Entity-based System Dynamics for Infrastructure Modeling

Exploring the Effects of Spatial Maintenance Cluster Strategies on Infrastructure System Performance

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Abstract

This paper addresses the imminent challenge of maintaining The Netherlands' aging bridge inventory, particularly the bridges built during the post-war era (1950 to 1990). A key challenge in the replacement task is the limited construction capacity, especially with an expected surge in maintenance between 2040 and 2080. Efficient and systemic asset management is pivotal in minimizing the required capacity increase and helping 'flatten the curve'. This paper introduces a novel spatially explicit Entity-based System Dynamics (SD) modeling method to analyze the effects of bridge maintenance cluster policies on infrastructure systems. It aims to identify effective maintenance cluster strategies for ensuring a steady and predictable maintenance capacity demand. The findings aim to guide effective asset management and policy-making to ensure safe and sustainable infrastructure in the face of increasing demands and resource constraints. We find that the approach presented in this paper provides several advantages, categorized in (1) replicability and (2) computational requirements, when modeling spatially explicit infrastructure systems, that can be used to appraise its usefulness over traditional SD modeling. To further enhance the applicability and effectiveness of the Entity-based SD methodology, there is a need for improvements in documentation and the maturity of the approach.

1. Introduction

The Netherlands is on the eve of the biggest maintenance operation in its history (Ministerie van Infrastructuur en Waterstaat, 2018). In the coming decades, the country has to invest an estimated minimum of 260 billion Euros to renew its aging inventory of civil constructions such as bridges, viaducts, and tunnels (Rasker, Bletsis, Brongers, Vervuurt, & Verweij, 2023), which is around sixty percent of the total expenditures of the Dutch government in 2024 (Ministerie van Algemene Zaken, 2023). Recognizing the urgency of this concern, the Dutch government redirected resources from new construction projects to prioritize essential maintenance of existing transport infrastructure in 2023, this project is labeled the replacement & renovation task (Ministerie van Infrastructuur en Waterstaat, 2023).

Within the replacement & renovation task, so-called 'Baby Boomer bridges' require the most attention (FIEC, n.d.). The Netherlands has a sizeable bridge inventory, 85.000 bridges, ranging from smaller pedestrian bridges to larger viaducts embedded in the Dutch highway network (Kompeer & Schellevis, 2021). Baby Boomer bridges refer to bridges built in the post-war era (1950 to 1980), when The Netherlands experienced mass construction of infrastructure during a period of high economic growth. Most of the 85.000 bridges in the Dutch bridge inventory were constructed in the years after the Second World War (Smits, 2016).

The condition of these post-war bridges poses serious safety concerns, exacerbated by factors such as increased stress and fatigue beyond their original design parameters and corrosion-related issues (Snijder & Hesselink, 2018; European Commission, 2019). Recent events, such as the 2016 closure of the Merwedebrug and the collapse of the Morandi bridge in Genoa in 2019, underscore the pressing need for proactive maintenance and management of aging infrastructure (NOS, 2019; Calvi et al., 2019; Mattioli, 2019).

The biggest challenge in the replacement & renovation task, is the limited construction capacity, in terms of workers and material resources (Kompeer & Schellevis, 2021). Due to the age of the Baby Boomer bridges, sizeable maintenance waves are expected between 2040 and 2080. This will require the Dutch government to increase their yearly maintenance capacity from an average of 5 bridges per year, to as much as 50 bridges per year (Copernicos Groep, n.d.). Furthermore, due to the growing housing shortage in the Netherlands, with an expected 900.000 new houses to be built before 2030, further shortages in the supply of construction workers and materials are expected (Rasker, 2023). To meet the replacement and renovation demand in the coming decades, efficient asset management is paramount to minimize the required capacity increase and to help 'flatten the curve'.

One of the core asset management strategies endorsed by the Dutch government is the clustering of bridge maintenance projects (Rijkswaterstaat, n,d.). Project clustering refers to the bundling of multiple maintenance projects with similar characteristics or geographical proximity into one portfolio (Gómez, Sanchez-Silva, Dueñas-Osorio, & Rosowsky, 2013). Y. Qiao, Fricker, and Labi (2019) found that small clusters of bridge maintenance projects outperformed stand-alone projects in terms of project duration, work-zone duration, costs of demobilization, and efficiency in equipment and material mobility between projects. The United States Federal Highway Administration (FHWA) has since also confirmed that the clustering of infrastructure projects is a proven and efficient way to reduce costs, improve efficiency, and prevent delays (Federal Highway Administration, 2022). Various asset and project characteristics can be used as a determining factor for the selection of clusters. Assaf and Assaad (2023) performed a comparative analysis of 23 different decision-making factors for project clustering, they found that the most critical decision-making factors are the geographic proximity, the similarity in project types, the homogeneity of work types, and the condition rating of projects.

There is a lack of existing research on the impact of various clustering strategies (i.e., different decision-making factors) on the broader transport system. Studies such as Y. J. Qiao, Fricker, Labi, and Mills (2018), Y. Qiao et al. (2019) and Xiong, Fricker, and Labi (2017) limit their scope to project-bound performance indicators, such as the project duration and the project costs. While this has confirmed the importance of project clustering in effective infrastructure asset management, there is little information to be found on the impact of project clustering on factors such as travel time or system-wide capacity utilization. Furthermore, the literature currently consists of retrospective studies (Assaf & Assaad, 2023; Y. Qiao et al., 2019; Xiong et al., 2017) that analyze the performance of project clustering using historical data from projects. These studies provide valuable insights into the effectiveness of project clustering, but do not offer insights into the effect of project clustering on the future behavior of the infrastructure system. This paper therefore sets out to address this gap in the literature by performing an exploratory modeling analysis on the effects of various cluster strategies on the functioning of the transport infrastructure network.

System Dynamics (SD) offers a top-down approach to infrastructure modeling, and is considered to be well-suited for the modeling of transportation infrastructure systems (Abbas & Bell, 1994; Fontoura & Ribeiro, 2021; Shepherd, 2014). One of the key strengths of SD is its ability to explicitly account for feedback interactions between supply and demand in transportation. This feature is essential for understanding the complex dynamics of transportation, where changes in supply and demand influence one another. Additionally, SD allows for the integration of the transport sector with other related sectors, facilitating a comprehensive view of the interconnectedness of various components in a system. SD, however, is not able to capture component-level dynamics like changes in the topological locations of assets (Ouyang, 2014). This is a crucial limitation of SD modeling in the context of this research.

