MASTER

Design of digital decision model for minimizing Schiphol's bridges' fatigue by allocating traffic using real-time measurement data

Georgopoulos, Prodromos

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Design of digital decision model for minimizing Schiphol's bridges' fatigue by allocating traffic using real-time measurement data

Master Thesis

Prodromos Georgopoulos

1556584

Supervisors:

Claudia Fecarotti (TU/e)

Melvin Drent (TU/e)

Albert Reitsema (Heijmans)

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Abstract

In this research, the exploitation of the data gathered by Heijmans's sensor system was investigated. This data was gathered by sensors installed under bridges that support airplane traffic in Schiphol airport. The sensors estimate the weight of each crossing airplane. By using Eurocode's equations, the fatigue of each bridge's deck caused by the crossing of each airplane can be calculated. Hence, the true loading for each bridge can be identified. Based on the data collected over a three-month period, a prediction model was developed for calculating the bridge's deck's remaining useful lifespan.

Furthermore, the application of the prediction model to the network concept was investigated in the second part of this research. The total fatigue of the network of three bridges was minimized based on the airplane traffic allocation. Specifically, the uniqueness of each bridge led to the identification of a unique prediction model for each bridge. Subsequently, the traffic of the network was allocated in a way that each bridge would allow some aircraft types based on their maximum take-off weight. A mathematical model was created to ensure the feasibility of the airplane traffic allocation to the bridges while minimizing the total cumulative fatigue of the network's bridges. Finally, a greedy heuristic was presented as an alternative less computationally intensive way to solve the proposed mathematical model when the network becomes larger.

Management Summary

Introduction

This research was based on a problem identified within Heijmans. Heijmans is, during the period that this research was conducted, responsible for asset maintenance in the area of Amsterdam Schiphol airport. Bridges are among the most expensive assets to be maintained. Those bridges connect the runways of Schiphol to the main airport hub and are being crossed by airplanes. After cyclic repetition of load, any bridge suffers from cumulative fatigue. Every bridge must be replaced before its cumulative fatigue reaches the limit of 100%. The remaining useful lifespan of a bridge refers to the time needed for the bridge until it gets replaced. The replacement of a bridge is costly; hence Schiphol needs to be prepared beforehand for such an expense. Heijmans introduced an innovative monitoring system. This system consists of sensors installed under a bridge or a tunnel. Those sensors gather real-time data on the load of that asset. The output data from these sensors is the exact time and the estimation of the weight of the airplane crossed that asset.

Problem description

The problem, this research was based on, was the capitalization of the innovative Heijmans monitoring system for bridges and tunnels. This monitoring system gathers data for the bridge's actual load. In other terms, this system provides an estimation of the weight of the crossing airplanes. Before the introduction of the Heijmans monitoring system, fatigue calculations were based on the maximum weight of an aircraft rather than the actual weight. The first goal of this thesis was to create a way to exploit the monitored data to update the calculations for the remaining useful lifespan of bridges based on the actual weight of the aircrafts crossing the assets. Moreover, the set of monitored bridges and tunnels formed a network. The second part of this research aimed to find an operational strategy that minimizes the cumulative fatigue across the assets of that network. Based on the aims of the research, the following main research question was formulated:

> *How can data-driven prediction of structural fatigue for each monitored bridge, within the asset network of Amsterdam Schiphol airport, be realized using Heijmans monitoring system? Additionally, how can these predictions be used to minimize the cumulative fatigue of the network of the three monitored bridges based on different operational policies?*

The scope of this research is limited to three assets in Schiphol that Heijmans's monitoring system was installed upon. Those assets were the only bridges and tunnels monitored since 2021.

Methodology

The first goal of this research was to exploit the data from Heijmans's monitoring system. To achieve that goal unique weight distributions for each type of aircraft had to be created. Those unique weight distributions were based on the comparison of data collected from the monitors and data from the GPS air traffic control of Schiphol. Additionally, each airplane's weight was translated to stress within the bridge by using a linear relationship between the two variables. Subsequently, Eurocode's fatigue equations were used to translate the bridge's stress to the

bridge's fatigue. Finally, the traffic volume prediction was added to the previous calculations to identify the remaining useful lifespan of each asset.

The second goal of this research was to implement the first model, which answered the first goal of this research, simultaneously to multiple assets. Those assets form a network. Different operational strategies of that network imply that each asset serves a unique portion of the total traffic. In other terms, by allocating each airplane's route the total accumulated fatigue across the network of assets would change. Next to the optimization of the model, a heuristic was created as an alternative computational less intensive way to solve the network model, when the network would get bigger. That heuristic has a starting point and by changing a single variable in each iteration, a new start point would be selected that would offer less cumulative fatigue across the network of assets compared to the first point. The heuristic would then stop when there is no other point that offers less total cumulative fatigue across the assets.

