

A SIMULATION FRAMEWORK FOR ASSET MANAGEMENT IN CLIMATE- CHANGE ADAPTATION OF TRANSPORTATION INFRASTRUCTURE

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INTRODUCTION

Asset management is comparatively a new science of infrastructure maintenance and management. Although, the skills of managing assets have been here for long, but they were not formalized as established procedures and standards until recently. It has now, an organised approach to manage assets at a good level of service for its users and has established procedures, that are adhered to by many organisations in the service industry, that are now published in the form of a Standard, PAS-55 (BSI, 2008) that covers twenty-eight aspects of assets throughout its life-cycle. Asset management, in more general terms, can be seen as a standardized approach to preparing profiles of risks, for assets, and their minimization through timely acquisition, construction, maintenance, rehabilitation and disposal of assets. As these practices have been formalized based on the past experiences of engineers and infrastructure managers, there is a big knowledge gap about the much recent and eminent risk to our infrastructure, the risk of climate change. Climate change and our understanding of it and its impact on humankind and our infrastructure is still very little. Understanding climate change involves dealing with twin-facets of mitigation (reduction of the causes) and adaptation (reduction of consequences). For asset managers, the facet of adaptation is of more value as it is about reducing the impacts of climate change on our infrastructure (Bhamidipati, van der Lei, & Herder, 2015).

With climate change gaining prominence, asset management is now starting to look at vulnerabilities of infrastructure assets especially with a focus on robustness and availability of the asset. Asset managers of a particular domain, most often, are interested only in their specific assets. Such an approach may be appropriate for general purposes, but in the context of climate change, it creates a mismatch in two main aspects. First, events of climate change have a large-area impact and affect an array of assets in their wake. This is unlike the damage of one or a few assets that can be predicted by their established deterioration profiles. The impact of a weather event on an area is irrespective of the category of an asset, or the asset in concern of a particular asset manager. The array of assets affected can be of one category (transportation or sewer-lines or underground cables etc.) or a combination of these categories in that area. Secondly, most reports and literature dealing with asset management and climate change deal with a static framework, in a sense that they recreate a most possible/probable scenario of an impact and analyse the outcomes. This may be appropriate for short-term measures or disaster preparedness, but are less useful for long-term asset management strategies.

Addressing these two shortcomings, in this paper we present a framework that is dynamic in nature and includes an integrated approach by involving interconnected assets. We use agent-based simulation technique to handle the dynamics of both short-term and long-term consequences and the logic of causal interactions between collocated infrastructures to handle assets of other sectors that may affect the transportation assets.

The paper is divided into four sections including this introduction to problem statement. In the second section, we present some relevant literature dealing with climate change and asset management and in the third section; the model building exercise and its results are described. The fourth section concludes with a discussion and possible policy relevance of this approach.

2. MODELING INTERACTIONS OF INFRASTRUCTURE

Management for transportation assets, more recently addressed as transportation asset management (TAM), for climate change, is quickly gaining importance among many transportation agencies. IPCC (Field et al., 2012) publication on risks of extreme events, combines disaster management options with climate adaption activities. And for the first time in its publications, IPCC discusses inclusion and formalization of asset management into mainstream evaluations of infrastructure. There has also been a recent impetus in this domain with the publications by USCCSP (2008), AASHTO (2011), and a series of publications by FHWA (2013). A definition of TAM more so specifically for climate change that can be summarized from all these publications is - because the climate change impacts (heat, precipitation, permafrost, sea level rise, snow, storms etc.) pose a serious threat to our infrastructure, our adaptation strategies should therefore involve activities like: protection, maintenance, renewal and construction of infrastructure to make them less vulnerable to climatic impacts. All these recent publications emphasize the importance of asset management in climate change adaptation activities.

Meyer et al (2010) discuss the requirements of incorporating asset management into TAM and describe the nascent state of this subject in USA and also worldwide. Authors present a quick review on international practices on TAM for adaptation and how most of focus is still on mitigation strategies. In an update to this status, Meyer et al (2012) show us a detailed framework for including weather related risks in TAM for considerations in investments. Lambert et al (2012) present a scenario based analytical approach to prioritizing investments in transportation assets in a setting of climate change. Jenelius et al (2012) takes a step further by presenting an easy approach to analyze impact of climate event with a case on Swedish transportation network. The author considers climate events as area disrupting events and studies them in various scenarios to analyze their impact on system-wide indices. As evident from these articles and others mentioned previously, asset management in context of climate change is being dealt only with static scenario building of mostly likely or a worst-case

scenario. Though this is a sufficient approach for high-level planning, the scenarios constructed are restricted to the understanding of the modeler or the focus group designing them, which therefore limits the understanding of random nature of climate events. An alternative approach would be to consider more dynamic and probabilistic simulation approaches, but climate change events and their effects being so recent, there are not many established probabilistic distributions, for these events, that can be used in simulations. This is probably the biggest knowledge gap we have in this field. This however, gives us an opportunity to explore a new simulation approach, that of agent-based modeling (ABM). We find it suitable for our objective of handling dynamic simulation approaches and integration of multiple infrastructure assets. Additionally, we study the impact of a climate event on a road network, its users and its managers. When dealing with such decision making human entities (agents), ABM has been found useful. In subsequent sections we shall see how the road users are designed to be intelligent to take their own decisions of trip making, and also about asset managers who make decisions on repair and maintenance investments. Such a combination of human actors and physical entities within simulation models fall under the realm of what are now popularly known as socio-technical systems (de Bruijn & Herder, 2009; Van Der Lei, Bekebrede, & Nikolic, 2010).

