Reinforcing the Bangladesh roadwork

Building components for data driven simulation

EPA133A: Advanced Simulation
Assignment 2

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Introduction

Background

Bangladesh faces natural disasters such as earthquakes, river flooding and cyclones more frequently [1]. As Bangladesh is a delta, the country is divided by a complex network of rivers and canals. This makes Bangladesh highly dependable on infrastructure such as bridges and roads that can keep regions connected. Therefore, the Bangladesh Infrastructure Upgrades project, initiated by the World Bank, aims to enhance the nation's transportation infrastructure. By analysing its vulnerability and robustness to natural disasters, possible policy interventions on specific bridges and roads can be assessed.

A first step towards a full analysis is to understand individual traffic flows and interactions with bridges being broken down and in repair. Therefore, this report mainly studies the effects of bridge maintenance or unavailability on traffic throughput for the major N1 road from Chittagong to Dhaka in Bangladesh.

To better understand how, on a system level, the collapse and maintenance of bridges may lead to traffic congestion, a simulation approach is used. The effect of bridge maintenance on traffic congestion behaviour is complex. Many small interactions together result in emerging traffic congestion. Simulating this behaviour is beneficial in several ways. First, by simulating the underlying mechanisms and the resulting emerging behaviour, the system itself can be better understood [3]. This is helpful when designing policy interventions and assessing their impact on the situation. Moreover, using simulation allows for exploring 'what if' scenarios without actually having to test these in real-life.

Due to the many complex interactions between vehicles, roads and bridges, it is difficult to model the whole system in an understandable way. Therefore, the model design that is presented in this report will be based on different components that are based on certain parts of the system. Following Hofmann, there are two benefits of using such a component-based modelling approach [5]. The first and also the clearest is the need to manage complexity. The real-world situation is too complex to model within the given time scope. The systems must be broken down into multiple parts and decisions must be made about which parts are relevant to the model. Secondly, breaking down the model into various parts will make it possible to develop different parts of the model in parallel, increasing the working efficiency drastically.

Structure of report

The report presents the following structure: Chapter 2 will explain the conceptual model and its components. Also, the data used for simulation will be shortly discussed. Whereas Chapter 3 describes the methods' model implementation, Chapter 4 discusses the experimental setup used for the analysis. Chapter 5 gives the simulation results under different scenarios. Lastly, Chapter 6 discusses the limitations and possible improvements of the model.

2

Model explanation and data usage

As stated in the introduction, a simulation model will be used to understand emerging behaviour of traffic flows as a result of bridge breakdowns and repairs. This chapter will first elaborate on the system demarcation of the model. Consequently, an approach to how the real-world system can be decomposed will be explored. An important part of understanding the model is its conceptual basis. This conceptual basis will be formed based on the system demarcation and decomposition. Finally, this chapter will also briefly touch upon the data that will be used and its quality.

System demarcation and background

As this report's focus is to understand individual traffic flows and interactions with bridges being broken down and in repair, the system will be limited to only one road in Bangladesh. However, this does not mean that the road to be modelled is chosen arbitrarily. Being the main road artery of Bangladesh, the N1 connects Chittagong to Dhaka. Given the N1's importance from a connectivity perspective, this road is a perfect candidate to use for simulation. Moreover, the effect of unavailability and maintenance of bridges on traffic flow will be the largest for the N1 because it has the most bridges. Figure 2.1 depicts the number of bridges for the ten roads that contain the most bridges. The figure shows that the N1 has the most bridges of all the roads, namely 653 bridges in total.

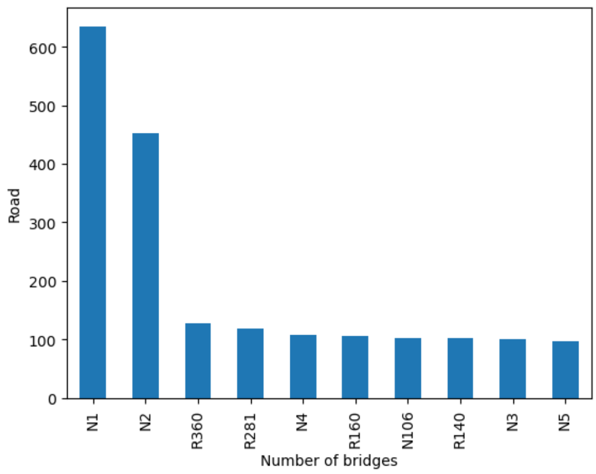

Figure 2.1: Number of bridges on the N1. Data from Verbraeck [6]

As shown in Figure 2.2 the N1 stretches through the whole of Bangladesh. The blue points indicate the bridges between Chittagong to Dhaka and the red points are not on the route between Chittagong to Dhaka. The Bridges themselves look to be fairly uniformly distributed over the road. The whole N1 is 465 kilometres. So, on average, every 0.69 kilometres there is a bridge.