Results

After the implementation of models 1 and 2, the results were presented in graphs. In those graphs, the significant reduction of the cumulative fatigue of the assets is depicted. For example, bridge 1 had to be replaced before 2077 based on the theoretical approach. After using the first model introduced in this thesis, the cumulative fatigue of the same asset was estimated at approximately 50% of the fatigue limit until 2083. That indicates that the remaining useful lifespan of that asset is larger when using the first model instead of the theoretical approach. In other terms, the theoretical approach is conservative regarding the remaining useful lifespan of the assets. Furthermore, the network of assets was optimized regarding cumulative fatigue across the assets of the network. As a result, the total cumulative fatigue of the network of assets is further decreased.

Recommendations

The sensitivity analysis of the results of the first model indicates that further research should be conducted to relax some assumptions made for this project. The directions of the proposed further research could include the relationship between airplane weight and bridge stress. The assumption of a linear relationship between weight and stress was made in this thesis, but further research should test this assumption. Moreover, another possible direction would be the relationship between fatigue, strength, and durability of a bridge which empirically identifies those variables to be independent. Before the exploitation of the monitored weights of the airplanes, the fatigue-related useful lifespan of each bridge was smaller comparer to the prediction of a useful lifespan based on the monitored weights of airplanes. The effect of this increase in the useful lifespan on the relationship between fatigue, strength, and durability of a bridge must be focused on in later research. In other terms, it is common to treat those attributes as independent based on the fact that the fatigue lifespan was the one prior to the new monitored-knowledge. As lifespan prediction changes, the common practice is not well-based anymore and further research on it is advised. Furthermore, more airplane data from the sensors should be gathered over a longer time. This data should be used to test the credibility and validity of the results of this project as well as to relax the assumption made for the A380s. The A380 is the heaviest type of aircraft in the scope of this thesis. Due to COVID-19 pandemic economic effects, the lack of data was dealt with by assuming that the weight of each A380 was as much as possible, namely their maximum take-off weight. Finally, the expenses of a bridge replacement should be costed. Therefore, the second model's objective function could include the cost and value depreciation of the assets. In other terms, the optimization of the model could refer to the solution that minimizes the total operation and maintenance cost of the network, instead of the cumulative fatigue across the network.

Preface Acknowledgements

This master thesis report marks the end of my studies in Operations Management and Logistics at the Eindhoven University of Technology (TU/e). The project has been supervised by Dr. Claudia Fecarotti and Dr. Melvin Drent from the TU/e, and Albert Reitsema from Heijmans.

First of all, I would like to express my sincere gratitude to my mentor and first supervisor, Dr. Claudia Fecarotti. Her extensive guidance, continuous encouragement, and positive attitude helped me through this challenging process. Her critical approach throughout the thesis steered me in the right direction when I needed it the most.

Besides, I would like to thank Albert Reitsema for the opportunity to perform my research within Heijmans and for his guidance throughout the complete project. I think his critical feedback and challenging questions helped me understand the complexity of the project and pushed the research to be better in every aspect. Moreover, I would like to thank all my colleagues at Heijmans for their contribution. They have endured my countless questions about their operations at the company and they were very enthusiastic about my research.

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1. Introduction

This research was based on a problem identified within Heijmans about the development of an asset management data-driven model and its implementation in the asset network of Schiphol Amsterdam airport.

1.1 Heijmans

Heijmans is a listed company that combines activities related to property development, construction, technical services, and infrastructure in the fields of living, working, and connecting. Their headquarters are in the southern part of the Netherlands in the town of Rosmalen. Approximately 4,700 employees work for Heijmans daily with their constant focus on quality improvements, innovation, and integrated solutions. Heijmans's competitive success lies in its ability to generate added value for its clients. This value is not just in the development and construction phases, but especially in the management phase. By managing to stay involved in their projects for longer and playing a significant role in maintenance and management after completion, Heijmans can find out more about the behavior of their end-users. They aim to learn from that and, respond through innovation by developing and implementing new services, which add value to their projects. Heijmans's focus involves innovation and improvement aimed toward a more sustainable future.

The activities of Heijmans, in the field of Living, Working, and Connecting are organized within the following four business areas:

- Property Development Business Unit. In the Netherlands, Property Development focuses on the area development of both large and smaller-scale projects in urban and out-of-town areas and acts as an initiator, developer, and seller of mainly residential properties.
- Residential Building Business Unit. The core activity of Residential Building is to build homes of several types. Activities consist of new-build, restoration, redevelopment, and renovation of existing housing stock.
- Non-Residential Business Unit. Non-Residential designs, realizes, and maintains high-quality electro-technical and mechanical installations. This realization consists of large-scale and complex construction contracts in customer and market segments of health care, government and semi-government organizations, commercial property, the high-tech clean industry (such as laboratories), and data centers.
- Infra Business Unit. Infra focuses on the construction, improvement, and maintenance of road infrastructure and public spaces in the Netherlands. This could include roads, viaducts, tunnels, and water treatment plants, but also technical work to make roads and public spaces safer, such as lighting and camera systems.