These socio-technical systems are part of the larger domain of complex systems. Barrat et al (2008) enlist three characteristics of when a system can be called complex: 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 analyzed, systems behavior still cannot be explained c) presence of complexity all scales. These are systems where whole is more than sum of its parts. Because of the complexities involved, behavior of the system is not the same as the aggregate of the individuals. To study such complex systems, Axelrod and Cohen developed a theory of Complex Adaptive Systems (CAS). The concept of CAS is beyond the scope of this paper and may be referred in Alexrod (1997). In brief, CAS ideally has many participants who interact with each other and continuously shape the future. One particular paradigm for modeling such complex systems and their behavior 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” (Axelrod, 1997; Epstein & Axtell, 1996). Such modeling technique provides insights to emergent phenomenon that we cannot perceive and show how our intuition can be poor reflection of the proceedings beyond a limited level of complexity. Osman (2012), Bernhardt (2008) 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. They use a variety of platforms, including commercial and closed platforms within their projects. For our model building exercise, we use GAMA modeling platform (Grignard et al., 2013). GAMA is free, open source ABM modeling and simulation

package with its own easy to use modeling language and has many advantages over other more popular but basic packages like NetLogo, especially with its strength over GIS integration. In the following section, we go through the process of building a complex system using ABM technique to help us address and achieve our objective of building a simulation framework in asset management for climate change.

3. MODEL FORMULATION

The model presented in this paper is divided into three stages. Starting from stage-I with an ideal theoretical example to stage-III with real world case. Each subsequent stage adds on to its previous stage in a gradual manner keeping intact the main theme of presenting a decision support tool for asset management. Each stage can stand on its own as an independent decision support tool. Each stage has its own implications and its own appeal to a different set of asset managers. As shown in an illustration in figure 1, the stage-I deals with an urban road network, daily trips on it, its deterioration and a asset manager who is maintaining the network to be in a good condition. In stage-II, an climate event is introduced and its impact on the whole network is measured in terms of trip makers delay time and possibilities of developing system wide indexes that can be of interest to a system manager who wants to keep it efficient on these indices. In stage-III, we add the influence of infrastructure assets of other sectors on the transportation assets (roads). This stage presents some very interesting opportunities for asset managers of different sectors to come together and act in an integrated manner and this enhances the real potential of agent based modelling technique underlying the model. The following sections describe this model building progression and procedure.

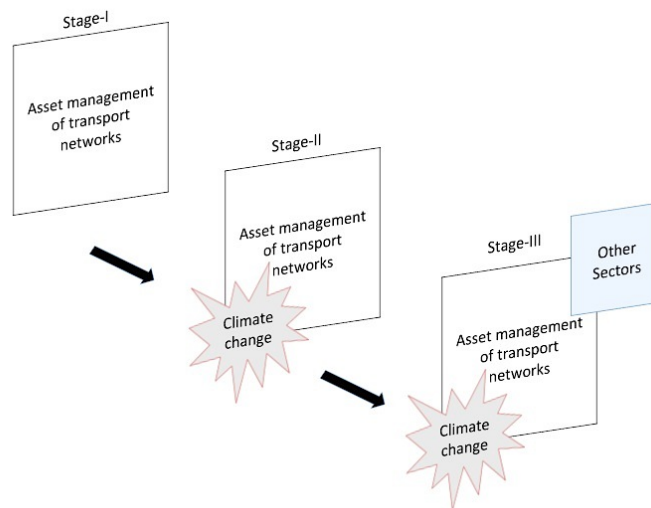


Figure 1: Illustration of model formulation in three stages

3.1 Introducing the Network Model – Stage I

This is the first stage, of the three-stage model, in which a road network is constructed in the proposed framework. For ease of understanding, a basic Manhattan style road network is built in the model to represent a sample city. In this city, the central core is modelled as the central business district (CBD) and the residential areas surrounding this core. In such a model it would be safe to assume that people will travel to the CBD in the morning for work purposes and will travel back to residential areas in the evening, as would be the case of a typical work trip. These *trip-makers* form the first category of agents in the model. These people use the road network available to them to reach their respective destinations in morning and evening. These movements are included with an OD matrix. The constituent *road-segments* of the city's road network form the second category of agents in the model. These road-segments experience their normal aging related deterioration and additionally the damage caused by the vehicles (of the trip-makers). To maintain these road-segments, and therefore the whole network, in a good condition, an asset manager keeps record of the condition of the road infrastructure. This *asset-manager* forms the third category of agents in this model. As in any ABM model, the most basic actions of the agent are defined to describe the behaviour of the agents. Table 1 shows the behaviour and actions of the three agents introduced in this model.

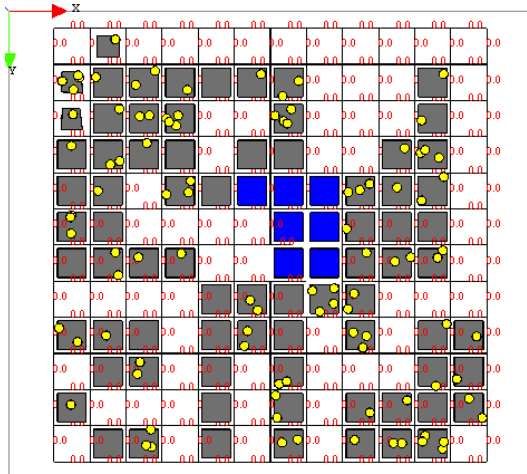
Table 1: agents and their descriptions for stage-I