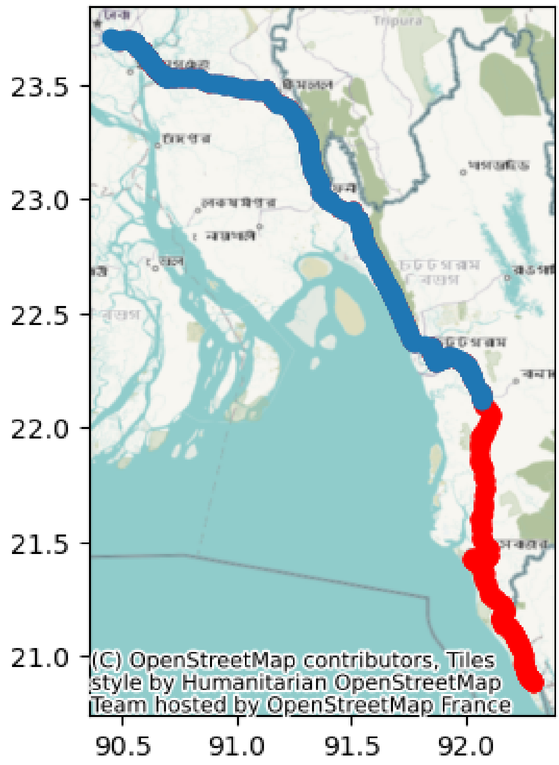

Figure 2.2: Bridge locations for N1.

In this experiment, the model only simulates the N1 from Chittagong to Dhaka (the blue line), with a length of 287 km. To accurately model the road, the bridges alone as the component will be insufficient, which is unclear if the truck is located on a bridge or road. To clarify the location of the truck, ”links” are added. Links represent the road segments in between bridges, with which the location of a truck is clear (bridge or link). However, other components are needed to model the truck entering and leaving the road. To do this, the model will create the start, ”source”, and the destination, ”sink”, representing the beginning and the end of the road.

System decomposition

The purpose of a model in general is to simulate a certain aspect of reality. What the model must represent and on which detail it must be modelled strongly depends on what the purpose of the model is and what the modeller wants to include or exclude. The study of Edmonds et al. [4] describes seven model purposes. One of these is modelling for explanation. Here, the model is created to show a possible explanation of how certain aspect, or behaviour in a system works. In this case it is giving insight in how damaged bridges influence travel times. To do this, a model is required that simulates the traffic flow of the N1. In reality, the traffic on the N1 is very complex. There are thousands of vehicle drivers on the road with different types of vehicles and different purposes. Furthermore, traffic intensity differs based on the time of day. Lastly, the weather conditions and the conditions of the road segments have a strong impact on the traffic flow. How to convert complex systems like this into an understandable and usable model is difficult. Therefore, as also stated in the introduction, decomposition of the system into smaller, less complex parts is necessary.

According to Hofmann [5], a model can be decomposed based on its structure, behaviour and goals. These different decomposition strategies can also be applied to the system of Bangladesh’s road and bridge infrastructure being analysed in this report.

Structure				
Link	Bridge	Truck	Source	Sink
Behaviour				
No specific behaviour	Collapse Repair	Drive Wait	Generate truck	Remove truck

Figure 2.3: Decomposition for the model. Based on Structural decomposition five agents are created. Then per agent behaviour is determined following behavioural decomposition.

When using a structural decomposition approach, the focus is on what kind of objects the system is made of [5]. In this case, structural decomposition can be achieved by dividing the system into vehicles, bridges and roads.

When using a behavioural decomposition approach, the focus is on what different kinds of behavioural characteristics there are in the system [5]. In the project case, this could be, for example, the trucks driving from source to sink, bridges breaking down and being repaired or the road being jammed because of congested traffic.

Lastly, when using a goal-based decomposition approach, the focus is on decomposing the system based on the different kinds of emergent behaviours the modeller wants to visualise [5]. In the project case, for example, the model could be divided into a part that has the goal to visualise emerging average driving time of a vehicle, and a part having the goal to visualise bridge collapse. Another example could be the road, aiming to give insight into the infrastructure layout and spatial distribution of the road.

Even though all three decomposition approaches are valid options in this project, the choice was made to decompose the system by first focusing on the structure of the system and then further decomposing the parts that come from the structural decomposition into smaller parts based on the behaviour characteristic of the individual parts. This way a clear distinction between relatable objects is created and within these objects, a clear distinction is made for the specific type of behaviour every object can show. An overview of the objects and their possible behaviour is given in Figure 2.3. What the behaviour entails will be explained in detail in the formalisation.

Model conceptualisation

Figure 2.4 shows an overview of the relation between bridges, links and trucks. It depicts the three main model components, being bridge, link and trucks.