"Asset life", which is a part of the Infra business unit of Heijmans, is dedicated to enabling their clients to better understand, activate, and manage their assets while optimizing their asset management decisions. One of the clients of the Infra business unit is Schiphol Amsterdam airport. This airport has transferred most of the operational control of its assets to Heijmans for the next six years. The operational control includes the maintenance and management of all assets in the area of the airport, such as lighting, asphalt, concrete structures, and draining ditches.

1.2 Aviation in the Netherlands

According to The International Air Transport Association (IATA) (*The Importance of Air Transport to the Netherlands | 2*, n.d.), aviation's economic impact on the Netherlands' economy can be measured in three ways: (1) the jobs and spending generated by airlines and their supply chain, (2) the flows of trading goods and tourism, and (3) the city-connections.

Airlines, airport on-site-enterprises, aircraft manufacturers, and air navigation service providers employ 85.000 people in the Netherlands. Additionally, their expenses support 59.000 local suppliers' jobs and additional 33.000 jobs are created through those employees' wages spent on consumer goods and services. While foreign tourists arrive by air to the Netherlands and spend their money in the local economy, 129.000 more jobs are estimated to be supported, adding to a total of 306.000 jobs in the Netherlands. The air transport industry is estimated to support USD 16.9 billion of the GDP in the Netherlands, while tourism adds a further 7.9 billion. In total 3.2 percent of the country's GDP is supported by the air transport sector and foreign tourists arriving by air. Finally, the virtual bridges created by air connection between cities enable the economic flows of goods, investments, people, and ideas that drive economic growth. In Figure 1 some relevant to the connectivity of the Netherlands data is depicted, for example the top ten countries regarding the number of passengers who flew from and to the Netherlands are presented on the left side of the figure. The data from the figure was generated by The International Air Transport Association (IATA) in 2018.

Figure 1 Aviation connections of the Netherlands

1.2.1 Schiphol

The busiest airport in the Netherlands is the Amsterdam Schiphol airport, located southeast of the city of Amsterdam. Royal Schiphol Group owns and operates Amsterdam Airport Schiphol as well as Rotterdam The Hague Airport, Lelystad Airport, and has a majority stake in Eindhoven Airport. Their vision is to create the most sustainable and high-quality airports in the world, with an excellent airport infrastructure and facilities for passengers and cargo.

Schiphol airport was the third busiest airport in Europe after Heathrow and Charles de Gaulle, with over 71 million passengers in 2018 (*The Most Important Airports in Europe | ETIAS.Info*, n.d.). Moreover, Schiphol publishes a detailed economic report yearly. Figure 2 depicts the summary of

2021 report on Schiphol airport. In the bottom right of the figure, Return Of Equity (ROE) is highlighted with the value of -8.8% since the annual report of 2021 was in the middle of the COVID-19 pandemic. Some other worth mentioning data from the figure is the nearly ten billion € in assets and the approximately 267 thousand air transport movements at Schiphol in 2021.

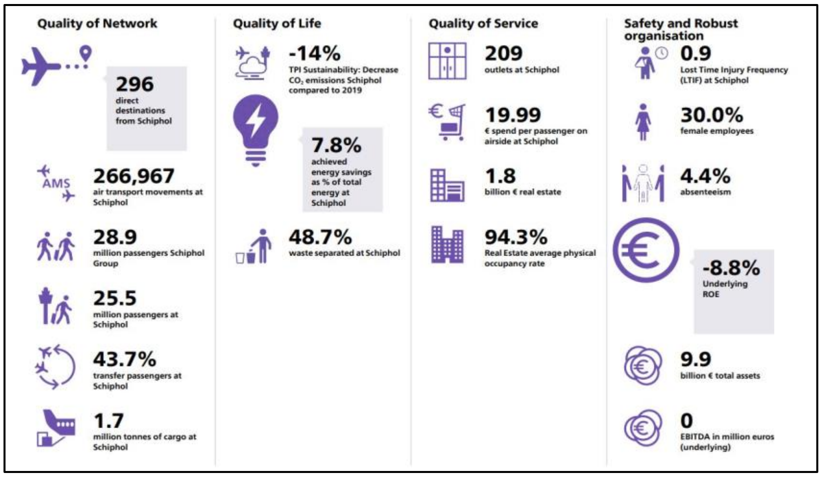


Figure 2 Annual report 2021

The assets of Schiphol were estimated at 9.9 billion EURO in the annual report 2021. Those assets cover the runways, roads, bridges, carriageways, terminals, fire stations, checkpoints, plantations, lighting, and more. The management of a subset of those assets was outsourced to Heijmans. Specifically, the management of the runways and road network, that airplanes use, were the most critical assets that Heijmans would manage. There are six runways in Schiphol, depicted in Figure 3. Those runways are used both as landing and take-off runways. This thesis's scope includes only the two western runways, namely runway-1 and runway-2. This is the case because the location of the bridges, which will be discussed later in the thesis, serves only the traffic from the airport hub to runways 1 and 2 and the traffic from runways 1 and 2 towards the airport hub.