Attempts have been made to extend the SD methodology to include a spatial component. For instance, Maxwell and Costanza (1997) introduced the Spatial Modeling Environment (SME). The SME can be used to link together non-spatial SD models to create a spatial model. Schwarz and Pruyt (2016) introduce a hybrid modeling and simulation approach, which integrates SD with ABM and GIS (Geographic Information System) software. Another approach is the use of subscripts in SD modeling software to model smaller-scale dynamics in a stock (Fallah-Fini, Rahmandad, Chen, Xue, & Wang, 2013). Benaich and Pruyt (2015) used subscripts in SD modeling software to model smaller-scale dynamics in a stock, which also allowed for the exploration of the effectiveness of various traffic and congestion policies. However, they noted that building complex networks can become a time-consuming task because the subscripts have to be modified manually. One suggestion made by Benaich and Pruyt (2015) to avoid this issue is to employ an Entity-based SD approach.

Entity-based SD is a relatively new modeling methodology and can be seen as a combination of agent-level (ABM) modeling and macro-level (SD) modeling. This combination is considered to offer many benefits for this research. Firstly, this combination will allow for the modeling of the behavior and attributes of individual bridges, roads, and regions, while retaining the capability of doing macro-level analyses. The entity-based approach also allows for the easy reuse of components, which makes the network building significantly less time-consuming and complex compared to traditional SD (Benaich, 2015).

As Entity-based SD is a relatively new methodology, however, no spatially explicit applications of the methodology can be currently found in the scientific literature. As such, this paper will pursue two objectives, (1) developing, and reflecting on the added value of a novel spatially explicit Entity-based SD modeling method when modeling the effect of bridge maintenance cluster policies on the wider infrastructure system, and (2) identifying maintenance cluster policies that are effective at facilitating a steady and predictable maintenance capacity demand.

The rest of this paper is structured as follows. Section 2 introduces the theoretical background and methodology used in this research. Section 3 presents the model results, and finally, section 4 discusses the added value of the proposed spatially explicit Entity-based SD methodology. This research was conducted on behalf of Copernicos Groep.

2. Methodology

2.1. Entity-based System Dynamics

Entity-based System Dynamics (Entity-based SD) is a modeling methodology developed by Yeager, Fiddaman, and Peterson (2014) in response to the limitations of traditional SD modeling. These limitations can be categorized in two main categories, (1) modularity and (2) agent detail. Firstly, the lack of modularity in traditional SD can negatively impact the speed at which large models can be constructed, as model components cannot be duplicated or reused. In the context of infrastructure network modeling, Benaich and Pruyt (2015) found that this drastically increases the complexity and time investment needed to model large networks. Secondly, traditional SD modeling is not able to capture agent-level behavior. While many systems can be represented through aggregate behavior, the modeling of many other complex systems requires the ability to capture and define agent-level behavior (Yeager et al., 2014). For instance, if you want to model the effect of different maintenance bundling strategies on the road infrastructure system that these bridges are part of, only capturing the aggregate behavior of all bridges does not suffice. Rather, the behavior of individual bridges is crucial, as temporarily closing one bridge will have effects on the traffic flow, and thereby the rate of degradation, of nearby bridges.

Entity-based SD addresses the two categories of problems by introducing entities (known as objects or agents in other modeling methodologies), which are smaller models of each type of component that is part of the system that is to be modeled. Entities can represent a wide variety of components, such as products, organizations, countries, and physical entities (Yeager et al., 2014). Through the addition of entities, Entity-based SD integrates SD with Agent-based Modelling, which creates the possibility of avoiding their individual limitations and benefit from the full potential of their complementary characteristics. This allows the Entity-based SD methodology to provide a more complete representation of complex dynamic systems (Nava Guerrero, Schwarz, & Slinger, 2016). In this research, Ventity version 5.0 beta 6 by Ventana Systems was used to construct the model.

Entity-based SD contains a few important extensions to SD. These extensions can be summarized in 6 categories (Yeager et al., 2014): (1) Entity types, (2) attributes, (3) collections, (4) aggregation, (5) references, and (6) actions. Firstly, entity types allow for the creation (or reuse) of model definition for every unique type of component in the system. Each entity type can be defined using traditional stock and flow diagrams. Secondly, each entity has one or more attributes, through which individual entities within entity types can be accessed. To illustrate this with an example: There could be an entity type named 'Country' with the attributes 'Country name', 'Language', and 'Continent', within this entity type you could then have the entities 'United States' and 'The Netherlands'. Through the attributes, it is possible to access sets of countries based on their language and continent or to access individual countries through the 'Country name' attribute. The third category refers to collections of entities, which contain all the entities of a specific type. Collections make it possible to access aggregate values such as the sum, average, min, or max. In Ventity it is also possible to make sub-collections based on a specific attribute value. For the country example, sub-collections could be made for Language and Continent so the modeler can easily access aggregate values for all countries from the same continent (or with the same language). Fourth, references enable disaggregated systems to be linked to each other. A reference is an information or causal link between entity types, which allows entity types to access values of variables from another entity type. Lastly, actions are model components that assist the modeler in, for instance, creating new entities during a model run or conditionally changing values of attributes. Actions provide access to certain agent-based and discrete event capabilities in Ventity.

2.2. Road infrastructure network

To effectively model the effects of various spatial maintenance policies on the performance of the road infrastructure system and maintenance capacity utilization, a spatially explicit network is needed as a base for the model. The network is regarded as an assembly of links and nodes, which are basic elements in network theory (Quimpo & Wu, 1997). A node represents a region, while links represent roads that act as connections between the nodes in the network. Each link is capable of containing a bridge. Links containing bridges are the only network components with the possibility of failure (i.e., closure), which results in the traffic flow of that specific link being set to 0 for the duration of the failure. Thus, the bridge network is characterized as a road network with a probability of failure of zero percent for the links without bridges and nodes, similar to the network described in Liu and Frangopol (2005). The figure below presents a simple network consisting of 3 nodes (A, B, and C) and 3 links. Links are bidirectional, but in order to correctly implement the network in Ventity, each direction is given a unique name by compounding the origin and destination of the link. In the figure below, that results in the following six links: AB, BA, AC, CA, CB, and BC. For the remainder of this paper, road, and region names will be referred to as ID's.

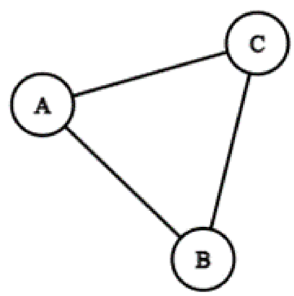

Figure 1: *Small network composed of 3 nodes and 3 links*

For this research, a hypothetical network has been designed to support the development of a proof-of-concept spatial Entity-based SD modeling approach. The network is in essence a larger, more complex, version of the network displayed in figure 1. It has a total of 14 nodes and 27 (bidirectional) links, which results in 58 unique link ID's. The network can be seen in figure 2. Regions B, G, E and F have the highest centrality, indicating that they are the most well-connected nodes in the model. On the contrary, the nodes along the edge of the network, specifically nodes A, M, L, I, K and N have the lowest centrality. This makes those nodes more vulnerable in terms of accessibility when bridges get closed for maintenance. The network contains 2 rivers which indicate the locations of bridges. When a river and a link cross, this indicates that that link contains a bridge, this holds true for both directions of that link.