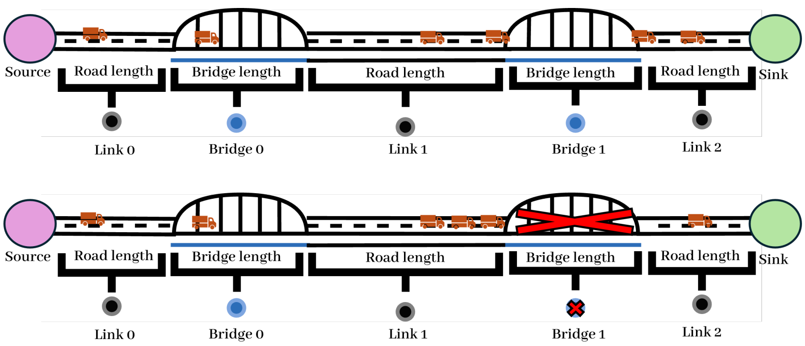

Figure 2.4: Illustrations for Links, Bridges and Trucks.

As shown in Figure 2.4 , links and bridges alternate with each other. Both the links and bridges have a certain length. Intuitively, the longer the length, the longer it takes to pass the link or bridge. The only functionality of the links is indicating how long the road in between the bridges is and if the trucks are driving on a road or a bridge. The bridges will, however, show different states. The bridges can be functional, in reparation, or broken.

When the bridge is functional it will behave the same as a link. This means that trucks can travel over it, without being delayed. A functional bridge has a certain condition that ranges from good (A) to bad (D). Per step there will be a chance that a bridge will break down, depending on the bridge condition. If a bridge breaks down, the bridge condition will change to 'broken down', which corresponds to (X).

When broken down the trucks can still pass the bridge, but with a delay time due to the necessary reparations. The delay time will vary based on the length of the bridge. For the time that the trucks have a delay time they will wait before a bridge. This is shown at the bottom of Figure 2.4. After the bridge is broken down it will be checked. When this happens the state goes from broken down to being repaired.

Conceptual assumptions

It is important to be aware of the assumptions that were made during conceptualisation. For simplicity reasons, the following conceptual assumptions were made. Firstly, if a bridge is repaired, it will be repaired in such a way that its condition will become the best condition (A). Furthermore, the repair time is the same for each bridge.

Data

To create the model, data on the bridges and roads are required. The data for the bridges is given in an Excel file from Verbraeck [6]. The current state of the bridge data files is not usable for the model. Hence, it first needs to be cleaned. Below, the data cleaning process is discussed.

Bridge

The bridge data is cleaned in two steps. First, missing values are handled. Afterwards, duplicates are processed, studied, and handled too.

Handle missing values.

Having missing values may introduce inconsistency for the dataset, hence the missing values are checked. In total, 315 missing values are found in the "name" column of the dataset while 9 missing values are found in the "length" column. The missing "name" values were filled in with a ".", as the proper name is difficult to retrieve when missing. The missing "length" values are imputed using two different methods. The first option is imputing the missing values by using the value of a bridge that has the same chainage. If there is no bridge with a similar chainage, the average length of all bridges on the road will be used. By applying these two methods, all missing values are resolved.

Process the duplicates.

In total, there are 159 bridges that have other bridges in the same location. Having multiple bridges in the same location can be due to two different reasons.

The first reason is that some bridges are two-directional and both have a left and a right lane. The left and the right side of the bridge are included in the dataset as two separate entities. These entities are indicated with either 'L' or 'R'. In that case, having duplicate bridges is not an issue, as the truck will either drive on the left or right side of the bridge, based on the direction it's driving.

The second reason is that some rows are real duplicates of a bridge. This is the case when the longitude and latitude are the same and the bridge is meant to facilitate the same direction of traffic, for example, if two bridges both have an "R" value. In this case, a decision must be made to decide which of the duplicates must be kept. This is done based on the bridge condition. This project aims to study the driving time for the trucks under different scenarios and identify which bridges are critical and vulnerable. For more reliable results, the worst conditions for the same bridge are used. Hence, bridge duplicates with the best conditions are dropped. This will assume the worst possible case for the scenario analysis. If the conditions are the same for the same bridge, the duplicates are randomly selected.

Road

The model will simulate the N1 road. Provided for this project is the road data in the form of location reference points (LRPs). It is decided to refrain from using this road data. The bridges themselves can already depict the road itself, as is shown in Figure 2.2. Furthermore, the bridges themselves already provide how far on the road they are located. Although adding the LRPs will provide extra detail in the road shape, it is expected this does not add extra value in fulfilling the purpose of the model.