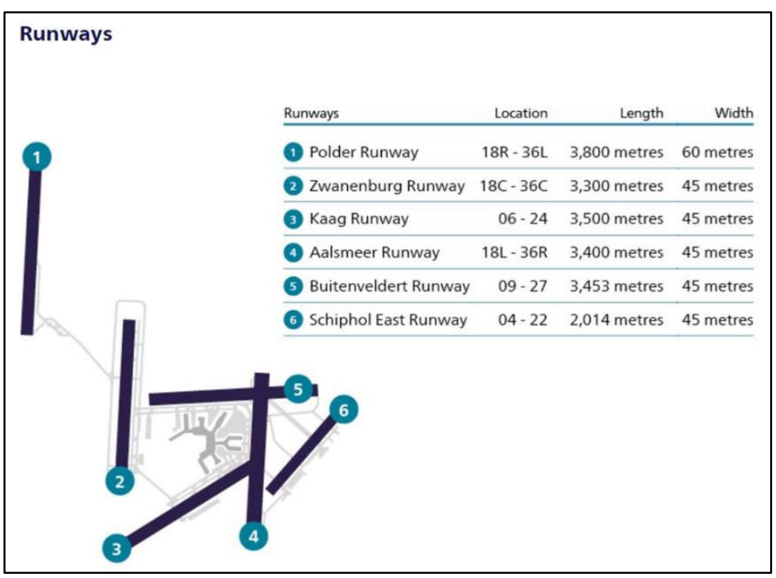


Figure 3 Schiphol's runways

1.3 Bridge's anatomy

In this section, a brief description of a bridge's components, as depicted in Figure 4, and their maintenance will be discussed. Firstly, every bridge consists of foundation piles, which are underground, and they support the whole structure. No maintenance is done for those piles throughout the lifespan of the bridge. On top of the foundation piles, one can find the pier and pier cap. The pier is visible above the ground level, and they connect the bridge deck to the ground below it. The maintenance operations for the pier are limited to repairing surface wear and cracks after annual visual checks.

Furthermore, the bridge deck may consist of the bridge deck slab and the span girders. The bridge deck slab is the most critical part of the structure. This is the case because it is the most expensive part, and it is meant to carry and divide the weight of the traffic crossing the bridge. Finally, the elastomeric bearing is located under the bridge deck, and it is there to support the bridge in a way that permits the load to shift slightly, in a horizontal direction, relative to the foundation. Without such bearings, the bridge support might crack due to thermal expansion and contraction. Those bearings are replaced every fifteen to twenty years.

The focus of this thesis will be the bridge deck and its preventive replacement because it is the most critical and expensive part of the bridge. Moreover, the innovative solution to calculate the actual loads of a structure, provided by Heijmans and discussed further in this research, is expected to affect the prediction of the lifespan of the bridge deck component of a bridge.

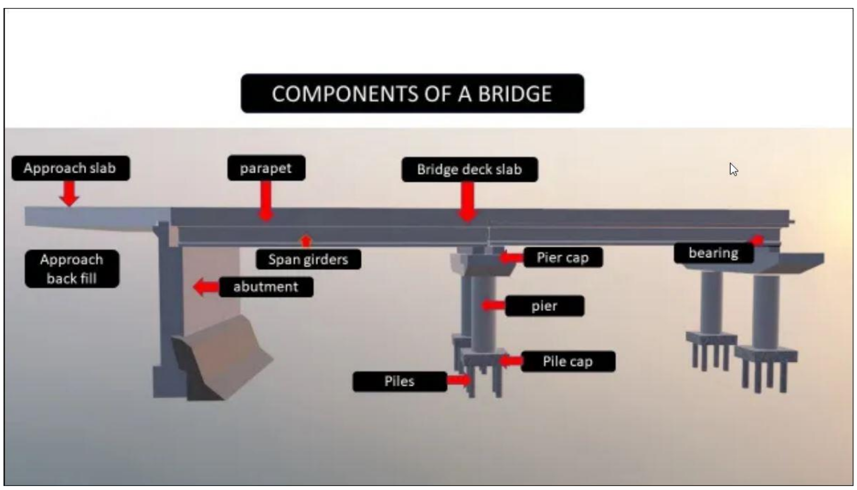


Figure 4 Typical Bridge

1.3.1 Replacement of a deck slab

In this section, information about the replacement of a bridge deck was briefly discussed. It was important to highlight some points obtained from the scientific area of civil engineering for a better understanding of the rest of this master's thesis.

