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A layered approach to model interconnected infrastructure and its significance for asset management

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Physical infrastructures facilitate much of societal and economic wellbeing of countries, regions and urban areas. In our increasingly urbanizing world, infrastructures in urban areas are densely located and interconnected. The effects of this interconnectedness are being studied increasingly, particularly in light of climate change effects. In this paper, we develop an agent-based simulation model that allows us to study interconnected infrastructure. We present a layered approach that is analogous to GIS overlay approaches, which allows us to integrate representations of different infrastructures. We explore how this approach can help asset managers to gain insights in interconnected infrastructure by estimating their total damage and repair requirements during a flood event. The results show a difference in these estimates, when compared to non-integrated models, highlighting the need for asset managers to consider interconnectedness in infrastructure.

Keywords: *asset management, interconnectedness, climate change, agent-based modelling*

1. Introduction

Asset management is a relatively new domain of infrastructure management and maintenance. It mainly focuses on taking actions based on information collected on various aspects of the assets over their entire life cycle. These include exercising options on feasibility, acquisition, maintenance and replacement of an asset for maintaining their operation in a safe and reliable manner. According to PAS-55 (BSI 2008), asset management (for physical assets) is the optimal use of the identified twenty-eight aspects of an asset starting from its first recognition to the final disposal. ISO-5500X (2014) superseding PAS-55 (BSI 2008) has expanded the definition of asset management as – coordinated activity of an organization to realize value from assets– to also include non-physical assets, see (BSI n.d.)[4].

Climate change impacts are unavoidable risks on our infrastructure assets and adaptation to these impacts is the focus of recent infrastructure planning strategies (Bhamidipati et al. 2015). Asset management is now starting to focus at vulnerabilities of infrastructure assets especially

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[4] At the time of this publication, it could not be verified if the new standard explicitly refers/addresses climate change or its impacts on assets other than treating it as external risks to assets.

with a focus on their availability during an extreme climate event and on impacts from prolonged exposure to long-term climate changes. However, this focus is mainly on *single-sector* infrastructure (individual asset categories) such as roads, bridges, and tunnels (Rowan et al. 2013; Lambert et al. 2013; Gharaibeh & Lindholm 2013); or assets at a network-level such as combination of roads with bridges and tunnels or combination of roads with rail etc (van der Velde et al. 2013; Meyer et al. 2010). Still, in these examples all assets were within a one sector (transport sector). For asset management within transport sector, there has been a recent impetus on climate change with the publications by USCCSP (2008), AASHTO (2011), FHWA (2013). These publications in transportation asset management, explicitly mention - because climate change impacts (heat, precipitation, permafrost, sea level rise, snow, storms etc.) pose a serious threat to our infrastructure assets; our adaptation strategies should involve activities like: protection, maintenance, renewal and construction of infrastructure assets to make them less vulnerable to climate impacts. All these recent publications emphasize the importance of climate change in asset management activities (Bhamidipati 2015).

However, a climate change event may have impact on vast geographic areas and consequently affect *multi-sector* infrastructures (multiple asset categories) such as transport, electricity, sewerage, water, ICT etc. (Chappin & van der Lei 2014; Bollinger et al. 2014). These assets are most often interconnected due to their locational proximity or their dependency, especially in our dense urban areas. Most studies that deal with infrastructure asset management consider an individual asset category and avoid the possibility of studying simultaneous effects on multiple asset categories. Vanier (2001) and Halfawy et al (2006) identify and discuss a few underlying reasons on why asset managers handle individual asset categories. These include: lack of interoperability across departments dealing with different infrastructures (sectors), incoherent data to conduct an integrated analysis, limitations of decision making tools (proprietary software) that prevent a smooth integration and most tools focus on short-term and day-to-day maintenance activities with no provisions for long-term strategic planning in investments etc.

Recent articles on asset management clearly indicate that public infrastructure in the developed world is ageing and needs replacement (Hall et al. 2013; Armbruster et al. 2013). Moreover, with climate change inevitable, asset managers are considering different ways to invest in sustainable infrastructure and are exploring on how to integrate them into already existing infrastructure. This is considered important as infrastructure is built for a long term and a wrong assessment now, would lead to an undesirable lock-in for future developments. In contrast, in fast developing countries, a huge portion of GDP is being put into infrastructure investments. These investments could lock them into unsustainable patterns of development for a very long time. Climate change impacts will also be experienced for a long time, therefore when making long-term decisions for our infrastructure, it is important that we consider climate change aspects in their assessments.

Sector-based (or single sector) planning has largely dominated infrastructure investments for the past many decades. Hall et al (2013) list many examples of failed approaches based on sector-based planning and discuss the need for a new paradigm of decision making tools to enable cross-sectorial or multi-sectorial planning of infrastructure. In this paper we step away from this traditional sector-based asset planning to a multi-sector based planning and present an integrated simulation model, based on a *layered*-approach. In this approach, we add each infrastructure asset as a layer and define its interactions with other infrastructure layers in the model. With this approach, our model is able to combine infrastructure of different sectors (multi-sector) and therefore can be used to gain insights about the implications of interconnectedness in infrastructure, for asset management. We place our model in the context of a climate event that triggers cascading effects in our assets due to interconnectedness. This layered approach has the potential to handle multi-sector asset categories under the impact from multiple climate events in a simulation model that can be run in a timeframe from minutes (short-term) to any number of years (long-term). In this paper we study the impact of a flood (one climate event) on multi-sector assets (sewer, electricity, and roads) for a time period of few days.

This article is organized as follows: in Section 2, we discuss the literature on interconnectedness and focus on asset management and its combination with agent-based modelling. Section 3, introduces the proposed layered approach in an agent-based simulation environment and in Section 4 we present a case as an application of this simulation model. In Section 5, we discuss the model outcomes and present some conclusions about the model, applicability and future scope for our layered approach.

2. Modelling infrastructure interconnectedness

Climate change has brought forward a serious and urgent challenge for controlling its causes (mitigation) and adjusting to its consequences (adaptation). As climate change impacts are considered to be inevitable, there is an urgent need to design and realign infrastructure systems to cope with the consequences. Climate change is anticipated to pose serious challenges to our infrastructure, more so in case of urban infrastructure because large populations that depend on them.