To connect between bridges, a link is added between every two unique bridges. Bridges with an identical latitude and longitude are not connected through a link since they are identified as the same. Adding these links results in a continuous road on which bridges are interspersed with links. The length of a link is calculated by subtracting the chainage of the previous bridge of the chainage of the next bridge. To get the actual length of the link, half of the length of the previous bridge and half of the length of the next bridge are subtracted. The chainage of a link is calculated by taking the average of the chainage of both the previous and the next bridge. At last, the latitude and longitude of a link is determined by interpolating between the latitude and longitude coordinates of both the previous and the next bridge.

Key performance indicators

Measuring the model's performance is crucial. It evaluates the results and guides decision-making processes accordingly. Two key performance indicators (KPIs) are used in this model:

- **Average driving time**: Driving time measures the ease of driving on the road. Better road conditions shorten the driving time. In the model, bridge conditions can affect the driving time. The better the bridge conditions, the lower the possibility for a bridge to break down, hence, less waiting time, less delay time, and less driving time.
- **Average delay time**: Bridge conditions are also associated with delay time. The better the condition, the lower the chance the bridge will break down. Consequently, less delay time is encountered.

The KPIs above were chosen because they are intuitive and obvious. Within the same road, longer driving and/or delay time means worse driving conditions, presenting the bridge conditions. Besides, they are also measurable and quantifiable - they can easily be calculated.

3 Formalisation

This chapter will explain how the conceptual model is translated into a formal model. The model will be simulated over 7200 steps and in each step, the agents will take several actions. To provide an overview of the actions the agents take, both step functions are visualised using a flow chart.

Agent steps

In this section, the step functions of both the Bridge and the Truck agent are discussed using a flow chart. The code for these step functions can be found in the components.py file [2].

Bridge

During each step of the model, several actions are performed on each bridge. An overview of these actions during a specific time step can be found in Figure 3.1. As shown in this figure, the first step is to check the bridge's condition. If the condition is equal to 'X', this means the bridge has already collapsed and needs repair. In that case, the reparation status will be checked. If the repair time of the bridge is equal to zero, the reparation will be finished. If not, the remaining repair time will be decreased by one time step.

Finishing the reparation consists of three actions: changing the condition of the bridge to 'A', setting the 'in repair' attribute to 'False', and giving the 'repair time' its original value. The repair time is an attribute of every bridge, even when the bridge doesn't collapse. However, only when a bridge collapses the repair time will be used. If in use the repair time will decrease every time step by one, until it reaches the value of zero. Then the bridge is fully repaired.

When the bridge has not already collapsed, it has either condition 'A', 'B', 'C' or 'D', with condition A>B>C>D. Based on this condition the chance that a bridge collapses is determined. The higher the quality of the bridge the lower the chance the bridge collapses. These collapse chances vary in 9 scenarios with increasing chances of collapsing. In Figure 3.1 the collapse chances of scenario 1 are shown. Once the collapse chance is determined, this chance will be compared to a random number between 0 and 1. When the chance is greater than this random number, the bridge collapses. The condition will be changed to 'X' and the 'in repair' attribute will be set to 'True'.