Agent	Behaviour /Actions
Trip-makers / vehicles	Travel to work and come back home in the evening along the shortest path, avoid congested roads by choosing the next best route, cause damage to roads, strictly follow the speed limits.
Road-segments	Deteriorate according their aging process, receive damage from vehicles
Asset manager	Asses the condition of the roads at regular intervals, make decisions on maintenance investments

The sample city is shown in figure 2 below. The central core in blue colour represents the CBD while the grey polygons represents the residential zones of the city. The road network can be seen as the black lines forming the Manhattan grid network. A random synthetic OD matrix of 100 trip makers was generated just to operationalize the concept of this model. These trip-makers are shown with yellow circles at locations of their origin. When the OD matrix was loaded on to the network, it is possible to see the traffic-loading pattern on the network. The figure on the right side with thick green lines indicates the traffic volumes on these links of the network. Obviously, with everybody coming to the CBD the volumes on the road-segments (links) around the inner core have high volumes compared to the peripheral road-segments. It is also important to note, that the

vehicles are defined with their minimum/maximum speeds and to strictly follow the speed limits on the roads.

The sample city with Manhattan grid style road network



Traffic volumes on the road network

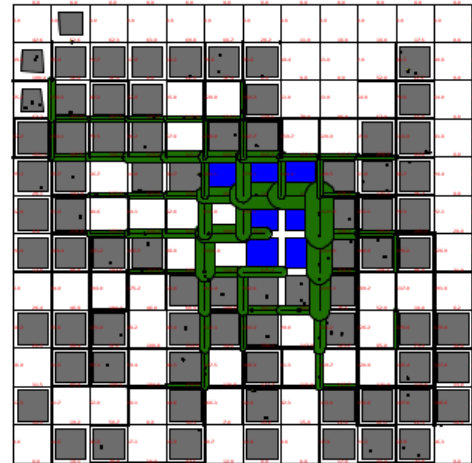


Figure 2: A theoretical Manhattan road network for stage-I

The road-segments are considered to be in good condition if they have a condition value of 1 while a value of 0 represents bad condition. As the paper presents only a framework, not much emphasis is given to the true real world values of these deterioration profiles. The real world deterioration profiles can easily be incorporated to replace the linear deterioration profiles assumed here in this paper. The simple linear profiles are adopted as it makes it easier to focus and understand the framework being presented and make the framework more transparent and interpretable. According to this linear profile, the condition of a road segment deteriorates by a value of 0.001 per day. The vehicles cause a fixed unit damage of value 0.02 with each passing on a road-segment along their route to their destination. Based on these values, the condition of the segments is updated during the simulation.

The role of asset manager is to keep the road network in a good condition, which in our case is to maintain a condition value of 1 for all the road-segments. In this case presented, again to maintain the simplicity of the framework, the asset manager receives a regular fixed funding for the repair and maintenance activities on the network. The asset manager has the options to choose whether a) to fix the worst segment first or b) to wait and repair them according to a predefined maintenance schedule (at regular intervals) or c) to repair when a condition value goes below an accepted threshold condition value. The maintenance costs assume a fixed cost that is associated with a repair of unit

length of road-segment and when repaired the road-segment returns to a state of good condition with a value 1.

As the simulation progresses, the asset manager receives on a dashboard (a) the current condition profile of the entire road network in a graphical form as shown in the left subfigure in figure 3 and (b) the budget profile that includes the investments made on repair and maintenance on this network. The budget profile is shown in the right subfigure in figure 3. It can be seen in the figure that regular investments are being made into the maintenance and the funding is replenished at regular intervals with a fixed amount of funding. The asset manager therefore, in this particular replication of the simulation, chose to the option of investing into maintenance at regular intervals of time. The snapshot of the budget profile shown in the figure is after about 1.8 (approximately 2 months) of running of the simulation model. Equally, in the left subfigure is a graphical representation of the deteriorated roads in the network after about 2 months of running into the simulation.

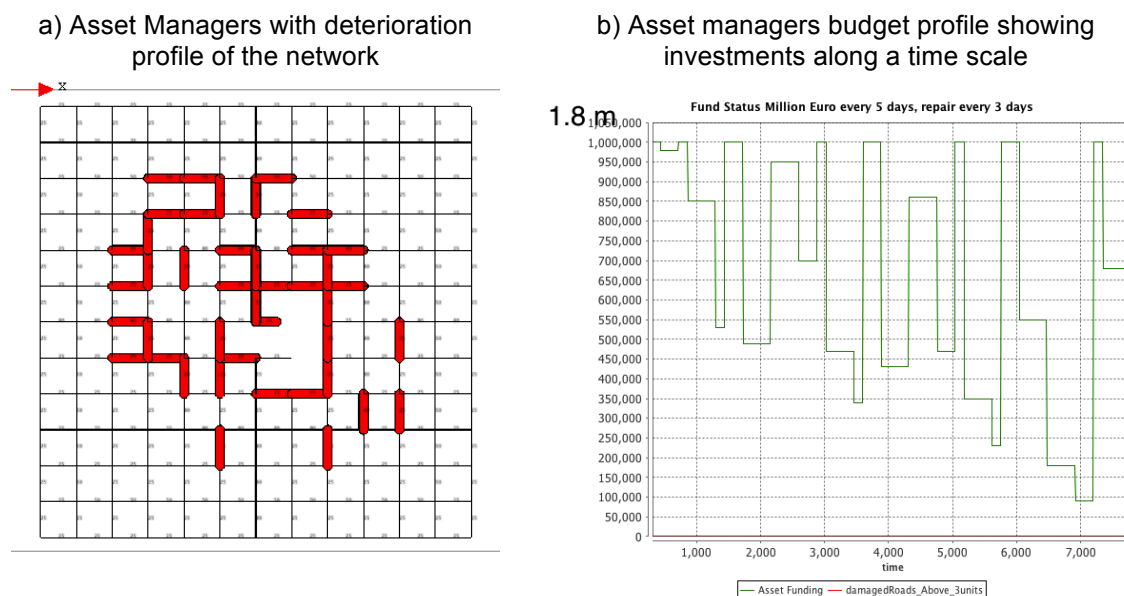


Figure 3: Asset managers dashboard showing a snapshot of deteriorated roads and maintenance expenditures made on the network