Infrastructure systems in urban areas are so densely located that interconnectedness between infrastructures of various sectors is unavoidable. Because of this dependence and connectedness, any disruption in infrastructure and its services will have a serious impact on its users. Broadly stated, interconnectedness is the presence of a physical or functional linking of lines/ channels/ systems, while interdependence is a state of being supplementary or symbiotic in nature. According to Rinaldi et al (2001), dependency is a unidirectional relationship among infrastructures while interdependency is a bidirectional relationship between infrastructures. They suggest four possible groups to classify infrastructure interconnectedness: physical, geographic, cyber and logical. However, they state that as systems become more and more complex, it is difficult to classify them into any one group and their relationships can fall under various possible combinations and configurations of these groups. To take a holistic approach on these complex relationships in interconnected infrastructure, they chose to use the term interdependencies instead of dependencies. Keeping with these definitions, in this paper we investigate interconnectedness in multiple infrastructures with unidirectional dependencies and its implications on damage assessments for an asset manager.

Islam et al (2012) consider asset management as planned activity and regard their interconnected infrastructure only with geographic connectedness. Examples of physical connectedness in single-sector infrastructure (e.g., in transport sector) include, buses feeding passengers to trains; or examples in cross-sector include, electricity lines providing power to a water distribution and pumping stations (Duenas-Osorio et al. 2007). Another example of interconnectedness can be that of a local street network bringing traffic to the urban arterials that in turn feed the regional highways with traffic flows. Similar flows can be observed in a water distribution system, from high-pressure pipes to low-pressure pipes near the customer; electricity distribution systems, from a high voltage power line to the customer through the distribution lines. This flow pattern is typical in all network infrastructures that consist of high and low capacity links supplementing each other to provide a service to the end user. This interconnectivity is discussed regularly in literature in the context of 'interconnected-infrastructure' (Heller 2001; Rinaldi et al. 2001; Pederson et al. 2006; Adachi 2007; Halfawy & Eng 2008; P. Chen et al. 2009; Deffuant & Gilbert 2011). Pederson et al (2006) in particular, present a detailed collection of various case studies and research efforts on critical infrastructure interdependency from around the world that includes on-going research work at universities, practices from organizations, and development of software tools.

Most literature dealing with interconnectedness subscribes to analysing the vulnerability of networks in a context of topological disruptions. In these cases, the methodologies deal with deliberate or random disruptions at a location in the network and their impact on the whole network (Kurauchi et al. 2009; Knoop et al. 2012; A. Chen et al. 2006). These methodologies are often conducted on infrastructure within the same sector (single-sector) i.e., in transportation networks, water distribution networks etc. In reality however, the locations identified for single-sector vulnerabilities can differ considerably if multi-sector vulnerabilities are considered. Kirshen et al (2008) look at dependencies across sectors with a specific focus on climate change, and they argue how adaptation options have impact on each asset (component) and the system as a whole. This is typical in systems where behaviour of one component depends on behaviour of other components, and are known as complex systems (Patt & Siebenhüner 2005).

To study such complex systems, Axelrod and Cohen (2001) developed a theory of Complex Adaptive Systems (CAS). CAS ideally has many participants (components) who interact with each other and continuously evolve and adapt to shape the future. Barrat et al (2008) enlist three characteristics of when a system can be called a complex system: a) systems that have emergent phenomena, i.e., they have spontaneous outcome and not engineered to blue print, b) if these systems are decomposed and individual components are analysed, systems behaviour still cannot be explained c) presence of complexity at all scales. These are systems where the whole is more than sum of its parts. Because of the complexities involved, behaviour of the system is not the same as the aggregate of the individuals, which is also referred to as *non-linearity*. One particular paradigm for modelling such complex systems and their behaviour is by use of agent-based models (ABM). An agent-based model is "a collection of heterogeneous, intelligent, and interacting agents, that operate and exist in an environment, which for its part is made up of agents" (Epstein & Axtell 1996; Axelrod 1997). Such modelling techniques provide insights to emergent phenomenon that we cannot perceive from our intuition.

Urban Infrastructures have been characterized as a complex adaptive systems by (Heller 2001; Little 2002; Rinaldi et al. 2001). Osman (2012), Bernhardt (2004) and Moore (2007) use ABM as a method to approach infrastructure as CAS and specifically apply it to pavement management systems and can be cited as works that are close to the work presented in this paper. Moore et al (2007) improve and extend the work of Bernhardt et al (2004) from a prototype model that considers user satisfaction on quality of pavements. Their satisfaction is reflected in their voting for the politician who is responsible for the state of infrastructure. However, authors' work does not consider agents making a route choice in case they encounter a lower quality road. Osman (2012) also presents a similar case on infrastructure asset management with a special attention on user satisfaction for assets and their service levels. This satisfaction is based on their tolerance levels for the service experienced, which is then reported to politicians who subsequently prioritize their investment policies. The author compares the agent-based approach with traditional system dynamics and Markov-chain models and his results point out better performance indicators for overall network condition when user feedback is included.

Within such complex systems when we introduce the notion of human interactions along with the decision making government bodies and institutional policies (as in examples of urban infrastructure above), these systems are called complex socio-technical systems (de Bruijn & Herder 2009; Van Der Lei et al. 2010; Chappin 2011). A socio-technical system essentially consists of a physical/technical part and a social part as described in Ottens (2006). They form a mix of interconnected and interdependent entities that are reacting to one another to evolve and adapt to their surroundings and environs. All the systems enable integration of physical infrastructure (entities or agents not capable of taking decisions e.g., roads, sewer pipes, electric substations) with humans and institutions (entities capable of decision making e.g., asset manager, maintenance personnel, road users). In the following sections we will show how the approach introduced in this paper falls under the same socio-technical systems paradigm and is advantageous in enabling us to model of these kinds of complex systems.