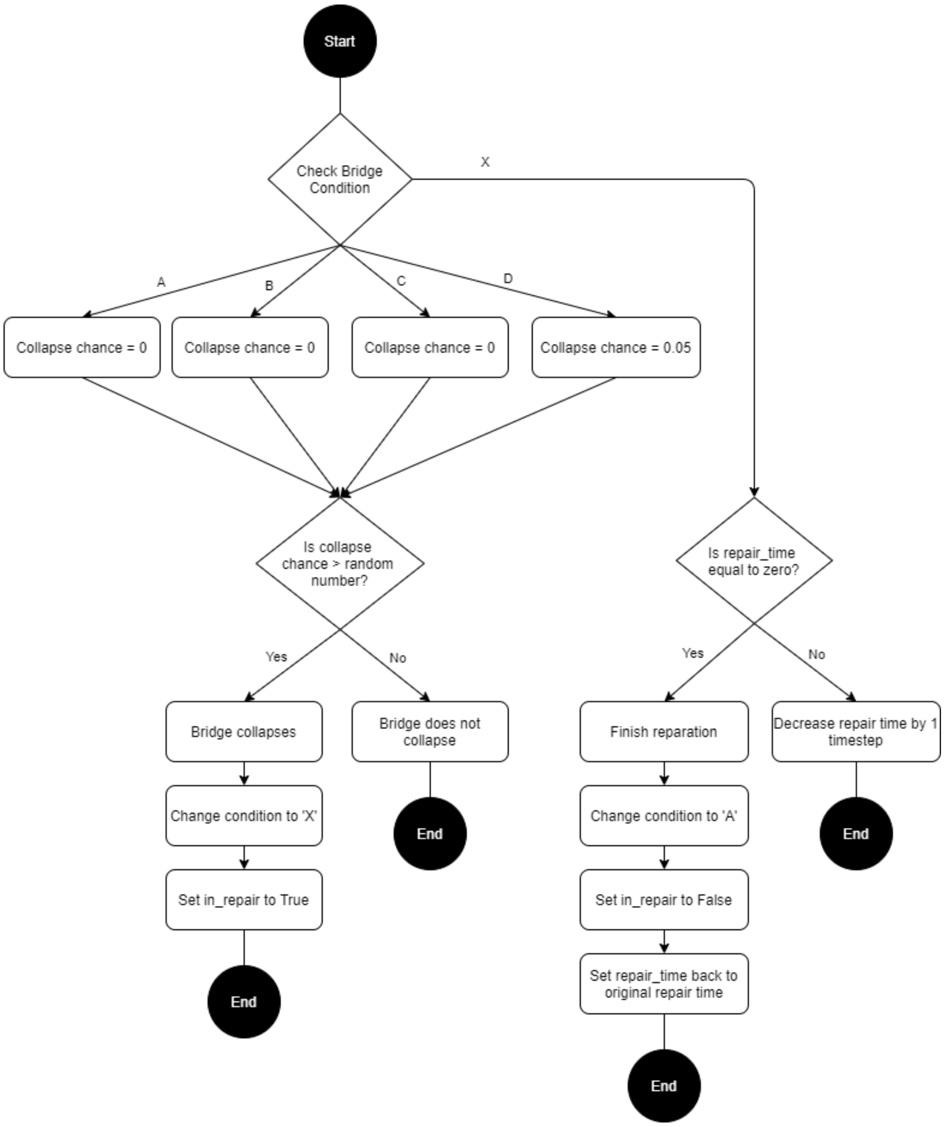

Figure 3.1: Flow chart of Step functions Bridge.

Truck

For each time step, a truck either drives or waits on an object (link or bridge) on the road. In Figure 3.2, the actions taken in each step are shown in a flow chart.

The first step is to check the state of the truck. If the state is 'Wait' the waiting time of the truck will be decreased by one time step. If the waiting time then reaches zero, the state of the truck will be set to 'Drive'. Otherwise, the state remains 'Wait' and the truck doesn't perform any more actions. If the truck's state is equal to 'Drive', the truck will drive a certain distance. The distance that the truck will travel is determined based on the speed of the truck and the length of the time step. If the distance to travel is greater than the remaining length of the object the truck is on, the truck will drive to the next object. Otherwise, the truck remains on that object and the location of the truck will be updated.

When the truck drives to the next object the remaining distance to travel is updated by deducting the remaining length of the previous object. When the truck arrives at the next object, it will first check the type of object. If the object is a sink, the truck will be removed from the model. When the object is a link, the truck will again compare the distance to the length of the object. At last, when the object is a bridge, the waiting time will be determined. When there is no waiting time, the truck will continue driving and compare the distance to the length of the bridge. If the waiting time is greater than zero, the truck will remain on that object and its state will be set to 'Wait'.