The model contains 15 bridges that have been selected from a database constructed by Copernicos Groep containing all the bridges in the Netherlands (Copernicos Groep, 2024). Within the database, a smaller subset was made containing only fixed concrete bridges built between 1950 and 1990 (post-war era) that are still in use. From this subset, a random selection was placed into the model. The bridge names have been substituted for more general names (b_1 though b_{15}). The network is a homogeneous network, where all regions have an equal population, an equal amount of initial vehicles, and the same distance between all other regions.

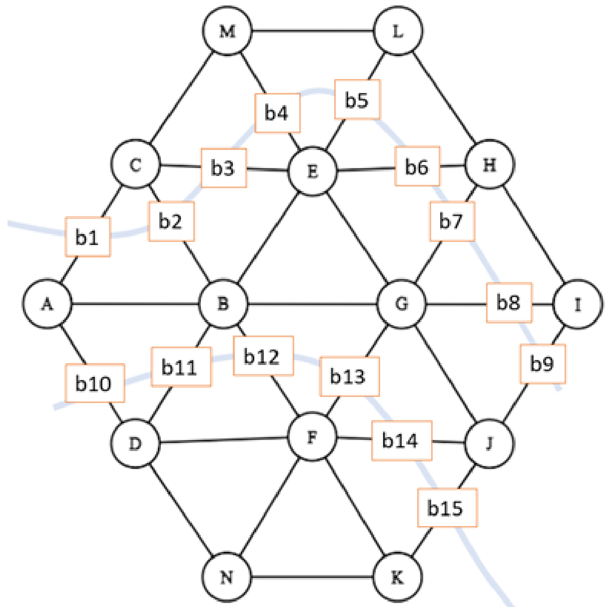

Figure 2: *Network with bridge placement*

2.3. Spatial component

This chapter will describe how the spatial component of the model was designed in Ventity. The goal of the spatial component was to translate the network presented in chapter 2.2 into an Entity-based SD model. The design of the spatial component was inspired by the GIM GOS 2 model (Ventana Systems, 2022), which is supplied as a sample model with Ventity.

An important consideration when designing the spatial component was replicability, as the approach would lose value and relevance if it were rigidly designed for only one (type of) network, in line with the findings of Benaich and Pruyt (2015). To achieve a high degree of replicability, the spatial component was designed using (1) entity types, (2) attributes, (3) references, and (4) external network initialization data. Firstly, three entity types were created and initialized to lay the foundation for the spatial component, Region, Road and Region to Region. The Region entity type defines the nodes from the network presented in the previous section. This entity only contains one attribute, RegionID, which allows Ventity to distinguish between Regions. Secondly, the links in the network are defined by the Road entity type. This entity type holds 4 attributes: FromRegion, ToRegion, RoadID, and PairID. The FromRegion and ToRegion attributes define the origin and destination of each road entity. The RoadID attribute contains a unique ID for each road that is determined by compounding the origin and destination of the road, the road from Region A to Region B will therefore be assigned the RoadID 'AB'. Lastly, the PairID was introduced to the model to be able to pair roads that reside on the same link of the network. In essence, this means that roads AB and BA, both residing on the link between Region A and B, get assigned the same PairID. The PairID allows for the closing of roads in both directions in case of bridge maintenance. The third entity type, Region to Region, defines the flow of traffic over a given road from Region X to Region Y. This entity type holds the same attributes as the Road entity type.

The Region to Region entity type connects variables defined in the Region and Road entity types through references. The attributes assigned to this entity type are attributes that are referenced from the Region entity type (FromRegion and ToRegion), and the Road entity type (RoadID and PairID). Figure 3 displays a simplified version of the stock-and-flow structure that facilitates traveling between regions.

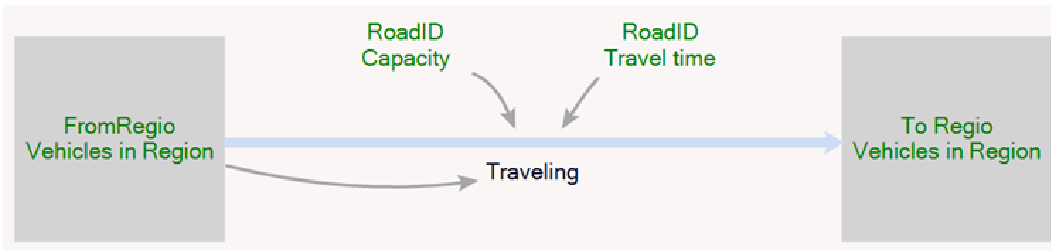

Figure 3: *Stock-flow structure Region to Region traveling*

The ToRegion and FromRegion stocks in the figure above are references to one 'vehicles in region' stock that is defined in the Region entity type. These attributes have to be categorized as a 'key' to the Region to Region entity type to allow for the creation of two stocks referencing different collections of regions. Each Region entity has an initial amount of vehicles which is defined in the entity initialization dataset. In this dataset, the combination of origins and destinations is also defined for the Region to Region entity type. Using these combinations, the Region to Region entity type is able to link the regions with the road that holds the same origin and destination combination. A Region to Regio entity then assigns the value for road capacity and travel time, using the RoadID of the road, to the flow between two regions. In a network with only 2 Regions, A and B, and one bidirectional road between the regions labeled AB and BA, the amount of vehicles in Region A $V_A(t)$ is determined as follows:

$$V_A(t) = V_A(t_0) + \int_{t_0}^{t} \left[\min\left(C_{B,A}, \frac{V_B(t)}{Tt_{B,A}} \right) - \min\left(C_{A,B}, \frac{V_A(t)}{Tt_{A,B}} \right) \right] dt \tag{1}$$

Where $V_n(t_0)$ is defined in the Region entity type and capacity $C_{n,m}$ and Travel time $Tt_{n,m}$ are defined in the Road entity type. The outflow of vehicles is determined as the minimum between the capacity of the road AB per timestep (which is considered to be a constant) and the amount of vehicles in region A $V_a(t)$ divided by the travel time between region A and region B. Similarly, the inflow is determined as the minimum between the capacity of the road BA and the amount of vehicles in region B $V_b(t)$ divided by the travel time between region B and region A. For larger networks, With N regions connected to Region A, the equation looks as follows:

$$V_A(t) = V_A(t_0) + \int_{t_0}^{t} \left[\min\left(C_{B,A}, \frac{V_B(t)}{Tt_{B,A}} \right) - \min\left(C_{A,B}, \frac{V_A(t)}{Tt_{A,B}} \right) \right] dt \tag{2}$$

Equation 2 includes a distribution variable $D_{i,j}$ which determines the share of vehicles in region i traveling to region j, since there are now multiple destinations to choose from for vehicles in any given region.