3.2 Incorporating climate event – Stage II

After setting the basic transport and asset management model in place, in this section, a climate event is incorporated into the model. A climate event like flood,

heavy rains; snow can affect large parts of our infrastructure networks. Almost all climate events can be considered as area wide damages. It is not only difficult to predict the occurrence of the event but it is also difficult to predict the size, location and duration of the climate event. This randomness is considered in the model both in terms of the time of occurrence and the size of the event. As the events are area wide events, a random sized polygon is introduced for a random duration of time and at a random location on the network.

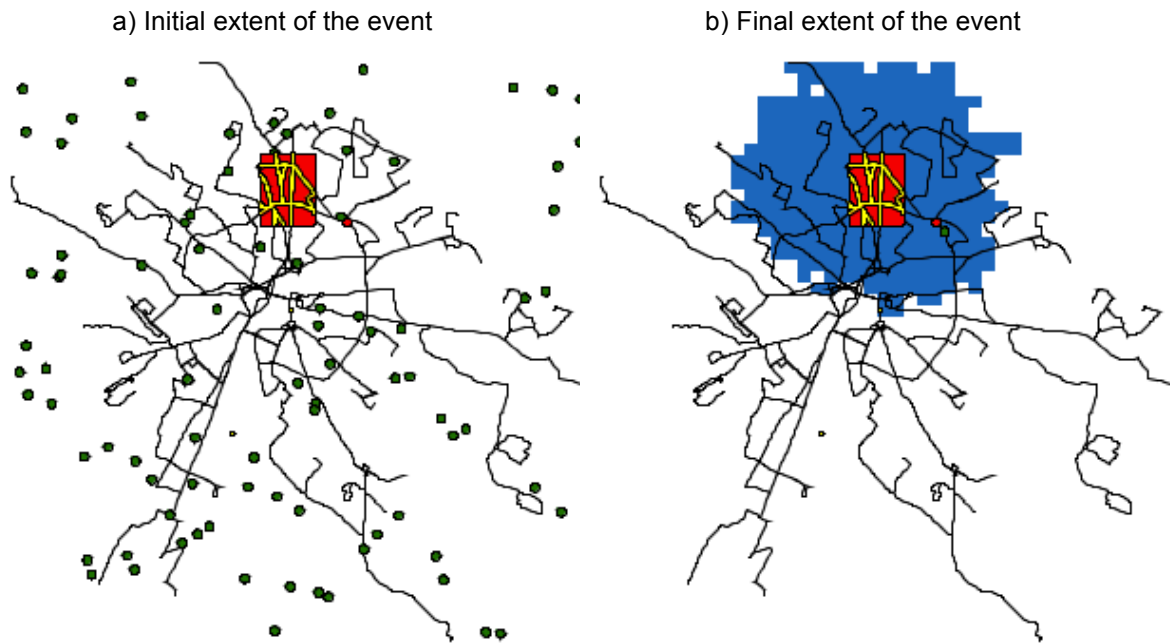


Figure 4: The road network showing the initial & final extents of the climate event

In figure 4, a random urban road network (borrowed from (Grignard et al., 2013)) is used instead of the basic Manhattan network defined in the first stage of the model. This helps in placing our climate event in a more realistic setting. In the left subfigure we see dots indicating the location of people (origins) and they move towards the city centre, as was the case in stage-I. Again a synthetic OD matrix was generated with 100 trip-makers placed across the network in various residential zones around the central core. The red polygon placed in the top half of the network, represents the random location and size of the climate event. In this particular case, flood is considered to be the climate event. This polygon is at a different location and of different size for each simulation run.

As the simulation progresses, the area of impact (flooded area) increases and the final extent of the whole event is shown in blue in the subfigure on the right. During the simulation, when the floodwater comes on to the road-segments, the

road segment is considered not to be traversable and the people (vehicles) have to choose an alternative route to reach their respective destinations. From the previous stage of the model, we are aware that these agents (people) have been defined with skills to reroute themselves around damaged road-segments. If we consider the time taken for one person to travel from origin to destination to be the trip-makers travel time, the sum of travel times of all the trip-makers can be considered as the total travel time of the whole transport system of the city, and let's express this measure as system-time. This measure is often taken as a parameter that network managers use for optimizing their transportation systems. This parameter is also sometimes considered as total system delay time, when the network managers measure it relative to their accepted norm of the systems' efficient and optimum time. Therefore in our case, when there is a climate event, it can be expected to increase the travel time of people on these road networks and consequently increase the system time as a whole in contrast to the acceptable time limits for an efficient transport system. During the simulation, the travel time of each trip-maker is measured from his/her origin to destination and as the climate event affects this travel time, the measured travel time in the simulation includes the delay caused due to any rerouting undertaken by the trip-maker.