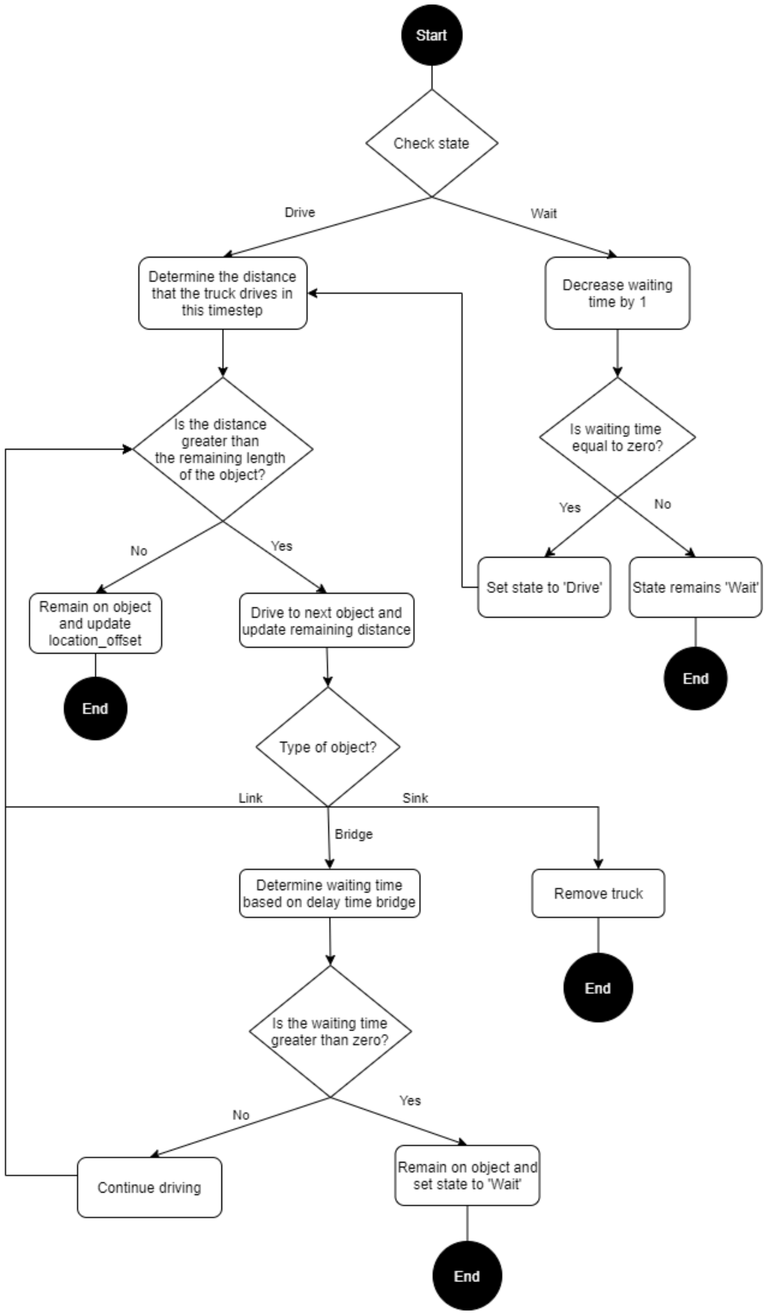

Figure 3.2: Flow chart of Step functions Truck.

Driving direction

In data cleaning, "L/R" attributes for the bridges are kept only if they are the same bridge that separates the left and right sides. In other words, data cleaning assures that "L" or "R" name only appears in the same bridges with different directions. For a more realistic simulation, bridge directions need to be considered, i.e., trucks must drive on the same side as their driving directions, otherwise, they will break the traffic rules.

Hence, trucks will check the bridge's name they will be going to. If "R" is contained in the name, the truck will skip this "R" bridge thereby making sure that only the "L" bridge is driven on. The "L" bridge is selected because Bangladesh drives on the left side of the road, and in the current model, the driving pattern is simulated in only one direction: from Chittagong to Dhaka. To increase the reusability of the model, e.g., the possibility of simulating different driving directions, "L" and "R" attributes are not removed at the data cleaning stage. Instead, they are filtered based on simulation requirements. Figure 3.3 shows the process of selecting L/R bridges.

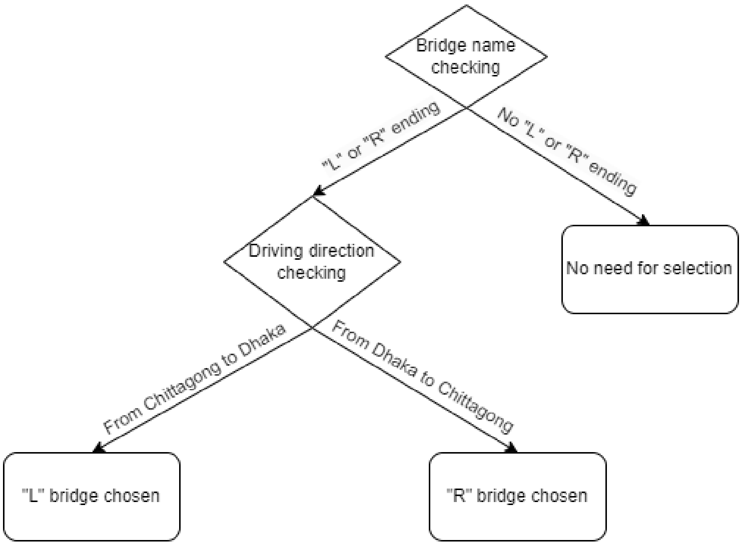

Figure 3.3: Flow chart for selecting left and right bridge.

Formalisation assumptions

It is important to be aware that the assumptions were made during the formalisation of the model. For simplicity reasons, the following assumptions were made. Firstly, following the conceptual assumption that the repair time for each bridge is the same, the repair time for this model was simply assumed to be one day. In reality, repair time of one day is far from enough, however, it is set proportional to the model's run time of five days. Importantly, repair time helps to extend the model in the future need. Besides, the average driving speed of a truck, without barriers, was set to 50 km/h. The delay time for a bridge that is in repair follows distributions based on the length of the bridge. This is shown in 3.1 below.

Table 3.1: Formalisation of delay time based on the length of the bridge.

Bridge length	**Delay time for a truck**
Over 200 m	Triangular (1,2,4) hours
Between 50 and 200 m	Uniform(45,90) minutes
Between 10 and 50 m	Uniform(15,60) minutes
Under 10 m	Uniform(10,20) minutes

4

Experimental setup

This section describes the choices for the setup of the experiments. At first, the experimental setup will be explained. Afterwards, a short description of the scenarios will be given.