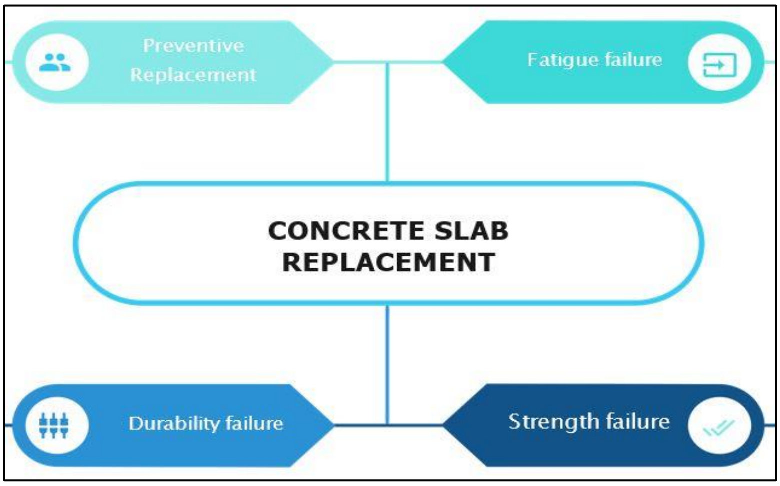


Figure 5. Concrete slab replacement

In Figure 5, the plausible causes of the replacement of a concrete slab (or a bridge deck) were depicted. There are three possible failure states resulting in the replacement of the slab. However, a concrete slab can be replaced before it fails. There are several reasons leading to a preventive replacement of a slab, such as maintenance-oriented or operational and economical decision-making. For instance, the need for increased width of a bridge for a new larger type of vehicle to be able to cross, which is an operational decision, might lead to the replacement of the concrete slab of that bridge. However, replacing a concrete slab due to visible decay is considered a preventive maintenance-related replacement.

On the other hand, replacing a concrete slab could be the result of the slab's failure. This failure is the consequence of one of the following reasons. Firstly, there is a strength-related failure. If an extreme force is applied to an object, it is possible that the object will not absorb or resist the stress and it will break. To tackle the risk of strength failure, the engineers make sure the physical characteristics of the chosen steel and concrete meet the required level of safety, during the design phase of the concrete slab. Furthermore, during and after the construction of the slab a series of non-destructive testing is applied to make sure the design requirements are met.

The second possible failure-related reason is durability. Durability measures the environmental impact on the slab, such as corrosion. Specifically, corrosion is the consequence of the steel within the concrete reacting to the molecules of air passing through the concrete. Corrosion of reinforcement leads to a reduced steel area which absorbs the stresses to which the material is subjected (Tuutti, 1982). Hence, the durability of a structure is known to be deteriorating over time. The rate of deterioration decreases as the concrete density increases because the denser the concrete the fewer air molecules pass through it.

Lastly, there is a fatigue-related failure. Fatigue is measuring the effect that repeated cycles of stress have on the object. Specifically, fatigue may be defined as a process of progressive and permanent internal damage in a material subjected to repeated loading (H. Li et al., 2007). When the permanent internal damage reaches a critical limit, named fatigue threshold, then the object breaks. Hence, the fatigue performance of concrete slabs is influenced by parameters such as loading conditions, load frequency, number of cycles, and mechanical properties. Fatigue is considered an irresistible consequence for concrete slabs while preventive replacement remains the only way to avoid fatigue failure. Pedersen suggests and explains in detail how the fatigue of an object is highly dependent on many other factors besides just the material (Melters Pedersen, 2018). Those factors include material strength, mean stress, surface roughness, size, and environmental effects. Corrosion is among the environmental effects discussed. However, in practice strength, durability, and fatigue are considered to be independent features while designing and evaluating concrete slabs.

1.4 Heijmans monitoring system

One of the projects that are ongoing in the Asset life unit is dedicated to developing a condition monitoring system for bridges and tunnels in Schiphol Amsterdam airport. This monitoring system is currently applied to three bridges that support aircraft commuting/traffic. Two of those bridges are built in 1965 and the third one was built in late 2021. The monitoring system collects everyday data from the two older bridges from the middle of 2019 until the present, while the new bridge had been monitored from the start of its life.

Under those bridges, sensors have been placed strategically. Those sensors measure the bending caused to the bridge's deck by the crossing airplane. When an aircraft crosses a bridge or a tunnel, the structure bends to absorb the force caused by the weight of the passing aircraft. By measuring the bending of the deck, Heijmans can estimate the actual weight of the crossing airplane.

This sensor-based monitoring system provides a constant flow of data from each of the three bridges that are being monitored. This data includes the bending caused to the bridge and after applying a calibrating algorithm, it translates to the expected actual weight of the crossing airplane. From the raw data obtained from the sensors, graphs of the bridge's operation are created. Those graphs include the daily number of aircrafts crossing each bridge and the weight distribution of aircrafts using each bridge. Heijmans's vision is that the data collected over several upcoming years will provide researchers and managers with valuable resources to make informed decisions for the maintenance and replacement of the structures by predicting future structure behavior.