Additionally, the size of the climate event and its location on the network is captured during the simulation. The size of the event is evidently important for damage assessment by the system manager (or asset manager as the context may be) and location of the event is equally important to understand the extent of the damage. In this case, we relate the location of the event to the node of highest importance in the network by measuring the distance between them. The node of highest importance is estimated by using the index of '*betweenness centrality*' from established graph theories. This index rates the nodes in a network based on the number of shortest paths passing through it for all possible pairs of node in the network. This node would represent the densely connected part of the network and usually is near the hub of economic activities. The underlying premise of using this location as a reference is to support the idea that a climate event closer to the crucial dense part (hub) of the network will cause more damage (delay in travel times) than an event occurring far from this location. If shown valid by the model results, then this also stands as a verification of the model.

To verify, 250 runs of the simulation were performed based on different random seeds. The results are plotted in figure 5, where the x-axis represents the distance of the event from the high-density area (hub) of the network while the y-axis represents the increase in travel time because of the climate event and each

dot represents one simulation run. It can be seen from the graph, that as the event occurs farther from the hub, the impact on travel time is minimal. And when the event occurs closer to the hub, there is a higher impact on the total travel time in the system.

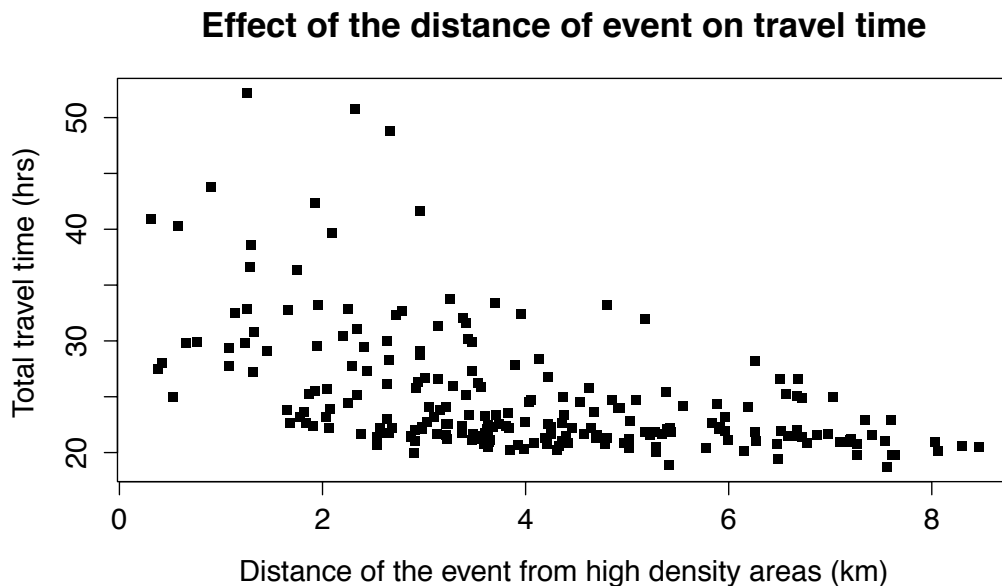


Figure 5: Scatterplot showing the result of simulation carried out to observe the effect of distance of even on total system travel time

The proposition above though valid, does not say anything about the size of the event. For a system manager, the size of the event, in terms geographic extent, in initial and final stages of the event is very important. In figure 6, drawn from the same 250 simulations runs, the size of the event (y-axis) is plotted against the distance of the event from the dense area (x-axis) and their relation/ impact on the total system travel time is shown as bubbles on the plot. It can be noticed from the figure, that the bigger circles (indicating larger impacts on travel time) are seen to the left of the plot. To the left bottom of the plot are regions of the network that are closer to the hub and a climate event closer to these areas will have high impact on travel times. To the left top of the plot are the regions of the network that are closer to the hub and also affected by large sized climate events again resulting in huge impact on travel times and this is indicated by the large sized circles on the left in contrast to the small sized circles to the right of the plot.

From both the plots in figure 5 and figure 6, it can be stated that the model behaviour produces results that are relatable to the common understanding of

consequences during such events. This simulation exercise in stage-II of the model also helps us in identifying areas in an urban space, which are prone to cause more impact in comparison to other areas in the same urban space. This gives us a good lead to move into the third and final stage of the model where a local area identified to have experienced more impact due to a climate event is analysed for not just transport infrastructure but also infrastructure of other sectors that are interconnected and support the transport infrastructure.