3. Prototype in ABM with layered approach

Literature that discusses and models interconnectedness in infrastructure deal with network vulnerability, reliability, robustness and stop at identifying critical infrastructure. And very few authors deal with management of these infrastructures from an asset manager's perspective i.e., in terms of their maintenance and replacement decisions. Our proposed approach allows for an asset manager's perspective in terms of identifying assets that need repair or replacement.

3.1 Model platform

We briefly introduce the two concepts of space and time, as applicable to our approach. In the last two decades, the representations of a physical entity under analysis, the analysis and visualization of this analysis in a spatial context has taken importance and this has given rise to the use of spatial analysis techniques like GIS, see (Akingbade et al. 2009) . The main advantage of GIS is in the use of different location sensitive data (objects-of-interest) as overlapping layers and combining them into one analysis unit. This helps in expressing the data, the analysis and subsequent results in a more spatially enriched context for easy decision-making (Hao et al. 2014). Similarly the concept of time has always been an inherent part of any analysis, whether it is for the purpose of forecasting or back casting. Almost two to three decades ago, until the improvements in computing, most time based analyses provided insights on variables or scenarios at a specified and distinct time in future or in past. Since then, the concept of time is intrinsic to modelling because of high computing power and the advent of various dynamic simulation techniques like: discrete event simulation, system dynamics, micro-simulation, agent-based simulation etc., see a review of these techniques by (Ouyang 2014).

Agent-based simulation models (ABM) are being used by social scientists for understanding social behaviour and natural ecosystems. However, these kinds of models are still not very popular because of the steep learning curve involved in getting familiar with the language of coding and also due to lack of integration with readily available GIS data. This limits their use to social scientists who are comfortable performing coding or programming tasks. Drogoul et al (2013) argue on these two very prominent shortcomings in existing popular ABM platforms. According to the authors, even though ABM platforms like Repast are mature enough to build simulation models, their language is very complex to build and design models. Another platform – Netlogo – solves this problem with much simpler language syntax to build models, but it still lacks abilities to integrate GIS data. In this data intensive world where large amounts of data is available in GIS databases, we feel that platforms that are used to build complex models should have the capability to integrate spatially rich GIS data in its various formats. One such simulation platform that addresses these shortcomings and provides easier language syntax as well as the ability to import and export GIS databases is 'GIS and Agent-based Modelling Architecture' (GAMA). Please refer Grignard et al (2013) for details about GAMA platform.

Our approach is analogous to layers and overlay analysis performed in GIS tools such as ArcGIS, QGIS etc., (Hao et al. 2014) and therefor we chose to call it a '*layered*' approach. This simpler name allowed us to connect to infrastructure asset managers who immediately recognised and understood the analogy of layers, as they were very familiar with GIS methods and its data. Our layered approach developed in GAMA, takes advantage of simulation techniques and also allows for incorporating the abundant GIS data available from the asset managers, the local authorities and from the Internet. For this paper we take this layered approach on infrastructure interconnectedness and combine it with a simulation technique (ABM). This combination is new in scientific literature especially in the field of asset management for interconnected infrastructure. We believe that when dealing with interconnected infrastructure, a layered approach like ours, that is also aware of the spatial connectivity and dependency can be very beneficial not only for analysis but also for visualizing the outputs.

3.2 *Layered approach*

Taking advantage of the advances in computing for space and time, we now describe our *layered* approach. In this layered approach (see figure 1), we define each agent type as a layer, and therefore '*N*' layers represent the 'N' agent types in the model. The boundaries of each layer define the spatial extent of each agent type (in XY plane). The *union*[5] of these layers delineates the complete spatial boundary of the model where all the agent behaviour and their interactions take place. On the Z-axis is time for simulation and it represents the time extent of the analysis. These layers are staked on the XY plane to indicate the spatial overlay and also into the Z-axis to suggest that the interactions amongst different agents take place at different time steps of the simulation. Also on this time-axis are some external factors (floods, precipitation, snowfall, extreme heat etc) that are introduced at random moments in time to replicate real-world climate events. These external factors have an impact on the agents and their interactions with other agents, thereby causing unanticipated outcomes to emerge from the simulation. We know that in complex systems (like interconnected infrastructure), behaviour that emerges from the system is non-linear and is different from the simple behaviour of its component agents (Bak & Paczuski 1995). Our framework using ABM, allows capturing such non-linearity through interactions amongst agents themselves and also with external factors over a period of time.

3.3 *Interconnectedness and interactions in infrastructure*

In this model we define 6 types of agents: pavement segments, sewer pipes, electricity sub-stations, a flood grid, car users, asset manager. The flood grid represents a digital terrain model (DTM) of the study area and is useful for simulating flood inundation. Each agent type has its own attributes and a set of defined interactions with agents of the other type. The interactions between the six agents are outlined in table 1 and the interconnectedness between them is depicted schematically in figure 2.

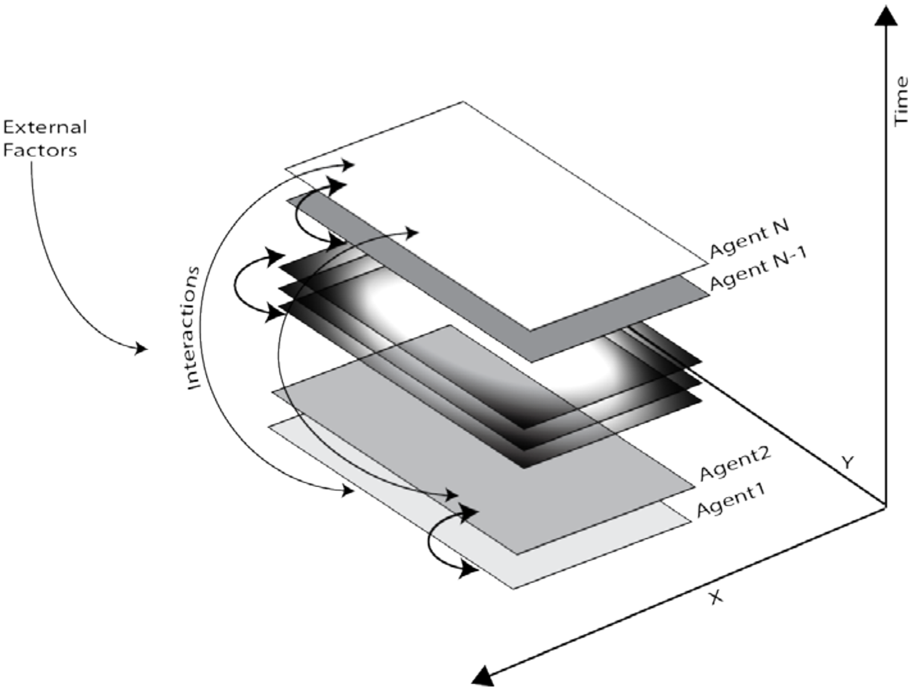

Figure 1. A 3D illustration of the layered approach where different infrastructure and decision makers are brought in as agents into the model