Model run

Every model run will consist of 7200 steps. Every step represents a minute and 7200 minutes is five days in total. Per five minutes a truck is created in the source. This means that the model will generate 1440 trucks, a truck per 5 minutes.

Replications

Due to stochastic effects, a single model run is never reliable. Therefore, each experiment will be run 10 consecutive times.

Any increase in replications compared to having no replications will be beneficial for the reliability of experiment results. However, there is a certain limitation to only using 10 replications for the experiments. Normally, more replications would be better as with only 10 replications there is still a significant chance that not all stochastic effects are included. However, due to time constraints, the choice was made to only do 10 replications for each experiment.

Scenarios

For this study, no interventions will be examined so only the scenarios will be used to differ the model configurations.

In this project, nine experiments will be done. One for every scenario. This means that the model will be used for nine experiments and run 10 times per experiment, resulting in 90 runs in total.

The scenarios will differ only on the probability of a bridge breaking down. This probability is different for every bridge condition. An overview of the probability per bridge condition per scenario is given in Table 4.1. The probability that the different bridge conditions break down increases per scenario where scenario one has the lowest probabilities and eight the highest.

Table 4.1: Scenarios with different probabilities.

Scenario	Cat A %	Cat B %	Cat C %	Cat D %
0	0	0	0	0
1	0	0	0	5
2	0	0	0	10
3	0	0	5	10
4	0	0	10	20
5	0	5	10	20
6	0	10	20	40
7	5	10	20	40
8	10	20	40	80

5 Results

In this section, the results of the experiments that are conducted will be shortly discussed. To analyse the results of the model, both the average driving time and the average delay time are used as Key Performance Indicators (KPI's).

Scenario results

In Figure 5.1, a bar plot of the average driving time per truck is shown for the different scenarios.

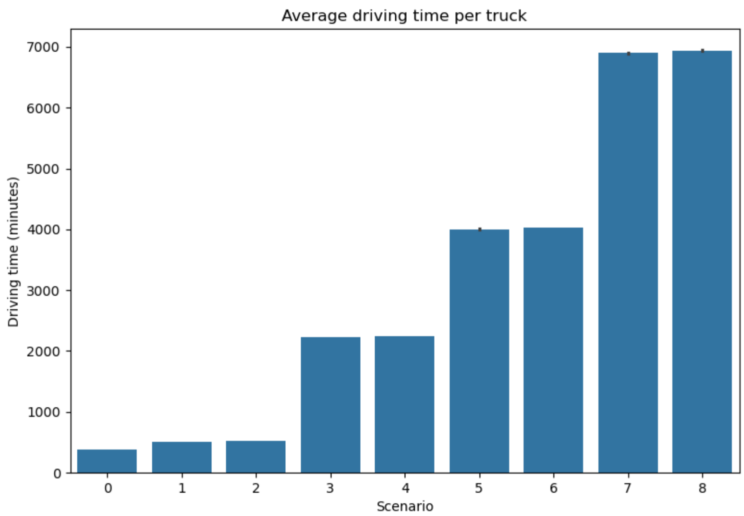

Figure 5.1: Barplot Average driving time.

The figure shows that following the order of scenarios, the average driving time increases. This behavior is also expected, as the scenarios follow an increase in collapse chance for the different bridge conditions. An increase in collapse chance will result in more bridges collapsing. Consequently, more bridges will need to be repaired, leading to more bridges having a delay time and more vehicles needing to wait. Ultimately, this will lead to an increase in the average driving time. The average driving time for scenario 0, the 'business as usual' scenario, is the lowest. This is to be expected, as in this scenario there are no bridges breaking down.

Interestingly, the figure shows that the increase in driving time goes in pairs of scenarios. This can be explained by reflecting on the experimental setup. As illustrated in the previous chapter, the chance of a bridge from a certain category collapsing differs between scenarios. This is done as follows: scenarios 1 and 2 only have an increase in collapse chance for bridges with category D. Next, an increase in collapse chance for bridges in category C is added in scenarios 3 and 4. This means that in these scenarios, two bridge categories have an increased chance of collapsing. Next, scenarios 5 and 6 have added a collapse chance for bridges of category B. This means that in these scenarios, three bridge categories have an increased chance of collapsing. The final two scenarios, 7 and 8, have an increased chance of collapse for all bridge categories.

The rise in driving time follows in pairs of scenarios since the amount of categories that have an increased chance of collapse are added in pairs too. In addition, this explains the relatively large differences between the scenario pairs. With each scenario pair, the chance of bridges collapsing increases significantly as an extra bridge condition has a chance to collapse. This effect is especially encountered in the final scenario pair, scenarios 7 and 8, as these include an increased collapse chance for all bridge conditions. In these scenarios, the chance of collapse for condition A is for the first time included. As condition A occurs most frequently in the data, the increase in collapse chance in scenarios 7 and 8 has an additional effect.