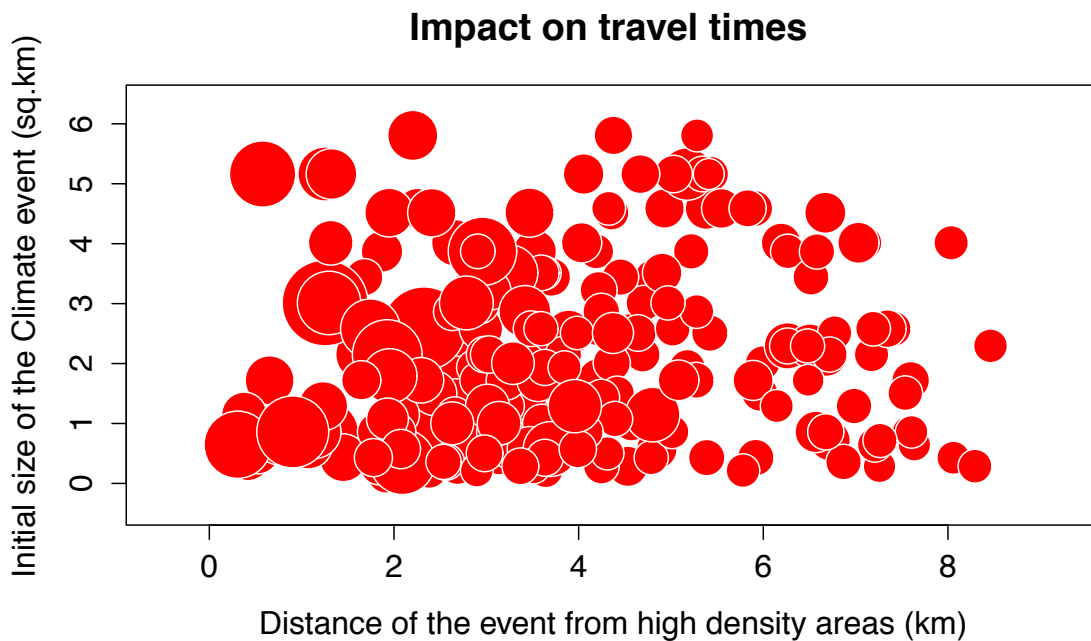


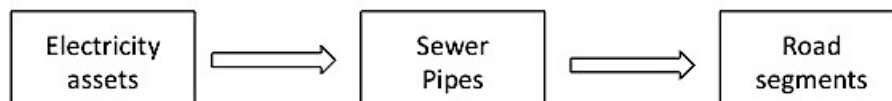
Figure 6: Bubble plot showing the result of simulation carried out to observe the effect of distance and size of event on total system travel time

3.3 Involving other sectors – Stage III

Most often when damage/ repair assessments are done in case of climate events, infrastructure sectors are often dealt in silos. That is, a transport system manager or asset manager would deal only with the damage and repairs to their own infrastructure. And especially when damages for anticipated climate change events are predicted, all the underlying causes are not investigated. For example, should we leave our model at stage 2, we would consider scenarios of various extents of flood or climate events, perform an overlay analysis and calculate the damage to the transportation infrastructure within that extent. However, due to the intense urbanisation processes, in our current urban spaces

infrastructure are densely collocated. In this stage of the model, it is shown how infrastructure of other sectors also affects transportation assets.

For this paper, a very specific case of climate event is considered – floods. One of the major impacts on other infrastructure during floods is that of sewer pipes. Sewer pipes are designed to sustain and balance the hydraulic forces inside the pipes and forces of earth on top of it. Sewer pipes are installed at a critical depth under the ground, a depth that is financially not expensive and structurally stable to keep the balance in external and internal forces. In the event of a flood, this balance is disturbed and the notwithstanding the differential forces, the pipes start to float to the surface at critical locations. This floating of sewer pipes is known to cause damage to the roads on top of them to such an extent that roads that are unaffected by floodwater, may be damaged by floating of pipes beneath them. This claim on some instances is disputed by the fact that it might be possible to pump the water out of the flooded areas before such a condition is reached. However, during a flood, there are many instances of power failure as a result of which the water could not be pumped out. Accordingly, to address this issue, the linkages between power supply and sewage infrastructure should be comprehended. For this paper, we therefore include a relationship between electricity assets and sewage infrastructure in a way that, should the sewage pumping station experience power failure during a flood event, the inability to pump sewage in the pipes will add to the imbalance of forces in the sewer pipes and they will float to the surface which in turn causes damage to the roads above them. A simple illustration to depict the chain of events during a flood event is shown below.



Therefore, we add two more agents (see table 2) into our model from stage-II. These include agents representing the electricity assets (substations) and the agents representing the sewage system (sewer pipes).

Table 2: Agents and their descriptions for stage-III

Agent	Behaviour /Actions
Substations	Supply power to lower voltage substations, and sewer pumping stations, fail when flood reaches height of 20cm
Sewer Pipes	React to failure of power stations and pumping stations, float when flood water reaches height of 20cm

To model the interconnectedness with other sectors and to take forward the model from its stage-II setting (where it was possible to identify vulnerable areas), we choose an area to the north of Rotterdam, which has been identified to be vulnerable (according to another project at Author's organisation) to a flood event. The study area is shown in figure 7 along with the existing road network in that area.

The flood is modelled as a function of a digital terrain surface. The surface is represented as a 2d grid and the flood modelling is based on a simple 2d flood inundation models as explained in Dawson et al (2011) where the flood water starts from a source cell and moves over the surface based on the elevation difference between adjacent cells of the grid. The flood inundation model used in this paper is a more refined version that is optimized for this simulation platform and is based on diffusion models by Grignard et al (2013).