Heijmans future goal is to install this sensor-based monitoring system in all the structures in the Schiphol airport, including bridges and tunnels. By collecting data from every structure, Heijmans will be able to predict the future behavior of every structure. Moreover, they will be able to suggest certain operational strategies to Schiphol to minimize the total cumulative fatigue across the network of assets, hence maximizing the network's availability. Those operational strategies could be for example the appliance of a weight limit for the airplanes allowed to cross each bridge.

1.5 Bending moment and stress

Before analyzing the methodology and result of this thesis it was considered necessary to discuss the theory behind structural fatigue in this sub-section. While an airplane crosses a bridge, the weight of the airplane causes the bridge' deck to bend. The moment of maximum bridge bending is called the bending moment in the civil engineering literature. This bending moment is used to calculate the stresses within the structure. Those stresses within the structure are the result of compression forces on the top side and dilation forces on the bottom side of the bridge deck. These stresses within the deck slab create micro-cracks that cannot be repaired. The cyclic repetition of the load on the bridge deck by multiple airplanes results in growing those micro cracks. Finally, those micro-cracks are known to civil engineering literature as structural fatigue. In the case of Schiphol airport, the civil engineering department has already calculated the stresses within the deck slab due to airplane load on the bridge. The result of their endeavor is summarized in Table 3 and Table 2, which will be discussed in detail in section 4.1.

1.6 Network of three bridges

During the time this research was conducted, Heijmans had installed their monitoring system under three bridges. In Figure 6, the map view of Schiphol is depicted, while the network of the three monitored bridges is located inside the red circle. Alternatively, in Figure 7, that network is presented as a three-dimension picture for better understanding through visualization. As shown in Figure 7, the network consists of two bridges, which we refer to as bridge 1 and bridge 2 connected in series, and one bridge in parallel, which we call bridge 3. This research was based on the monitoring and management of this network.

Figure 6 Schiphol map (the network of three bridges in red circle)

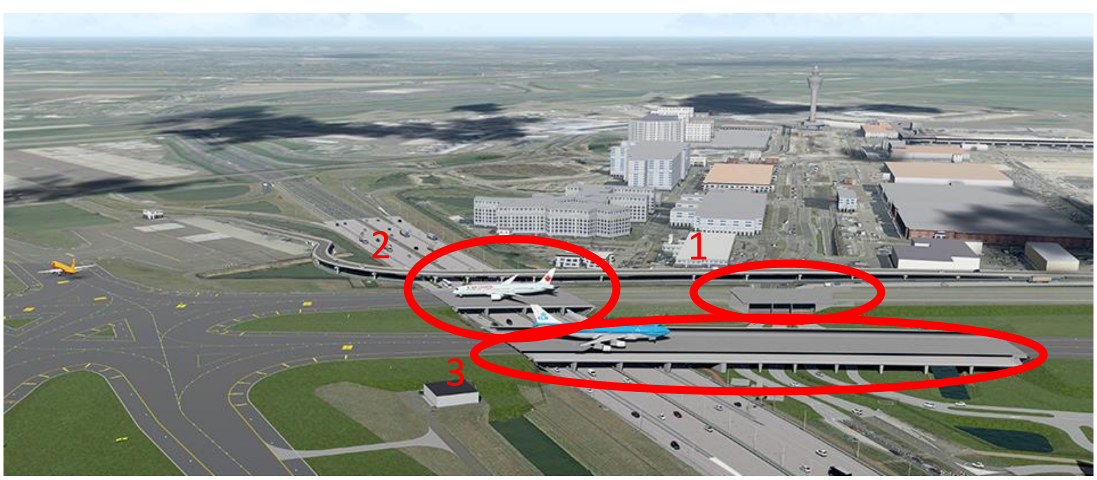


Figure 7 Picture of the network of the three bridges

2. Problem definition

Until recently, bridge structural health monitoring systems were not widely accepted or used. The main difficulty was the needed collaboration between civil, mechanical, electrical, and computer engineering, combined with some other challenges (distributed and embedded sensing, data management and storage, data mining and knowledge discovery, diagnostic methods, and presentation of useful and reliable information to bridge owners/managers for decision making on maintenance and management) (Ko & Ni, 2005). Hence, the structural health prediction was limited to theoretical equations provided by Eurocode (*EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings*, 2004), traffic predictions, and conservative weight assumptions. The exploitation of sensor data for managerial purposes is the main problem that this thesis is trying to tackle. In other words, how can the data from the monitors be effectively used to improve the management of Schiphol's bridges and tunnels?