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[5] Union is a geometric operation in GIS that is analogous to the concept of union in Set Theory

To understand the interconnectedness and interactions among the assets in our model, let us consider the case of a flood event due to a dike breach in an urban area (section 4 discusses the specifics of this case). As the flood progresses from the dike into the surrounding areas, the model estimates the damage to the assets on a continuous time-scale and presents the extent and quantities of damaged assets to the asset manager. The first direct impact of the flood is on roads and the car users. The flood on roads causes the car users to re-route their trips along other alternative roads. On the other hand, the weight of the floodwater (based on depth of standing floodwater) affects the net forces acting on the pipes below the ground. This weight (force) especially affects sewer pipes, because unlike water pipes they are not always completely full with sewage (air fills the remainder space in the pipes). This imbalance in the upward and downward forces causes the pipes to float to the ground surface. When these pipes float to the surface, there exists a higher chance of damage to the roads or other infrastructure located on top of them. This is especially true in our urban areas where infrastructure is densely located due to lack of space.

As the flood progresses, it may reach electricity substations that provide power supply to that area. These substations are vulnerable at certain floodwater depths and get damaged (submerged) or have to be turned off for safety. If there is a power failure as a consequence of the flood damaging any of these vulnerable substations, it disrupts the power supply to sewerage pumping stations in that area. This disruption affects the pumping of sewage in the pipes and causes unstable proportions of air and sewage in the pipes. Secondly, as described before, the additional weight of floodwater above these pipes increases their chances of floating to the surface. Consequently, these floating pipes damage the roads on top of them and force the car users to re-route themselves. It is important to model the car users because they increase the damage (deterioration) on other assets (roads) because of re-routing. All these damages are estimated by the model and presented to the asset manager. The asset manager therefore has an overview of the whole system in a multi-sector perspective and can then decide on suitable strategies to repair or replace the damaged assets. The connections are illustrated in figure 2.

Table 1. Description of agents, their characteristics and defined actions

Agent	Characteristics	Behaviour/ Interactions
Road Pavement	Length, number of lanes, speed-limits, asset condition index	Deteriorates by use from cars, damaged by flood, and floating sewer pipes
Sewer pipe	Vulnerability criteria[6]	Float to the surface when flood reaches threshold levels; damage the roads on top of them when floating, increased chance of floating in case of pump station failure
Electricity Substation	Vulnerability criteria (Bollinger 2015)	Breaks down when flood reaches threshold levels and affects the pumping stations of sewerage system
Flood grid	Elevation, flood depth	Floodwater flows in the direction of downward slope
Car users	Origin and destination	Move from origin to destination and cause damage to the pavements, switch roads in case of congestion or damage
Asset Manager	Asses the damage	Estimate the damage over multiple-assets

3.4 *Agent descriptions*

When urban areas are considered as complex systems, infrastructure assets form an important part of these systems. Their state depends a lot on the usage patterns, their natural deterioration and also on interventions from asset owners and managers. Additionally, when considering interconnected infrastructure, their state also depends on other connected assets. As these agents cannot make their own decisions but are able to get information and react to their environments, they can be considered to have a passive behaviour. In this paper, we conceptualize these infrastructure assets as *passive* agents and all other non-infrastructure agents as *active* agents. For for some examples where physical objects are used as agents, see (Borshchev 2013) , (Moore et al. 2007) , (Osman 2012)). Our layered approach facilitates inclusion and combination of human (active) and non-human (passive) entities for modelling systems as socio-technical systems. All the agents in our model are shown in solid boxes in figure 2. Each agent type has its own attributes and defined interactions with agents of the other type. The agent types, their characteristics are shown in table 1 and their interactions are shown in figure 2.

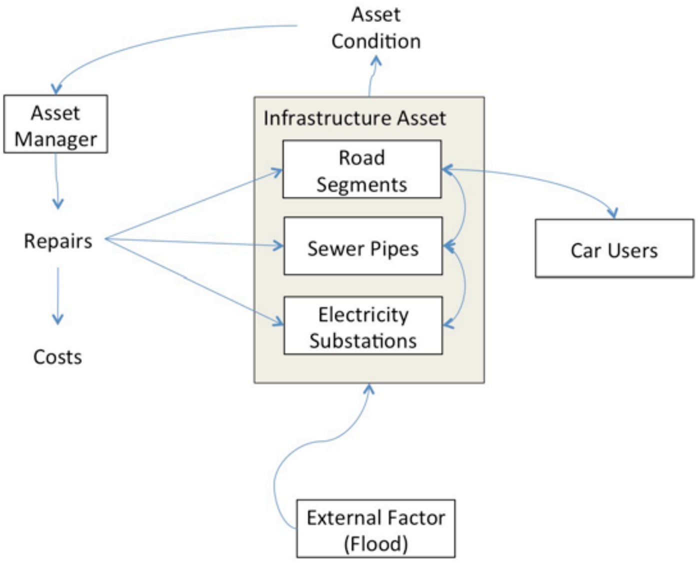

Figure 2. Schematic illustration of interconnectedness in assets, and its relation to users and owners

Road Pavement Segments: We assume these will deteriorate by a constant unit of damage per day and that caused by each car user agents using that particular road segment. All road pavements are given same initial condition index, and the damage from car users causes a degradation of this index.