Lastly, the entities have to be initialized with data that define the spatial relations in the model. Ventity supports external datasets for the initialization of entities in the model, which is beneficial for the replicability of the spatial component presented in this section. The external dataset used for the network in this research is an Excel (.xslx) file in tidy format (see section 2.3.2). By using the 'Generate External File Template' function in the Data Sources section in Ventity, the correct data format can be generated easily. In the Excel file, attributes and variables that have been marked as 'constants' in Ventity can be given values for each unique entity within an entity type.

Figure 4 presents the attributes and values required in tidy format for the small 3-node model presented in figure 1 in section 2.2. Each entity type has a different sheet in the Excel file, but they have been displayed in the same figure for convenience.

Region		Road						Road to Road			
Region ID	Initial vehicles in Region	RoadID	FromRegion	ToRegion	PairID	Capacity[1]	Traveltime[2]	RoadID	FromRegion	ToRegion	PairID
A	100	AB	A	B	AB	500	1	AB	A	B	AB
B	100	BA	B	A	AB	500	1	BA	B	A	AB
C	100	BC	B	C	BC	500	2	BC	B	C	BC
		CB	C	B	BC	500	2	CB	C	B	BC
		CA	C	A	AC	500	1	CA	C	A	AC
		AC	A	C	AC	500	1	AC	A	C	AC

Figure 4: *Network initialization data for a small 3 node network*

The spatial component was initially constructed using only the Region and Region to Region entity types, where the specific attributes for each road were initialized in the Region to Region entity type. This proved to be a valid approach to the construction of a spatial component, however, this construction made it impossible to later assign bridges (or other assets) to specific roads. This is because no sub-collections can be made that refer to entity types with more than 1 key. For bridges to be assigned to roads, every bridge has to be assigned a RoadID or PairID that matches that of the road. A sub-collection of the bridge entity type was then made using either the RoadID or PairID to aggregate the data of interest per road, so it can be used in the Region to Region entity type to determine if a road should be closed based on the status of the bridge. This last step is only possible when including the Road Entity type, as it only holds one key (RoadID).

During the modeling process, the decision was made to not include a vehicle entity type. This addition would have allowed for more detail and information on individual vehicles in the model. For instance, it is possible to specify the distribution of vehicles in the vehicle entity type by using an action. In this action, the model can create a weighted list of destinations for every vehicle entity, which allocates the distribution of traffic flows on the level of individual vehicles. However, for this paper, the aggregated view of traffic flows via the Road and Region to Region entity types was considered to be sufficient. Additionally, the decision was made to analyze the distribution of traffic flows at the road level, as opposed to continuously assigning destinations for each vehicle entity in the model. This choice was driven by the anticipation that determining vehicle-level distributions would incur higher computational costs.

One final important consideration when designing a spatial component is the timestep that is used in the model. The bridge replacement & renovation model, which was used as a base for the spatially explicit model, was modeled with a timestep of 1 and a time unit of year. This led to the model calculating the status of each of the bridges in the model every year, and making renovation or replacement decisions accordingly. However, when modeling traffic flows, the values calculated each timestep become very large, leading to the model malfunctioning. The traffic component only showed the expected behavior when the timestep was decreased to 0.125 years or smaller. Unfortunately, the smaller timestep led to the malfunctioning of the replacement and renovation part of the model, as this part was designed to function with a timestep of 1. As of writing this paper, Ventity does not support more than one integration method so the influence of other methods on this issue cannot be discussed. To solve the issue, the traffic flows were divided by a factor of 10.000 to obtain flows of traffic per 10.000 vehicles. Through this decrease in traffic flow values, both sides of the model now showed their expected behaviors. At points in the model where variables are calculated per vehicle, these variables are multiplied by 10.000.

2.4. Model map

Figure 5 shows a highly aggregated model map, that highlights the entity types and actions in the model and their relations to other entity types. The model was constructed using the bridge replacement and restoration model from Copernicos Groep as a base. A green color indicates a collection of an entity, these collections either hold the aggregate values for all entities in an entity type (denoted as Entitytype[]) or the aggregate values of a subset of entities in an entity type based on a specific attribute. The model can be roughly divided into two submodels, (1) the bridge model, and (2) the spatially explicit traffic flow model described in the previous section. Both parts of the model are connected through the collections Road by PairID and Bridge by PairID. The Bridge by PairID collection is used to indicate which bridges are currently closed due to maintenance works to the Region to Region entity, which in turn affects the distribution of traffic flows in the network. The Road by PairID collection is used to aggregate the yearly traffic load on roads and assigns these values the corresponding bridge entities in the bridge entity type.