2.1 Schiphol's assumption

The assumption made by Schiphol to compensate for the lack of monitoring was about the estimation of each bridge's load. The lack of knowledge of the actual load of each bridge by Schiphol, was the result of the confidential information of the private airlines. Every private airline has data on the actual number of passengers, total weight of luggage, and fuel within every one of their airplanes. This data is not shared due to confidentiality. Hence, the assumption made by Schiphol was that every airplane would be estimated to weight as much as possible. Every airplane has a designated maximum take-off weight. This number is allocated by the design team of the airplane's manufacturer, and it is the maximum weight that an airplane could weigh to be able to take-off. This characteristic is shared with the public for every type of airplane flying to and from Schiphol.

The assumption used by Schiphol to estimate the weight of the planes crossing each bridge, was that the airplane would weight 100% of its maximum take-off weight before take-off, and 75% of its maximum take-off weight after landing. The decreased estimation of weight after landing compared to the one before take-off was due to fuel consumption. Specifically, the 25% weight decrease was considered a safe assumption for the fuel burnt during the duration of the flight by Schiphol. Identifying a structural load estimator, the weight of the airplanes, and predicting the future airplane traffic crossing each asset, were the two needed steps to predict the future fatigue of the bridge using the concrete fatigue equations (*EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings*, 2004).

2.2 Monitoring raw data and benefits

The monitoring system provides real-time measurement data in a CSV file format. However, the provided data is collected and provided in a raw form. One entry in the data consists of a timestamp, a specific date and time, and an estimation of the weight of the airplane that crossed the bridge at that timestamp. In other terms, the sensors output different values of weights for the crossing airplanes, but the aircraft types of the crossing planes were unknown. Therefore, the first part of the research aimed to resolve the fact that the data from the monitoring system had to be translated to useful weight distributions, which were explained in sub-section 4.3.3. However, the translation of the monitor system data was not the only problem that this research aimed to resolve.

By applying monitoring to the assets of Schiphol, the actual load of the assets can be estimated less conservatively. This was the value proposition of the business model presented to Schiphol by Heijmans before Schiphol decided to outsource its asset management to Heijmans. Heijmans monitoring system, presented in section 1.4, was meant to provide measurement data to estimate the actual load of the bridges and tunnels in the network of Schiphol's assets.

To better understand Heijmans' value proposition, the ratio of the estimated plane weight and its maximum take-off weight was formed. This ratio was introduced to provide a visual impression of the weight distribution of the airplanes crossing bridge 1. Figure 8 depicts the scatterplot of the ratio for distinct types of airplanes. Each dot on the scatterplot represents an airplane that was monitored and linked to one specific weight class. Distinct types of planes have different maximum take-off weights, which is the horizontal axis of Figure 8. While the ratio's value is closer to 1, it means that the airplane is closer to its maximum take-off weight. Schiphol's assumption was more accurate the closer the scatterplot points were to 1 along the maximum take-off weight axis. The data used for creating this figure were produced by comparing GPS data from Schiphol air traffic control and Heijmans' monitoring system across the duration of three months, namely July, August, and September of 2021. Before interpreting the finding in the scatterplot, it is necessary to highlight that the data was gathered from a period when the COVID-19 pandemic had a huge negative impact on aviation across the globe (Suau-Sanchez et al., 2020).

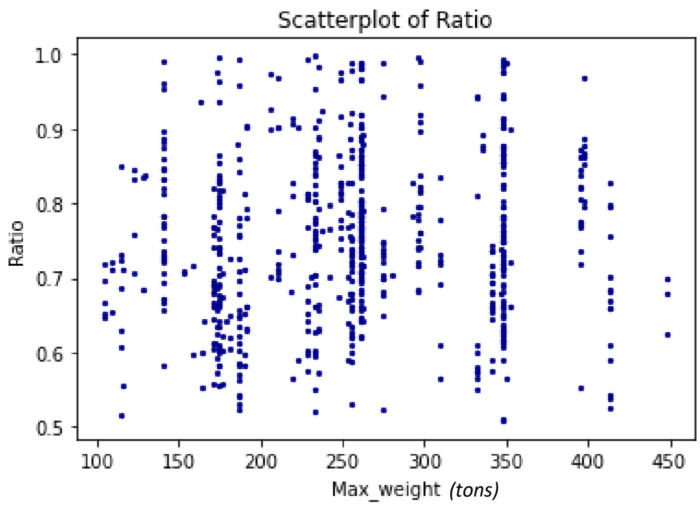
In Figure 8, the horizontal axis range is between 100 and 450 tons, whereas the vertical axis ranges from 0.5 to 1. Ratio cannot be higher than 1 because of the technical limitation that every plane must weight at most its maximum take-off weight. The smaller value of the vertical axis range was selected such that the airplanes weighting less than half of their maximum take-off weight were considered outliers. In Table 1 the minimum (operating empty weight) and maximum (maximum take-off weight) of five aircraft types are presented. The operating empty weight is the sum of the 'as built', plus any standard items and any operator items. One can see that all five types of airplanes' minimum weight are approximately a bit less than half the weight of their maximum value. That is the reason that any ratio less than 0.5 was considered an outlier.