Sewer pipes: As the depth of flood increases, its weight and downward force on sewer pipe network results into an imbalance of forces, causing sewer pipes to float at vulnerable locations. This floating of pipes to the surface may make roads inaccessible and as a result, car users need to re-route themselves or re-plan their trips. The vulnerability and location of sewer pipes is based on the imbalance between forces inside the pipe and above the pipe (flood water). These calculations were adopted from Wols (2014)[6].

Electricity Substations: A series of substations of varying capacities transform high voltage power lines to low voltage power lines in successive small steps to provide energy to residential and

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[6] pers. comm. Wols Bas calculations are beyond the scope of this paper and are based on a Dutch Standard: NEN BS 3650-1 Requirements for pipeline systems - Part 1: General requirements.

industrial areas of the city. These are located in different parts of the study area depending on the capacity of a substation. These stations can be vulnerable to floods based on their elevation levels and the flood depth.

Sewer Pump Stations: This layer contains agents for the sewer pump stations. These pumping stations are modelled as agents to link electricity substations to the sewer network. We make an assumption that failure of these stations will increase the chance of uncontrolled flow in the sewer pipes resulting in imbalance inside the pipe and consequently causing the pipes to float to the surface.

Flood grid: The flood is modelled as a function of the digital terrain surface. This surface is represented as a 2d grid with each cell having a elevation value. The flood model used in this paper is adapted from Grignard et al (2013). The flood modelling is based on a simple 2d flood inundation model where the flood water starts from a source cell and moves over the surface based on the difference in elevation between adjacent cells of the grid, for details see Dawson et al(2011). The depth of floodwater calculated from this model is used to determine: vulnerability and breakdown of electric substations; the extra force applicable on sewer pipes; and inaccessibility of vehicles to certain portions of the road network.

Car Users: They have a predefined starting point (origin) and ending point (destination). These agents travel from origin to destination on the shortest (time) paths. In case of any obstruction (traffic, flood, damaged roads) they change their path, en-route, to the next best shortest path. They cause a constant unit of damage to the pavement segments that they travel on and the cumulative amount of damage by all the users on a particular road segment is reflected by decline in its condition index.

Asset Manager: The asset manager is represented as a passive agent in the model. The model provides information about the entire network and its assets on: their condition, their deterioration and their damage. The model therefore serves as a decision support tool that allows the manager to prepare damage estimates for repairs or replacements of these assets.

4. Model implementation and a test case

A small area of 12 sq.km in North Rotterdam, The Netherlands, which includes the Rotterdam Airport is taken as a case study (see figure 3). This area has been identified as a hotspot (critical) area in Rotterdam under the INCAH program (Infrastructure Networks Climate Adaptation and Hotspots, see Acknowledgments). This area consists of residential and commercial areas, and an airport. Various research studies were conducted to understand the vulnerability of this area to a climate event and especially for a dyke breach. In this section we demonstrate the use of our layered approach as described in section 3. Three dykes on the major canals surrounding this area bind the study area. For this case study, one of the dykes – Schie Noord – is assumed to break down causing a flood on adjoining land that includes, roads, sewer network, and electric substations. This flood causes, inaccessibility, rerouting of traffic, floating of sewer pipes, instability of road embankments, and breakdown of substations.

Road Pavement Segments: In this study area there are 424 road segments in total.

Sewer pipes (47848 agents): This layer contains linear agents representing the 47878 sewer pipes of different configurations (size and material) providing sewer services in the study area. Each sewer pipe has a vulnerability index that is based on net forces applicable on the pipe and is derived from its depth below ground surface, density of pipe material, ratio of fluid/gas in the pipe and other variables as indicated in the previous section. In this case, the vulnerability based on net forces acting on the pipe was calculated for a floodwater depth of 20cm. The 20cm threshold is based on the maximum floodwater depth observed in the first 5 days after the breach in dyke has occurred. It is assumed that flood is brought under control after 5 days and hence the limit of 5 days (or 120 hours as shown on x-axis for charts in figure 4) used for assessing the maximum floodwater depth. Sewer pipes can be seen in red colour in figure 3. In this case, the diameters of various sewer pipes range from 63mm (2.4 inches) to 1500mm (59 inches). For the sake of presenting our approach, we simplified the pipes into three classes based on diameter, each class being represented by its higher end of the range as shown in table 2.

Table 2. Re-classification of pipes into three broad categories.

Pipe diameter ranges	Re-classification	Notation used
0-499 mm	<500 mm (18 inch)	Ø500
500 -999 mm	1000 mm (36 inch)	Ø1000
1000-1500 mm	1500 mm (54 inch)	Ø1500

Electricity Substations (50 agents): This layer contains about 50 electricity substations within the study area. These include substation of three capacities: 0.4kV (25 stations), 10KV (15 stations) and 25kV (10 stations). Based on their capacities, each substation has its vulnerability index in terms of flood depth that can cause a close down of the operations of that particular station. Depending on the interdependency, a higher voltage substation can also shut down its dependent lower voltage substations if the floodwater depth reaches the heights that can make it vulnerable. The criteria are adopted from Bollinger (2015) who studied vulnerability of various substations in the same study area. According to this criterion, 0.4kV substations are vulnerable at a floodwater depth of 20 cm, 10kV substations are vulnerable at a floodwater depth of 25 cm and substation of capacity 25kV or more have vulnerability at floodwater depths of 100 cm and more. However, it should be mentioned that for this publication, the location and number of substations has been randomized because of the sensitivity of the data.

Flood grid (7990 agents): This layer is represented as a grid with a resolution of 50mx50m and has 7990 cells completely covering the study area. At the start of the simulation, one particular cell representing the location of Schie Noord dyke starts discharging the water according to a predefined hydrograph (a time series graph indicating the amount of water discharged from the breach in the dyke). The grid is shown in the figure 3 below with the location of the Schie Noord dyke visible in darker shade.

Sewer Pump Stations (62 agents): This layer contains an agent each for the sewer pump stations. These stations are linked to the 0.4kV substations and failure of these substations will cause a power failure at these substations.