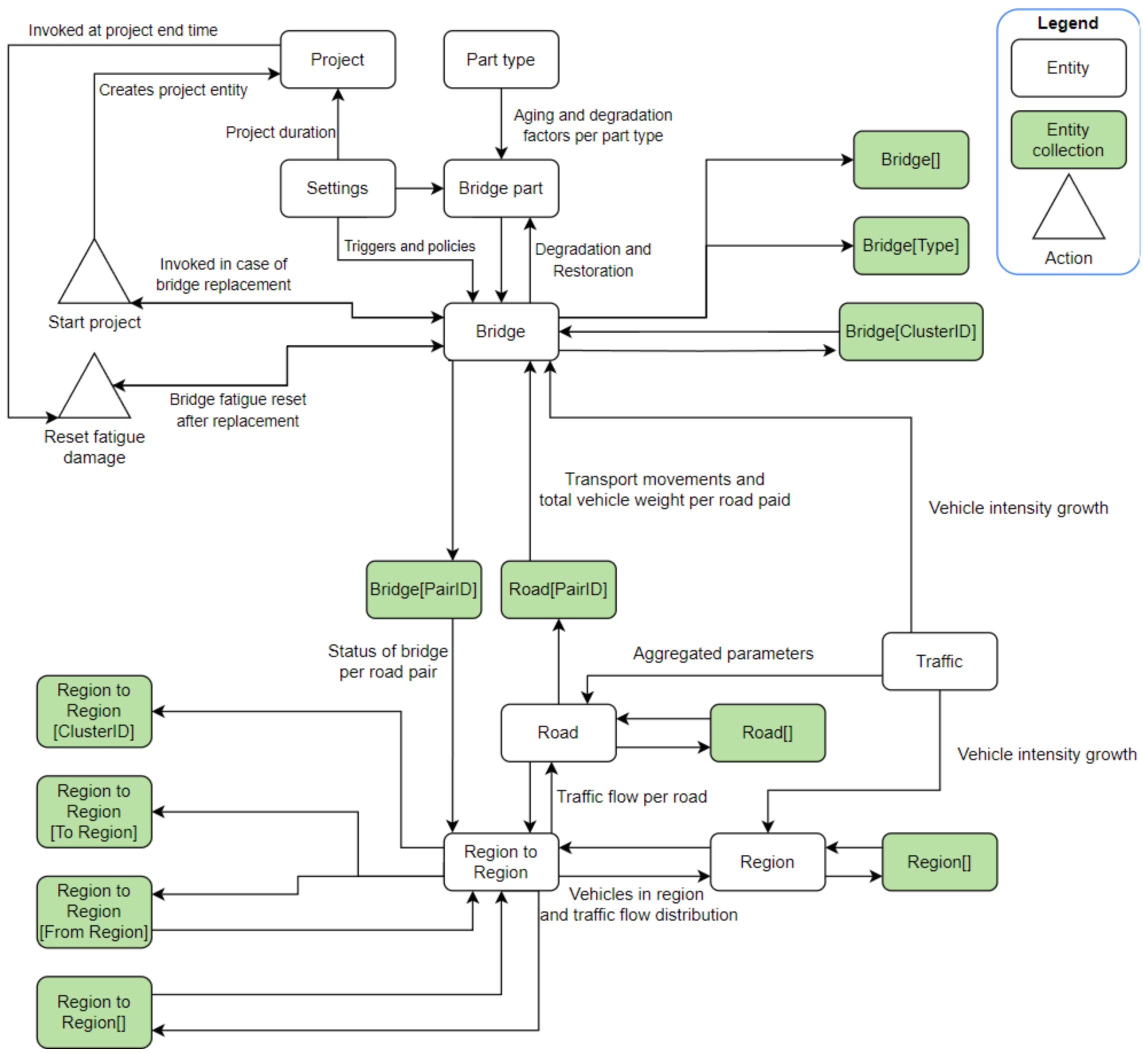

Figure 5: *Model map showing relationship between entity types*

2.5. Behavioral validation

The relationship between the spatial component and the bridge degradation is presented in figure 6 and figure 7. Firstly, figure 6 shows the bridge load, load capacity and status of bridge b1 (situated on the road between region A and C in the network). The bridge load is determined by the vehicles driving over the bridge and the weight of the deck of the bridge. When the bridge is closed (indicated by the light blue bar) due to maintenance, the capacity increases in the next timestep, indicating that the maintenance is completed. The load on the bridge drops to 0 in the following timestep, as traffic is unable to cross the bridge. Both the capacity and load change 1 timestep later than the bridge status, as both are calculated using stock-flow structures. The stock that holds the relevant information updates the timestep after the maintenance trigger is active.

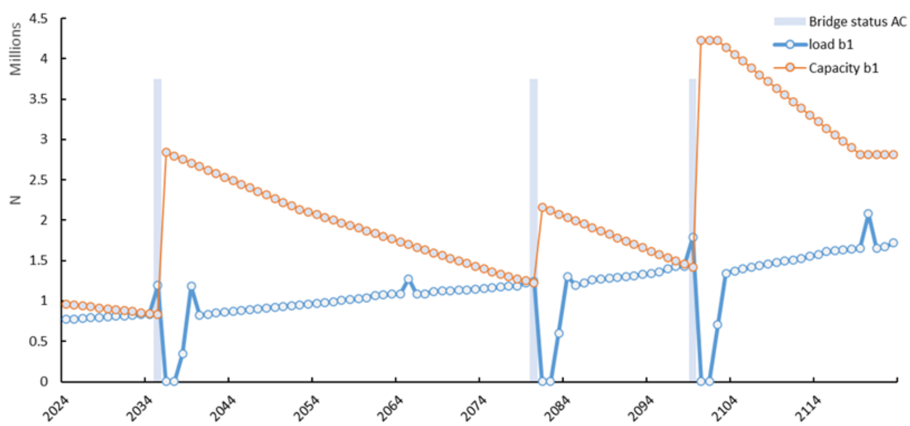

Figure 6: *Bridge status, load and capacity*

Figure 7 shows the relationship between the traffic flow and the load on bridge b1. An increased traffic flow is the direct result of the closure of another bridge linked to either region A or C, and a decreased (not to 0) traffic flow is the result of the opening of another bridge linked to region A or C. A traffic flow equal to 0 indicates that the bridge on road AC is currently closed. As the figure shows, the load on a bridge moves with the change in traffic flow on the road. As explained above, due to the load on bridge variable being calculated via a stock-flow structure, the load is updated one timestep after the traffic flow.

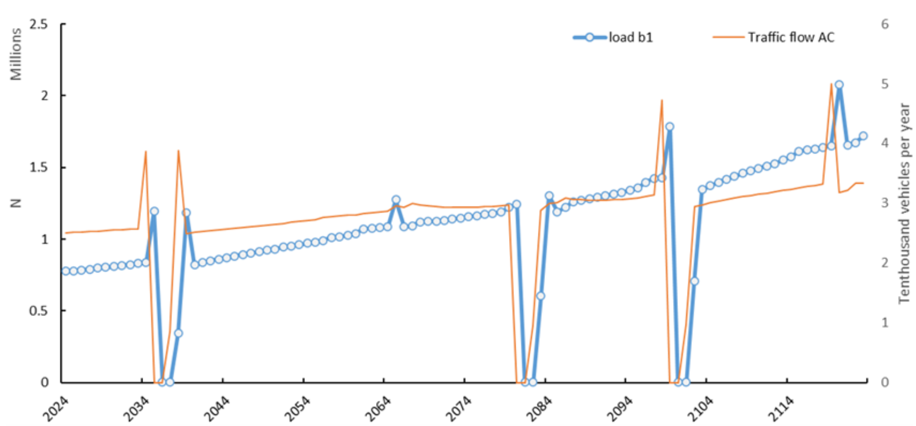

Figure 7: *Bridge load and traffic flow*

2.6. Experimental setup

This research contains a set of 6 policy options. (1) Geographical clustering (Small, Medium, and Large), (2) construction type clustering, and (3) construction period clustering. In the model, these policy levers are modeled as triggers. The bridge model contains three triggers that determine if a bridge gets maintenance. To allow for clustered maintenance and replacement works, these triggers are all paired with a secondary cluster trigger. These cluster triggers check, when maintenance or replacement works are triggered, if the bridge is part of a cluster (e.g., a geographical cluster). If true, the cluster trigger is used to signify maintenance events for all bridges in the cluster instead of the singular triggers described above. As the set of bridges only includes concrete bridges, only reinforcement maintenance will be performed during a model run. Table 1 presents an overview of the 6 policies, their number of clusters, and the average size of each cluster. Figure 8 presents a visualization of each of the policies. The colors of the bridges in each network signify the clusters that they belong to.