The minor difference between the 'business as usual' scenario and the first scenario pair, scenarios 1 and 2, can be attributed to the fact that in this first scenario pair only one bridge category (D) has the chance to collapse, which in turn is also very small (only 5 and 10 percent).

The figure also shows that within the pairs of scenarios, there is not a relatively large difference in average driving time. Especially for the last scenario 'pair', scenarios 7 and 8, this seems counter-intuitive as the chance of a category bridge collapsing is doubled in scenario 8, when compared to scenario 7. Apparently, the average driving time is only influenced by an increased bridge collapse chance to a certain extent. Why this is the case, would need to be further investigated in future research.

In Figure 5.2 a barplot of the average delay time per truck is shown.

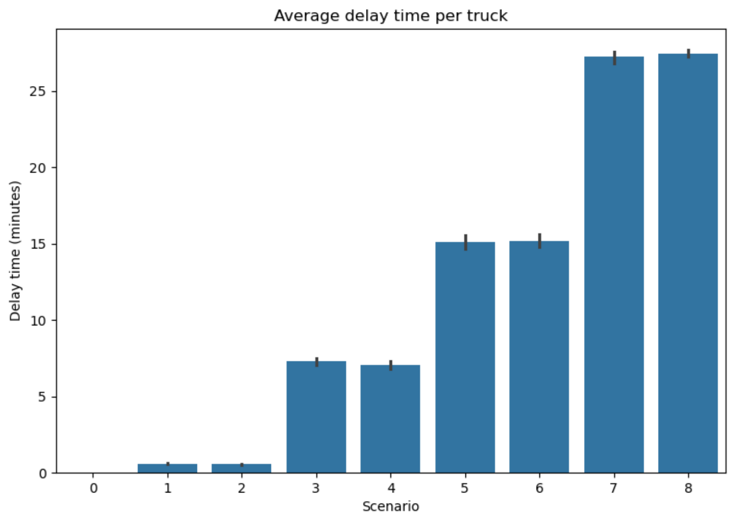

Figure 5.2: Barplot Average delay time, for different scenarios.

Similar to the average driving time, the average delay time increases when the chance of a bridge collapsing is higher. The average delay time in scenario 0 is equal to zero, which is to be expected as there are no bridges collapsing in this scenario. Note that the delay time is, on average, encountered at every bridge for every truck.

6 Reflection

The purpose of the model is to represent a certain aspect of a real-life system. In this study, the truck drives over the N1 road. Constructing a model that mirrors the real system is impossible and unwanted. Hence, simplifications are made and assumptions on how the systems work are made. The main four limitations of the model are given below.

(1) The trucks can only drive over the N1. Hence, it is not possible to change routes to avoid broken bridges. The absence of alternative routes can result in longer delays than in reality. This could be solved by adding roads that will provide alternative driving routes.

(2) The trucks all have the same speed. In the real world, not all trucks drive at the same speed. Using a uniform distribution, more realistic speed values are used in the simulation.

(3) One of the big issues with the bridges on the N1 is that they are vulnerable to flooding events. The current model does not simulate such flooding events. To make this realistic the model could be simulated that on a certain time step, a flood event happens. During the flood event, all the bridges could have a certain chance of breaking down. This could replace the current way how bridges break down to make it more realistic.

(4) The model does not take into account different amounts of damage to the bridge. Now if a bridge is damaged, it will always have a repair time of one day and when repaired it will always be repaired to the highest condition. It would be more realistic if the repair time would differ and the bridges would be repaired to the highest grade.

A general improvement could be to examine different routes. Due to time constraints, only the N1 is examined, while the data for other routes is present. Examining different routes could give insight into whether the problems with the criticality and vulnerability only apply to the N1 or if it is a bigger problem for the whole road network.

Future research could enhance our findings by several extensions:

- **Extension towards not only simulating one road.** This can be done by expanding the list of road names. In the model, N1 is read into a list. By adding more road names, N2, N3 etc., the number of roads could be examined by the model increases.
- **Extension of different directions of the bridges.** In the bridge component, ”L” and ”R” names for the bridges are not eliminated in the data cleaning step yet. The idea behind this is that the model could be expanded to cover different driving directions in the future. Then, the name of the road could be used to filter the directions of the bridges and assign trucks to the correspondent side of the bridges.
- **Extension of introducing a more realistic repair time.** In the model, repair time was set to a short time - only one day. With the assumption of a 5-day simulation time, setting repair time to 5 days or more is meaningless. However, for a more realistic simulation, the model can be extended to a longer driving time and repair time.

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