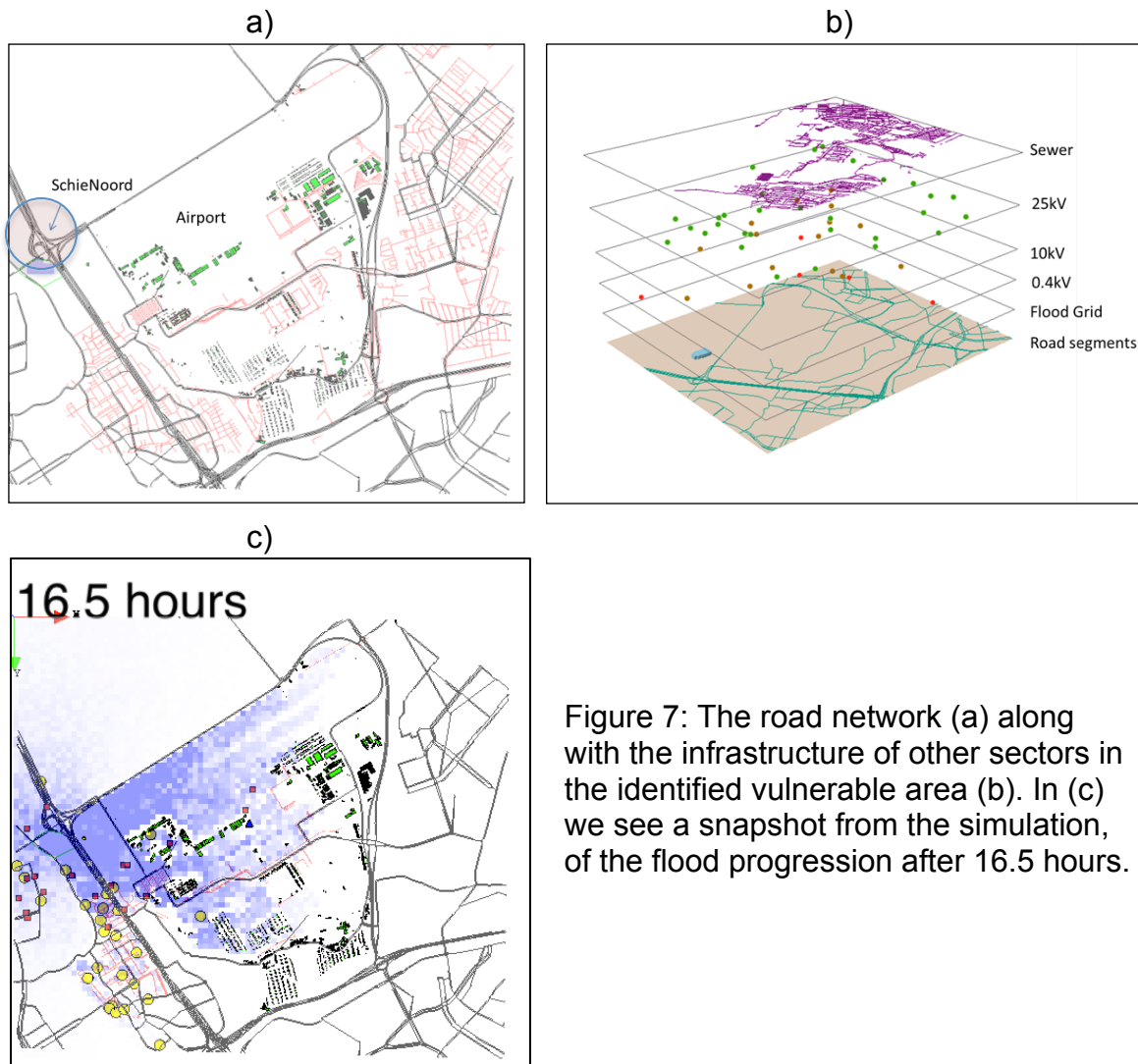


Figure 7: The road network (a) along with the infrastructure of other sectors in the identified vulnerable area (b). In (c) we see a snapshot from the simulation, of the flood progression after 16.5 hours.

The model in stage-III inherits all the behaviours from stage-I and stage-II with respect to a) the trip-makers taking shortest path, and rerouting themselves around congested regions b) asset manager trying to maintain the assets to their good condition c) asset manager trying to keep the total system downtime to its minimum etc. Additionally here in this stage, we calculate the damage to transportation assets (roads) in three small experiments. These bring forward the interconnectedness of infrastructure of other sectors in a step-by-step progression in an area identified to be vulnerable. In the first experiment, we consider road-segments to be affected only by the flood and its extent. The total length of roads affected, in this case is shown by the red line in figure 7. In the second experiment, we consider that flood affects the sewer pipes as soon as the floodwater on top of the pipes reaches a depth of 20cm (Bollinger, n.d.). This causes the floating of the sewer pipes, which in turn cause damage to the road. The total length of roads affected, in this case is shown below by the green line in figure 7. In the third experiment, in addition to experiment 2, if there is any power failure because of the floodwater reaching undesirable depths at a substation, then the substation ceases to work and causes the linked sewage stations also to shutdown. This shutdown cause floating of sewer pipes as explained previously and causing further damage to the roads. The total length of roads affected, in this case is indicated by a blue line in figure 8.

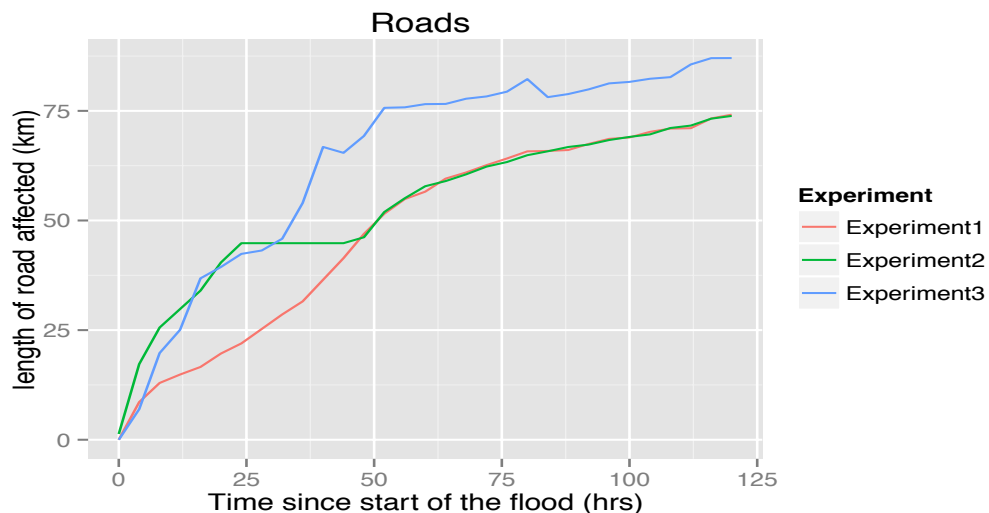


Figure 8: A graph showing variations in the damage assessments of transportation infrastructure based on three different experiments.