Table 1: *Policy overview*

Policy	Number of clusters	Average cluster size
Geographical clustering (Small)	8	1.9
Geographical clustering (Medium)	5	3
Geographical clustering (Large)	4	3.8
Construction type clustering	2	7.5
Construction year clustering	4	3.8
No clustering	0	0

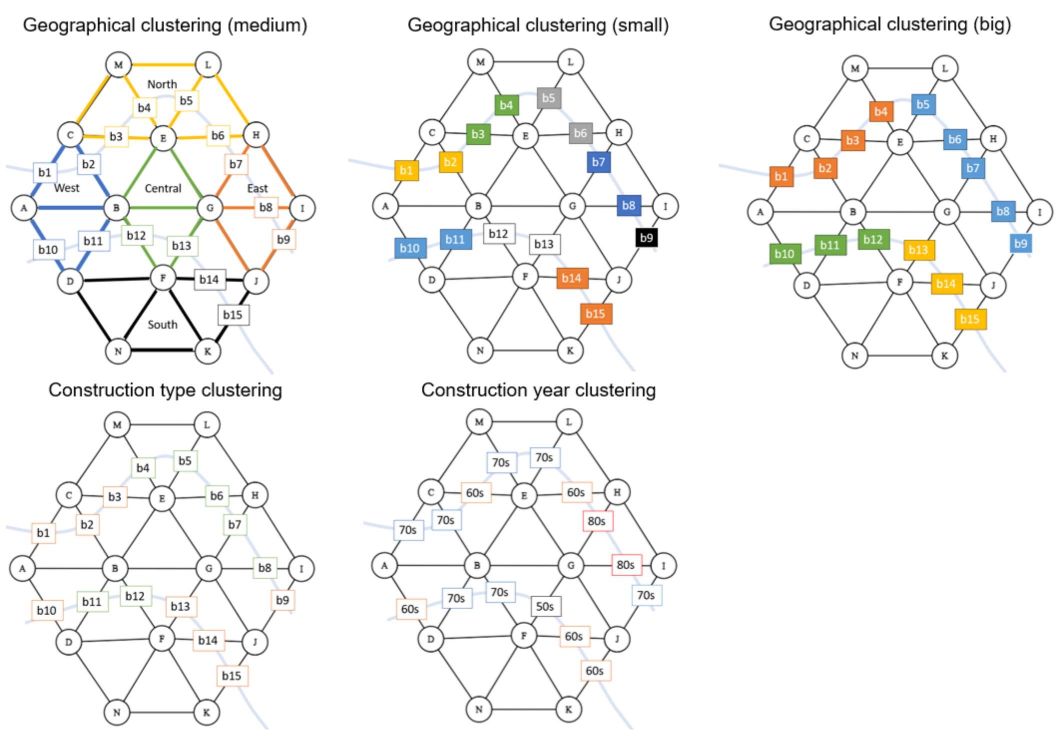

Figure 8: *Policies visualized*

The policy options will be evaluated using the change in capacity utilization and the total amount of projects executed as the outcomes of interest. The change in capacity utilization represents the percentage change in maintenance projects in each year, compared to the year before. The total projects executed is chosen as it gives an overview of the total maintenance capacity needed over the model simulation time. As an extension to this, the change in capacity utilization represents the percentage change in maintenance projects in each year, compared to the year before. The change in capacity utilization is chosen because it is desirable to obtain a constant and predictable flow of maintenance projects, instead of a select few years where big maintenance 'bubbles' have to be processed.

The model results have been generated and analyzed using a combination of the sensitivity analysis function in Ventity and the EMA Workbench (Kwakkel, 2017). The generation of model results is done using the sensitivity analysis function in Ventity, where the same run seed will be used for all the policies. The model contains a series of exogenous parameters that require a manual data input. The uncertainties that will be sampled over using the EMA Workbench. Table 2 presents an overview of the uncertainties and their ranges.

Table 2: *Policy overview*

Name	Unit	Min	Max
Yearly growth average vehicle weight	%	0.35	0.8
Yearly growth in traffic intensity	%	0.24	0.36
Population growth	%	2.5	5.0
Average vehicle speed	Km/hour	60	100
Safety margin bridge load	%	1	10
Period between bridge reinforcement works	Year	10	30
Aging factor construction	%	0.83	1.25
Aging factor E & W	%	1.12	1.68
Factor historical annual deterioration in condition construction	%	0.0024	0.0036
Factor historical annual deterioration in condition E & W	%	0.0040	0.0060
Factor historical annual reduction in condition recovery construction	%	0.00064	0.00096
Factor historical annual reduction in condition recovery E & W	%	0.004	0.006
Periodic bridge maintenance	Dimensionless	0	1

The model is run 5000 times per policy option, using a timestep of 1 years, with a simulation time of 100 years (2024 to 2123). To decrease the output file size and the simulation time, a savelist is created in Ventity which ensures that only the variables of interest are exported into the output file. With the savelist active, 30.000 runs (5.000 runs for 6 policies) only take around 3 minutes to complete using an HP Zbook Studio x360 G5 with an Intel Core i7 processor. However, due to the large sizes of the output files, the amount of runs has been limited to 5000 per policy. For the analysis of the model runs, the EMA workbench version 2.5.0 was used in combination with Python version 3.8.8.

3. Results

Table 3 presents an overview of the abbreviations used in the legends of the figures of this chapter and their corresponding policies. To increase interpretability, the figures used in this chapter are generated using only 100 runs per policy option, resulting in a maximum of 600 lines per figure.

Table 3: *Policy overview*

Policy name	Abbreviation
Geographical clustering (Small)	GC small
Geographical clustering (Medium)	GC
Geographical clustering (Large)	GC big
Construction type clustering	CTC
Construction year clustering	CYC
No clustering	NC

Figure 9 shows the cumulative amount of projects executed over time per policy. Policy options that utilize larger clusters (Construction type clustering and construction year clustering) have a higher density of outcomes in the lower values, as is visible from the kernel density estimation plot (kde) on the right-hand side of the figure. On the contrary, the distribution of expected outcomes of the geographical clustering policies, which have smaller clusters than the construction type and construction year cluster policies, and the no clustering policy is skewed towards higher total project values. Furthermore, the geographical clustering policy has a distribution of expected outcomes that is relatively high in the highest values of the outcome space.

