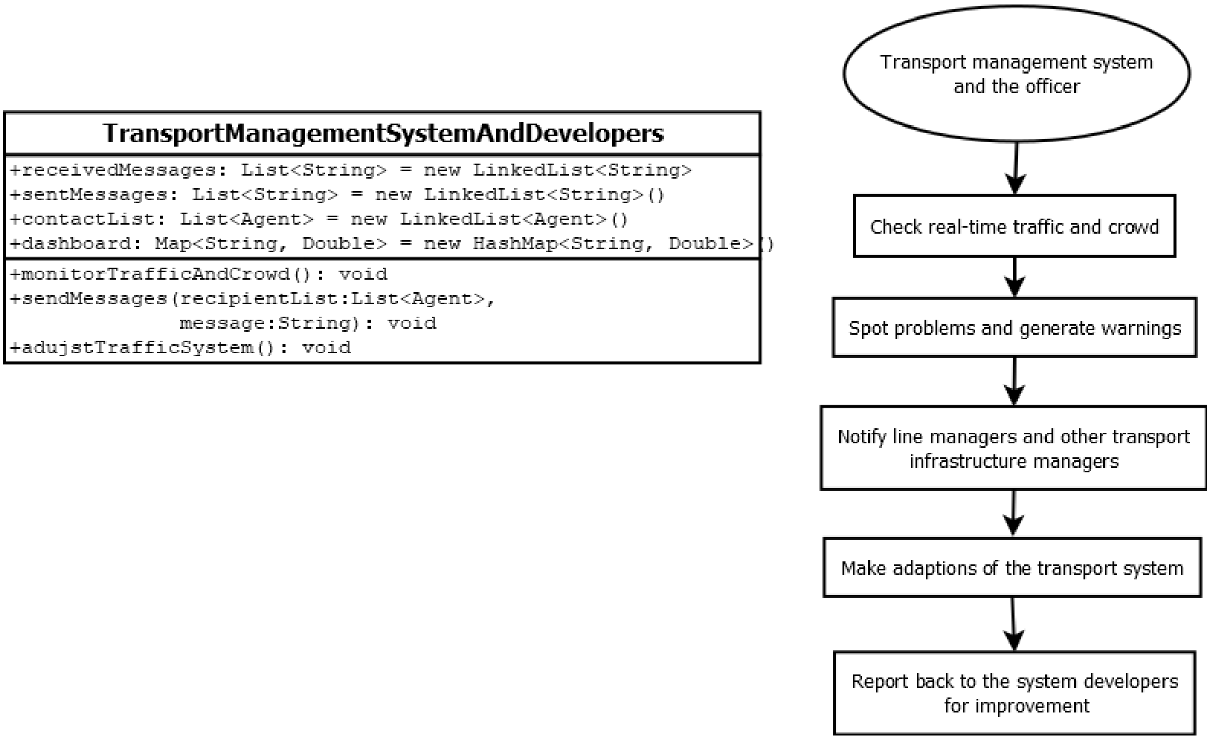


Figure A.6 The transport management system and the developers agent

Agent relationships

In the city of Bristol model, different relationships are formed among agents. A relationship can be physical or social. One typical physical relationship is neighbouring. Social relationships among agents simulates the connections among people and organisations in the society, for example, family, friends and colleagues, pub/sub connections between people and between people and organisations on social media and in daily life. Relationships form social networks, through which agents can share information and knowledge.

The model of Bristol city could have the following agents connected through different type of relationships

- Groups of pedestrians
  Family or friends travel in groups and visit the city together. They will stay close physically in the city. Even if they are separated from each other, they connect each other via mobile phone and social media.
- Pedestrians who are strangers, but stand next to each other
  Pedestrians who are stranded in the same area can think and act collectively, even if they do not know each other.
- CSB agent and all the pedestrian agents on the bridge
  Because the pedestrians are on the CSB, CSB agent can inform these agents directly about the upcoming operation, for example, making announcement that the bridge is closing in 10 minutes. Pedestrians on the bridge can also sense the crowd situation on the bridge and observe the bridge operations by themselves.
- CSB agent and the bridge management agent
  The bridge management agent can decide the CSB's operations according to their protocols and updated information from other sources, for example, the SHM system.
- CSB trust and the bridge management team

CSB Trust and the bridge management team work together to decide long-term maintenance and development strategies of the bridge.

- SHM system, engineers and the bridge management agent
  Engineers work with SHM system to ensure the bridge is safe in daily operations. SHM system and engineers inform the bridge management agent about the situation that the bridge is in and help the management agent to make swift decisions.
- The bridge management agent and the public
  The bridge management announces changes of the bridge operations to the public through different channels, including radio, TV and online media

Contact

Project lead ETH Zürich

Project coordinator Prof. Dr. Domenico Giardini

Project manager Dr. Kauzar Saleh

Project office ETH Department of Earth Sciences

Sonneggstrasse 5, NO H-floor, CH-8092 Zürich

sera_office@erdw.ethz.ch

+41 44 632 9690

Project website www.sera-eu.org