Car Users: There are 100 car user agents taken as input to the model. Each user causing a constant 0.003 ESAL[7] units of damage to the pavement on which they travel.

To understand the consequences of interconnectedness in infrastructure, we designed three experiments with gradually increasing complexity in their level of interconnectivity and in the context of a flood event. These experiments were defined as follows:

Experiment 1: In the first experiment, we show the base case where the infrastructure is not interconnected to each other, and the damage from flood is expressed solely in terms of individual assets. For example, in case of roads, the model estimates the length of roads that is under flood. In such a case, the road is not damaged but only unusable for traffic. Similarly, for other assets, which are affected by flood, are estimated as affected assets.

Experiment 2: In the second experiment, we present results based on the fact that damage to sewer causes their floating and this leads to the damage of the road above it. We call this the first order interconnectedness. For example, in case of roads, the sewer pipes below them start to float and

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[7] Based on Equivalent Single Axle Load for a fully loaded large passenger car weighing between 2000 to 7000lbs. Retrieved from http://www.pavementinteractive.org/article/equivalent-single-axle-load/ on 27.06.2014

damage the roads (collapse of subgrade, shoulders of the road or slopes of the embankments). In such a case the roads are damaged not merely affected as in experiment one, but physically damaged.

Experiment 3: In the third experiment, we present results based on the fact that, damage to electric substation from flood, will cause the sewer pumps to falter which in turn damage the functioning of sewer pipes and they float to the surface. This effect subsequently damages the roads on top of them, and we call this second order interconnectedness.

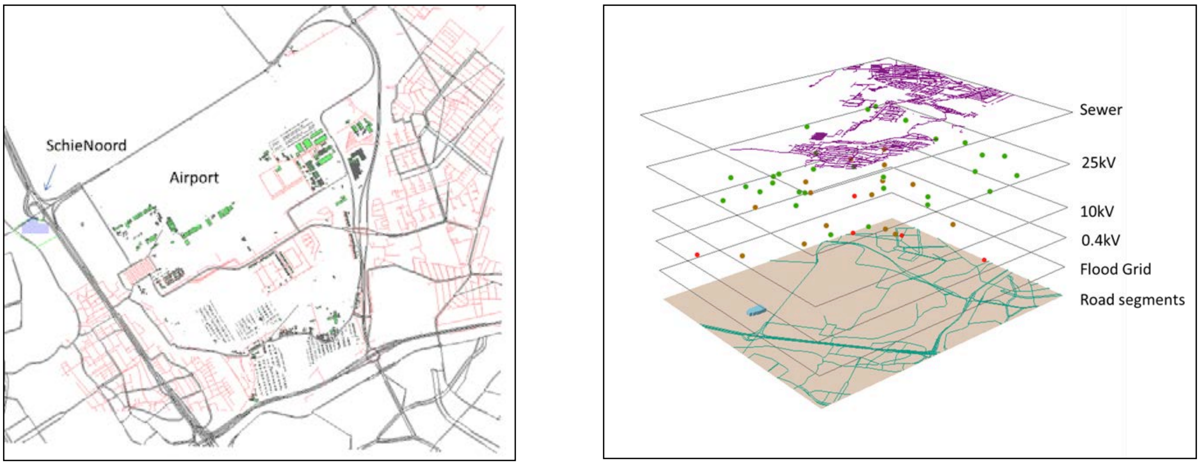
Table 3. Description of the simulation experiments.

Experiments	Connectivity	Interconnectedness in Assets involved
Experiment1	None	Individual assets: Electric substations, sewer pipes, roads
Experiment2	First order	Sewer network affects roads
Experiment3	Second order	Electric substations affect sewage stations, sewage stations effect sewage network, and sewage network affects roads

The results comparing the three experiments are summarized with three charts as shown in figure 4. The first chart shows the comparison of effects on the electric substations. It can be seen that there is no difference between the first two experiments as the model was designed with no interconnectedness for the substations. A variation is observed because of the natural randomness of the model that affects the flood depth. But with the third experiment, where we design the connectedness and hierarchy of electric substations, we notice a higher number of substations becoming affected.

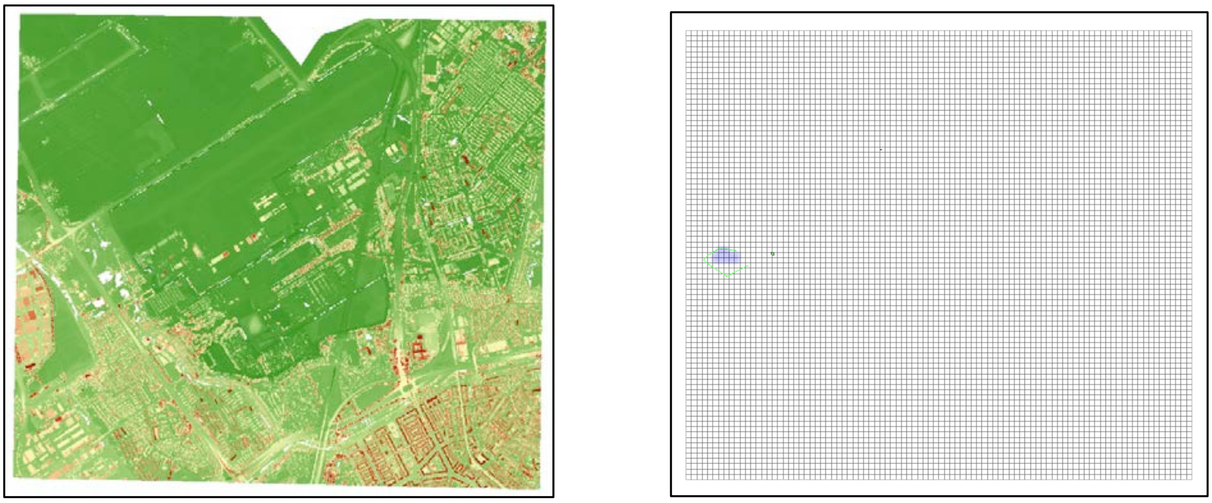
The second chart shows the comparison of effects on the sewer pipes in the study area. The length of affected pipes again has a variation due to the natural randomness of the model that affects the flood depth. Furthermore, we do not observe any significant difference in damages between the first two experiments because the model does not allow for any dependencies of sewer network at this stage. In the third experiment however, we model the connectedness of electric substation to the pumping stations in the sewer network and as a result we see damage to a larger area and therefore higher number of pipes getting damaged in all categories (pipes of diameter 500mm, 1000mm and 1500mm).