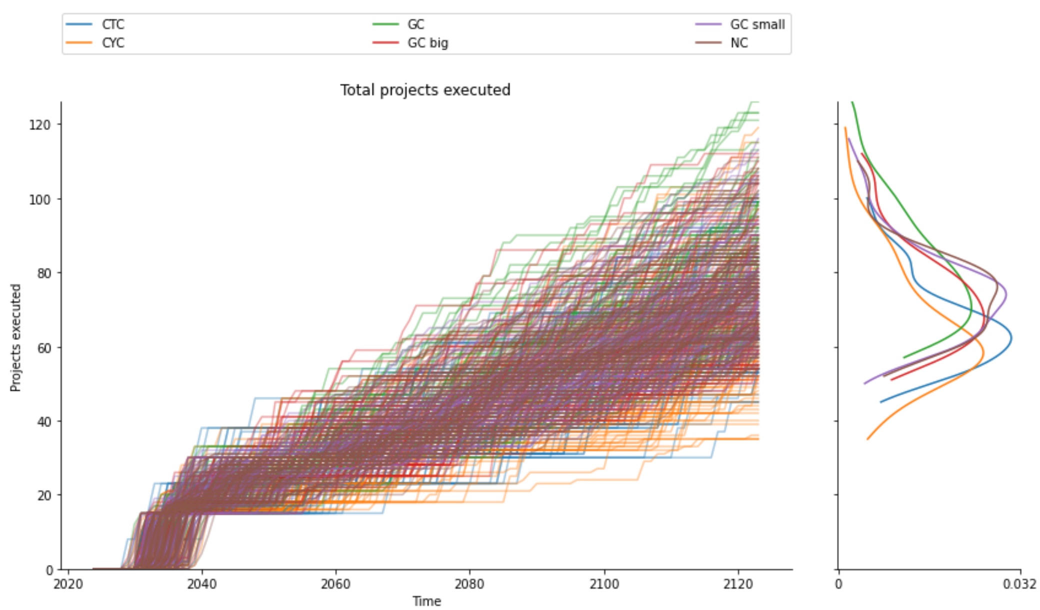

Figure 9: *Total projects executed line plot (left) and kde plot (right)*

Figure 10 shows a line plot of the change in capacity utilization per policy over time. A high value indicates that the capacity utilization increases considerably compared to the year prior. On the contrary, a low value indicates that the capacity utilization remained comparable to the year prior. Consistent low values are considered to be desirable for this outcome, as this indicates that the requested capacity remains consistent, and therefore predictable, over time. The period 2030-2040 shows a maximum value of 1 (100%) for the change in capacity utilization. This is because the first projects in all runs are executed during this time period. The change in capacity utilization is expressed as the percentage change in projects being executed in year t, compared to year t-1. An increase from 1 to >1 projects therefore returns a change in capacity utilization of 1 (100

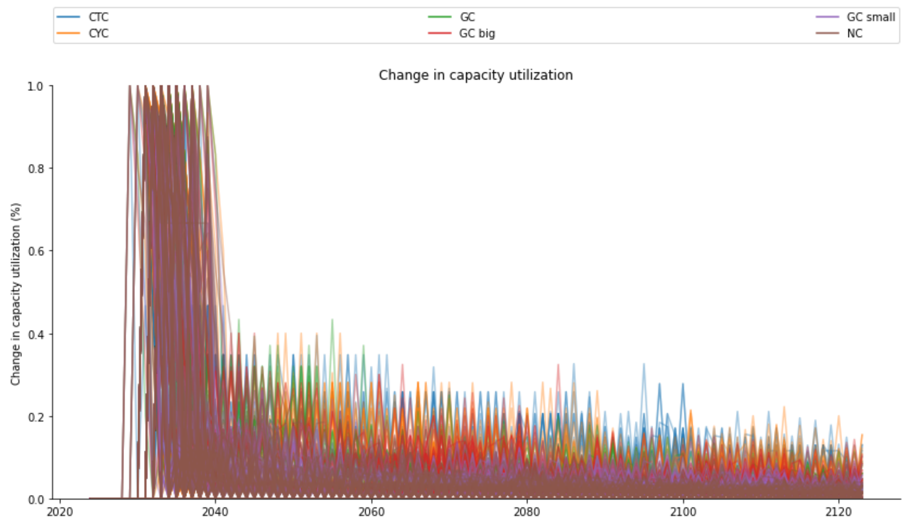

Figure 10: *Change in capacity utilization per policy option*

Figure 11 presents a heatmap plot per policy of the change in capacity utilization, which provides a clear overview of the density of values over the 5.000 runs per policy over time. A lighter color in the heatmap indicates a higher density of values over all the runs.

The heatmaps indicates that the policies with large clusters (Construction type clustering and construction year clustering) have a higher density of values in the higher sections of the y-axis (i.e., a higher change in capacity demand). This can be explained by the fact that larger clusters lead to larger values for capacity utilization change, as more projects get executed at the same timestep. Furthermore, we can clearly see that the no clustering and the small geographic clustering policy have the highest concentration of density in the lowest section of the y-axis.

The smaller geographic cluster from the small geographical clustering policy result in a relatively stable distribution in the density of values over time. When compared to the no cluster policy, the density follows a more stable pattern over time. Furthermore, the maintenance wave between 2030 and 2040 holds a higher density in the lower section of the y-axis for the geographically clustered policies than for the no cluster policy.