The total damage to roads increases dramatically in the second experiment as we start to consider the additional behaviour of sewer pipes to float and damage the overlying roads. The initial increase in damage is not sustained throughout the simulation period because the location of the start of flood (shown by a circle

in figure 6a) is closer to the densest part of the network causing a sudden acute increase of damage by virtue of interconnectedness with secondary sectors. As the simulation progresses, the flood propagates toward less denser and open land, and therefore after an intense rise in damaged roads, the measure of damaged roads settles down and matches the damage profile of experiment 1. However, in the third experiment, as soon as we start considering affect of failure of electric substations and their connections to the sewage system, the intense initial increase in damage profile is sustained throughout the simulation period. This is because, the failure of power supply reaches further areas much faster than the flood and therefore causing a damage on infrastructure and its operations much ahead of the flood reaching those locations. This is the reason why we observe a higher damage in experiment 3. At this point, it is convenient to remind ourselves that had we considered damage on roads with just the extent of flood, the asset manager would seriously underestimate the actual damage. This simulation when run for long periods of time, with random occurrences of climate events with random location, size and duration, can give rich insights for an asset manager for planning of robust and resilient infrastructure along with more informed budget plans.

4. DISCUSSION AND CONCLUSIONS

The research provides a framework in agent-based modelling for exploring both long term and storm term implications for asset management. This paper presents three most innovative aspects that differentiate itself from other contemporary research available in literature. Most asset management frameworks present static snapshot assessments for a future scenario. This framework gives a dynamic framework for asset management, which adds the possibility to assess cumulative damage of the asset at any given time point. This dynamics also allows us to incorporate a climate event at any given random point of time, as it would happen in reality. The dynamic framework also allows for studying detailed progression of a climate event and its impact on other infrastructure that could indirectly affect the transportation assets. This kind of damage and repair assessment involving asset behaviour across sectors is unique and seldom seen in literature. In the remaining part of this section we discuss some possible policy implications of the model if can be used with more real and factual data.

For stage-I of the model, we recount the capabilities and policy relevance at this stage. Firstly, it is possible to include regular transport networks along with their OD matrices to model real world scenarios and network loadings. Additionally agents are intelligent to take diversions and choose alternate routes to avoid inconvenience and delays. Secondly, the linear deterioration profiles can be replaced with real non-linear deterioration profiles if the exact pavement material and their behaviour are available. Thirdly, the asset manager can readily see the

current state of condition of the entire network and the past investment decisions made on the network, currently available budget and therefore plan the next investments. This information can be used to prioritize investments on certain links based on their importance to the network. The framework also enables to test various policy decisions of the asset management agency on investments; for example, policies of investing in worst first, periodic investments, threshold or trigger-based investments, importance of a particular link to the network etc. This can be very useful considering the fact that the model can be run for very long time periods (months and years).

For stage-II of the model, it has the capabilities of measuring system-wide measures in the context of a climate event. It gives the transportation system manager a good insight on various system indices. Although neither addressed nor modelled in our paper, it is possible to operationalize evacuation strategies within the model; this is because the agents (trip-maker/ vehicles) are intelligent enough to receive information about a new destination while they are en-route. As discussed in the model, it is possible to measure system-wide travel times and therefore the system transport manager can plan for rerouting to get a system optimum performance in case of a climate event. As the trip-makers movement is based on an OD matrix, and as each trip maker is modelled individually, it is possible to derive which OD pairs are impacted the most because of a climate event, this could be very important for a system manager to plan infrastructure and facilities that have less downtime and people from certain zones have access to alternate facilities. The model can be run for very long periods and with climate events apparent to be more frequent, this model can be very useful as it can place various kinds of climate events either simultaneously or in sequence and at desired frequencies.

Stage-III of the model, which includes impacts due to affects from infrastructure of other sectors, is highly relevant for our current urban spaces where infrastructures is collocated or are in a very close geographic proximity because of lack of space and increasing demand. This aspect is often skipped in most impact assessments because of lack of integration. These cross-sectoral dependencies are highlighted in this model and the results clearly show underestimation of the damage and subsequent maintenance strategies. The advantage of the framework presented here is, it identifies assets of non-transportation sectors, their damage and their impact on transportation assets. This gives a good platform for asset managers of these sectors to come together and analyse the situation and act with a synchronized approach that can help in quick and efficient restoration of services and for economic allocation of resources. The possibility of collaboration and involvement of multi-actors agents (asset managers) in this stage enriches the application of ABM technique for such research questions. A complete dynamic model with all these decision-making actors and the emerging scenarios from their decisions can be very

useful to understand the implications of climate change on assets and is the future direction of this research.

All in all, if all the three stages of the model are put together, it gives a very powerful decision support tool especially for planning future risk and budget profiles of transportation assets and their maintenance activities. The paper also emphasizes the importance of such integrated models and also the fact for asset managers to consider non-linear cost estimates in their assessments.

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