The third chart compares the length of roads affected in the study area in the three experiments. Here we see a change in the three experiments because for the second experiment we have designed the model to consider connectedness between sewer network and the roads. And for the third experiment, electricity network affects the sewer network, which in turn affects the road network. As explained previously, when sewerage pipes start floating they damage the roads on top of them making the roads unusable. This damage is often omitted when assets are considered in silos or per asset category.



a) Test case study area with roads and sewer lines

d) Various agent layers in use for the test case



b) Digital Terrain Model (DTM) of the test case area

c) DTM as Grid layer for flood modeling and the location of the dyke breach indicated in dark shaded cells.

Figure 3. Test case area with various assets and their representation in the framework

In experiment 1, a road is affected when the floodwater is higher than 20 cm on the road. In which case, the traffic may still be permissible for some unavoidable conditions and to avoid lack of connectivity (e.g., emergency vehicles, maintenance vehicles, military vehicles). However, when we consider experiment 2, traffic cannot be allowed because there is a real physical damage to the road from the pipes, which makes them unsafe for the traffic. In experiment 2, there is a steep increase in the length of damaged roads in the initial hours after the flood, compared to later hours. This can be attributed to two reasons: first, the density of road network is higher near to the point of flood breach and later as the flood progresses, it reaches more vacant and open lands with less density of roads and other infrastructure; second, the floating of sewer pipes causes a more damage to the road surface and longer stretches of roads are damaged quickly. Later as the flood progresses into the vacant land, we notice that the damage profile evens out and matches the profile of experiment 1. For experiment 3, we observe that the number of roads damaged is even higher compared to the previous two experiments. This is because of the second order connectivity where the sewer pumps are dependent on electric supply. As the sewer pumping stations fail; it creates an imbalance in the forces inside the pipes and accelerates the damage on roads.

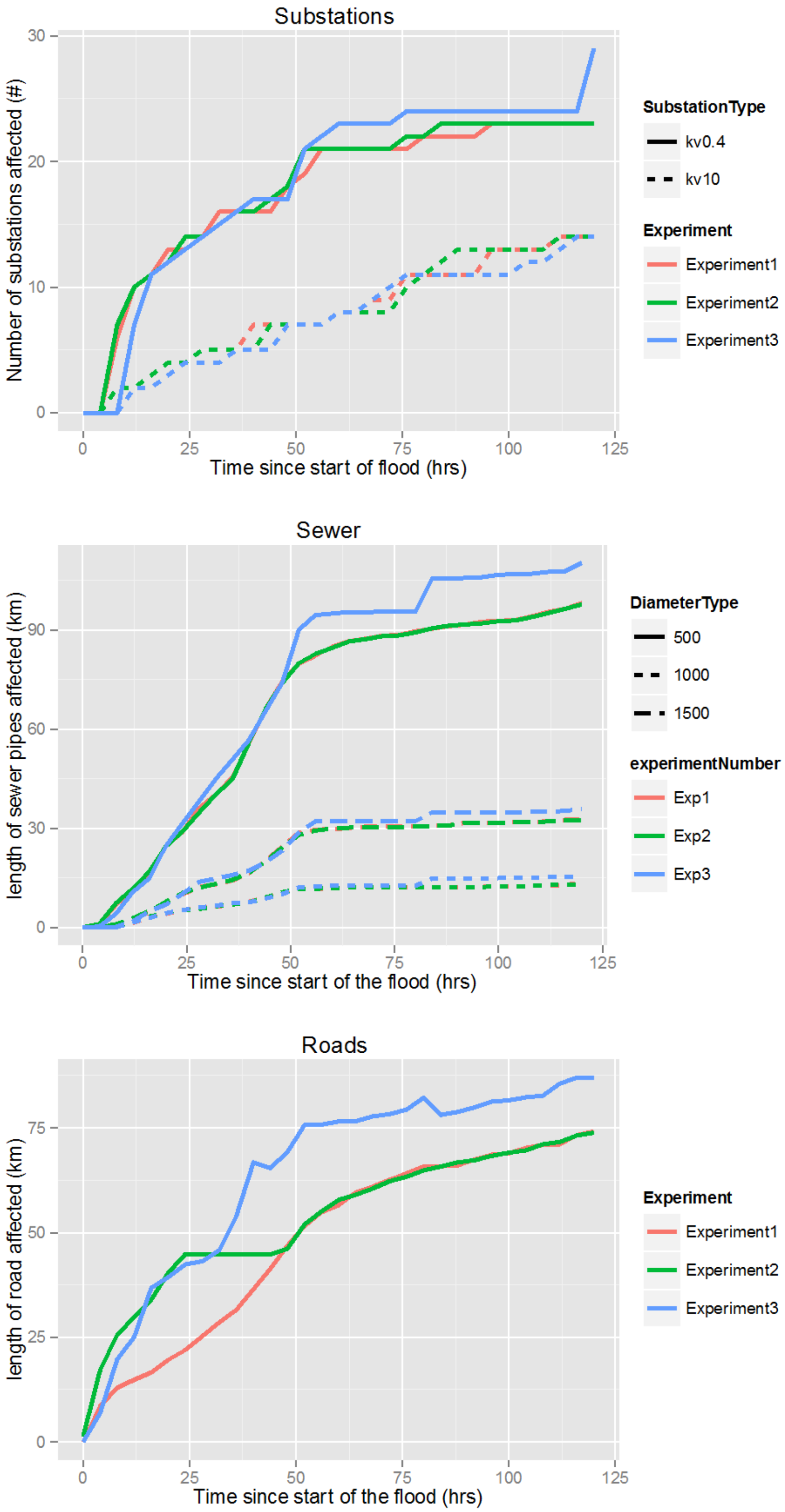


Figure 4. Results from three experiments showing the quantity of assets affected in each category