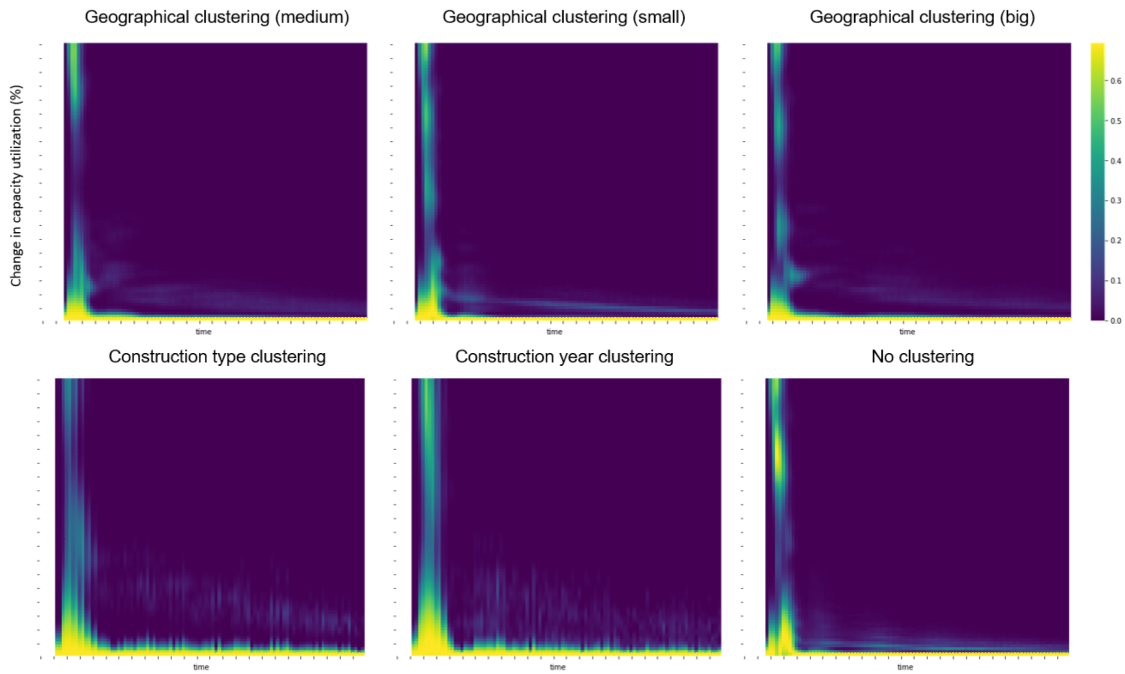

Figure 11: *Heatmaps of the change in capacity utilization per policy option*

4. Discussion

When compared to existing attempts at spatially explicit System Dynamics (SD) models, such as those presented by Benaich and Pruyt (2015), BenDor and Metcalf (2006) and Fallah-Fini et al. (2013), the approach presented in this paper provides a number of advantages that can be used to appraise its usefulness over traditional SD modeling. These advantages have been divided into 2 categories, (1) replicability and (2) computational requirements. First, the replicability of the spatial component. As stated in chapter 3.2, the focal consideration when designing the spatial component was ensuring a high degree of replicability, which was achieved by making use of 4 Entity-based SD specific features, (1) entity types, (2) attributes, (3) references and (4) external network initialization data. Because entity types can be independently defined, infrastructure components can be individually modeled in as much or as little detail as is appropriate for the modeler. As stated by Shepherd (2014), SD models that use spatial elements through subscripts or arrays, such as the model presented by Fallah-Fini et al. (2013), quickly lose their 'white box model' status as the communicability and the computational power required get strongly affected as the network in the model gets larger. Through the use of multiple model views, one for each defined entity type, the communicability of the spatial Entity-based SD model to stakeholders remains at a high level, as there are no 'hidden' variables present (i.e., subscripts).
Furthermore, entity types are defined and saved individually to the folder containing the Ventity model, which allows for the easy reuse of pre-made entity types in other models. As such, the Region to Region, Road Region entity types constructed for the model presented in this paper can be integrated into any existing Ventity model. The only remaining difficulty here is to identify through which references and variables these entity types, which jointly comprise the spatial component, the connection to the rest of the model should be made.

Through the externalization of the network (or entity) initialization data, the spatial Entity-based SD approach is able to introduce a new dimension of replicability to spatial SD modeling. This implies that all the relevant network data, such as the length, direction, and capacity of roads and the identification of all regions (nodes) in the network, are not modeled in the Ventity model. Rather, this data is captured in an Excel file and is read by Ventity upon a model run. The spatial SD models presented by Benaich and Pruyt (2015) and Fallah-Fini et al. (2013), require the modeler to manually alter the subscripts (i.e., individual roads or regions) in case the modeler wants to expand or change the network that is used in the model. While this is not necessarily a problem when modeling a small network, the modeling and verification of large networks can become complex and time-consuming (Benaich & Pruyt, 2015). By separating the dynamics of infrastructure components and the network specification data, components can be altered individually without the need to alter the other. This also plays a large role in the scalability of the presented approach, as the only addition necessary would be the expansion of the data points in the external Excel file. A first exploration of the scalability of the approach was performed during the modeling process, as the initial network (figure 1) used for testing the dynamics of the individual entity types was scaled up to the network used in the results section of this paper (figure 2). During this test, the amount of nodes (regions) in the network were increased from 3 to 14, the amount of links (roads) increased from 6 to 58, and the amount of bridges increased from 3 to 15. The upscaling of the network, performed by only editing the network initialization file, required no further work in the Ventity model, as all the dynamics of the entity types were correctly transferred to the new roads, regions, and bridges. The increased network size also did not result in a noticeable drop in model run speed.

Second, the computational requirements of the spatial Entity-based SD approach is limited compared to traditional SD models. As reported by Ouyang (2014), for infrastructure modeling, SD is considered to be a medium computational complexity approach. This indicates that a single model run takes between several seconds to several minutes. Moreover, Benaich (2015) states that the subscript-driven spatial SD approach is not computationally efficient, and is unsuitable for modeling larger networks. In comparison, the spatial Entity-based SD model constructed in this research takes a fraction of a second to complete one model run, which would place it in the small computational complexity category in the framework presented by Ouyang (2014). Also, as stated before, the upscaling of the network used in the model did not result in any noticeable increase in required computational power, which is a first indication that the findings of Benaich (2015) do not hold true for this spatial Entity-based SD approach. However, as only one upscaling exercise was attempted, and the network used in this research is still limited in size, additional research will be needed to confirm if the spatial Entity-based SD approach will remain computationally efficient even when modeling increasingly larger networks.

Regarding the model, an important finding is that the model presented in this paper is not fit to analyze the impact of bridge maintenance clustering policies on travel time. This can be attributed to 2 factors, (1) the assumption that all roads in the network have sufficient capacity at all times and (2) the lack of a destination-based traffic flow distribution in combination with a shortest route algorithm. The road capacity assumption was made to decrease the complexity of the Region to Region entity type, as exceeding the capacity of a road would lead to traffic jams, which in turn should impact the average speed on the road and the distribution of traffic in proximity of the road. Secondly, the distribution of traffic is only impacted by the status of bridges and the population of regions in the network. This is another assumption that was made to decrease the complexity of the Region to Region entity type. As an unintended consequence, however, these assumptions led to the closing of a bridge not causing any significant impact on the travel time in the model. In the event of a bridge closure, an equal proportion of the diverted traffic is allocated to nearby roads, which all have enough capacity to absorb the diverted traffic. Since the model does not allocate a specific destination to each traffic flow, however, the diverted traffic does end up at the same destination it would have had before the closure of a bridge. Rather, the other regions connected to a region with a closed bridge all receive more traffic, but after arriving at the new region the distribution remains unchanged. An improvement here could be to add a vehicle entity to the model, which allows each vehicle to decide its destination. This could be modeled using an allocate action in the vehicle entity, which ranks the possible destinations in the model for each timestep based on a set of weighted criteria (such as economic activity and inhabitants).

This paper has served as a first investigation into a novel Entity-based SD approach to infrastructure modeling. To further enhance the applicability and effectiveness of the Entity-based SD methodology, there is a need for improvements in documentation and the maturity of the approach. This includes developing comprehensive guides and resources to facilitate modelers in utilizing the approach for infrastructure modeling. Another interesting point of further research is discovering if the computational requirements of the approach remain low when increasingly larger networks are used as a basis for the model. Furthermore, it is recommended to apply the spatially explicit Entity-based SD method to other types of infrastructure systems, such as water, energy, or communication networks. This can help to test the generalizability and scalability of the method. Lastly, modelers and practitioners adopting the approach should also consider collaborating to create a knowledge-sharing platform to exchange best practices, improving the overall understanding and utilization of Entity-based SD.

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