5. Discussion

This research provides a framework for the use of agent-based models to simulate interconnected assets. Capturing interconnectedness is not trivial, but modelling each asset as a layer gives a greater flexibility as demonstrated in our layered approach. Moreover, when details in data increase for a layer, the estimates from individual asset layers can be improved further without affecting other connected asset layers. For example, to emphasize on the process of model building, we simplified our case study by classifying our sewer pipes into three broad classes based on their diameters. Similarly, classifying the roads based on their pavement material; accurate mapping of connections between substations and pumping stations etc., can already improve the accuracy of the results. The flexibility of our layered approach becomes even more enhanced when a layer is weighted to signify its importance compared to other layers. These weights can be based on: its impact to the system, availability of resources, funding, its necessity and also its priority for its end-users. This can be useful for more real-world situations where asset managers of different sectors have different priorities and funding allocations for their assets. And an asset manager, modelled as an intelligent agent, can make strategies for more informed allocation of available resources.

Chart 3 in figure 4 shows a difference of about 20% increase in the final damage estimates of roads when considering the interconnected assets such as sewer and electricity. If road asset managers are also aware of vulnerabilities from the condition of other connected assets, they can collaborate with these other asset managers to fix their assets. This collaboration can reduce the damage to roads by up to 20%. It should however be noted that since we considered all road segments to be of same material and expressed the damage in unit lengths, these damages may vary by a different extent if they are substituted by costs of actual pavement materials. It can be argued that these results can be established by many modelling methods, but an inherent advantage of using ABM becomes more visible for this collaboration between asset managers of different assets. To limit the scope of our paper, we wanted to emphasize on the possibility of interactions among infrastructures in our model and we see the interaction between asset owners and managers as a future direction of our research. These interactions between asset-managers gives rise to the possibility using this model for studying interconnected infrastructure along the lines of cross-asset investment strategies (Deix et al. 2012).

In this particular test case, the main roads formed the periphery of the selected area. This meant that most of the traffic was moving on the peripheral roads and not truly going in and out of the study area. This did not allow us to study the impact on road users' (vehicular traffic) route choice behaviour. However, the manner in which agents in the model are designed and if the model were to be transferred to a larger areas with different road patters; it is capable of simulating road users' behaviour on how they would divert to alternate routes (assets) to avoid the damaged portion (flooded area) of the network. This diverted traffic onto other routes can give the asset manager many other insights on varied usage of the assets in the network and hence a varied deterioration and maintenance requirements on a longer term.

Secondly, the site of dike breach was very close to the main road carrying the traffic such that the flood almost immediately affects this road and car users completely by-pass the study area. Therefore the behaviour of car agents, in terms of choosing an alternative path, in case of an event, was not very evident. Because of this, the aim of incorporating the impact for car users did not play a major role. However, if the model is run for a long term and by tuning flood events to occur more frequently, we expect that both effects from car users and that caused by flood can be studied. This can help an asset manager to estimate recovery time and repair costs. Despite the negligible effect of car users seen in our model, their impact on asset management cannot be ignored. Their impact although acknowledged in Jollands et al (2007) and Moore et al (2007), it was only recently studied analytically (Vergereau & Macmillan 2014) and using simulations (Bhamidipati 2015) in terms of risk estimates and costs to asset managers and the user.

In appreciation of climate change, especially in case of heavy rains or flood events like the case presented here, damage to sewage network (and storm-water network) plays a significant role in damage assessment. The problem often cited for collapse of the sewage system and its interconnected infrastructure is because of its inadequate design capacity and therefore their inability to handle flood and rain water. This could delay the recession of floodwater from the area and in-turn affect the downward forces acting on the pipes resulting in even more number of pipes to float to the surface. This problem will only escalate in the future given that the frequency and intensity of rain and floods will increase with climate change. Hence inclusion of sewage network as interdependent asset is warranted for such studies. And this becomes crucial for asset managers dealing with roads to be aware of such implications and to associate with asset managers of sewerage networks to collaborate and compliment each other for maintenance and upgrade estimates.

6. Conclusions

In this paper, we developed an agent-based simulation model with a layered approach that is analogous to GIS overlay approaches, wherein different infrastructures are coupled physically and functionally for their effective representation. We explored how this coupling can help asset managers to gain insights in estimating the total damage and repair requirements in a given geographic area. Given the physical proximity and dense installations of infrastructure in our urban areas like our test case, asset managers should carefully consider the non-linearity in damage assessments and therefore the risk and cost estimates. These estimates are different from the currently used non-integrated models. To summarize, the layered approach developed in this research has the following advantages:

Transferability: The proposed framework can be used to study asset deterioration by integrating effects of climate events on multiple infrastructures and their interconnectedness. Because of its layered approach, layers in the framework can be weighed to priorities and customized to areas-of-interest in different geographic regions and climate patterns.

Flexibility: An ABM platform provides the ease of a bottom-up approach that allows describing the basic activities of agents and their interactions in order to understand the system's complex behaviour especially in unseen climate change scenarios. Additionally, the layered approach taken in this research enables different experts and stakeholders to model assets or events in their domain and include it as a layer to increase the richness and practical usability of the model.

Associativity: As the framework enables study of assets of the same type and of different types, same asset owner or different asset owners, same service provider or different service providers; it has the potential to engage and associate different asset managers and stakeholders in a single platform for collaboration and optimal use of resources.

Although we describe the case of a flood event, with the advantages listed above, the same procedure can be used to model other climate events or even combination of events such as rain, snow or temperature changes. With the frequency of these climate events to increase in the coming future, we see a potential for this model to explore the possible impacts on our interconnect infrastructure networks. Moreover, because of the ability of our model to run simulations from minutes (short-term) to years (long-term) asset managers can gain insights for long-term investment strategies.

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