AC-type	Operating empty weight (tons)	Maximum take off weight (tons)
B767-300	82	182
MD11ER	125	266
B747-400	180	397
B767-8	220	450
A380	277	600

Table 1 Minimum and maximum airplane weight

For the horizontal axis, the range was selected in a way to include the heavier types of airplanes since the fatigue impact of the heavier airplanes is exponentially larger than the one caused by lighter airplanes, explained further in this research as equation (1). Moreover, the 450 tons mark was the maximum take-off weight of the heaviest type of airplane measured within the three months that this data was gathered. For this scatterplot, all airplane data, regardless of inbound or outbound state, was used. The only difference between inbound and outbound planes is that the maximum take-off weight is multiplied by a factor of 1 for the outbound and with a factor of 0.75 for the inbound, as explained in the previous sub-section.

Looking at Figure 8, it is noticeable that most airplanes with the same maximum take-off weight had an average ratio value lower than 1. Therefore, the assumption made by Schiphol that every plane would be treated as weighting their maximum take-off weight was considered conservative and a limitation of the current fatigue prediction approach.



$$Ratio = \frac{Monitored\ weight}{Max\ take\ off\ weight}$$

Figure 8 Ratio scatterplot

2.3 Network application

Despite gathering data, its usage was limited to visualization purposes, as exemplified in Figure 9. In that figure, the estimated weight distribution of all airplanes that crossed bridge 1 in 2019 is depicted as a histogram. The vertical axis depicts the number of airplanes monitored, while the horizontal axis depicts the estimation of weight in tons.

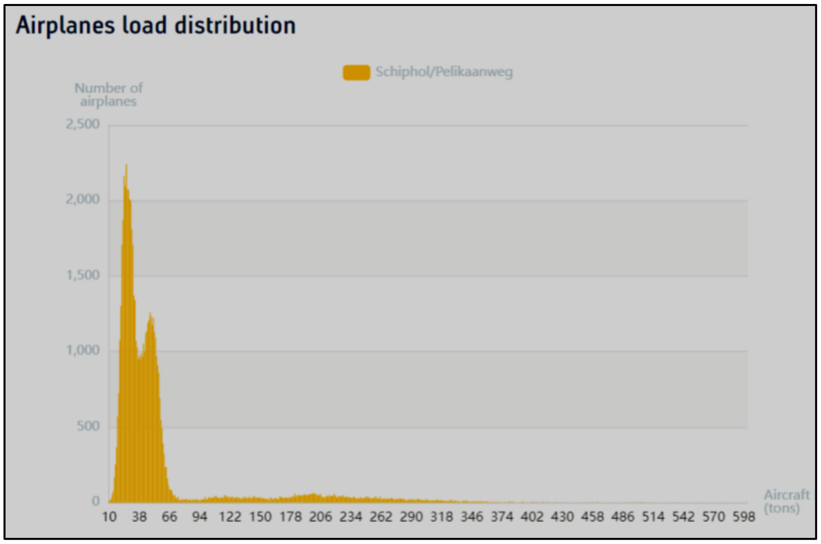


Figure 9 Visualization of monitoring data, weight distribution of all planes crossed in 2019

The exploitation of the data for managerial purposes was missing from the value proposition of Heijmans. Therefore, the future goal of Heijmans and the goal of this thesis are focused on the design and implementation of a network application model. The network is referred to the sub-set of assets that are being monitored in Schiphol's set of assets, while the application model refers to the management of the airplane traffic to reduce the cumulative fatigue of the bridges. Specifically, the model in question would use the monitoring data from Heijmans' monitoring system from multiple assets, forming a network, to allocate airplane traffic such that the cumulative fatigue of those assets is minimized. The network application model is described in detail further in this thesis, in section 5.

2.4 Research questions

Based on the problem identified in the previous paragraphs this research aimed to accurately design and implement an optimization model for the minimization of the total fatigue across the network of three monitored bridges in Schiphol, by allocating the airplane traffic across the assets of that network. This model would find the operational strategy such that the cumulative fatigue of the network of assets would be minimized. The operational strategy refers to the operational constraints applied to each asset. For instance, bridge 1 would not allow any airplane heavier than 400 tons to cross. Based on the aims of the research, the following main research question was formulated:

> *How can data-driven prediction of structural fatigue for each monitored bridge, within the asset network of Amsterdam Schiphol airport, be realized using the Heijmans monitoring system? Additionally, how can these predictions be used to minimize the cumulative fatigue of the network of the three monitored bridges based on different operational policies?*

For the realization of the model, further assumptions and data comparisons had to be made. Firstly, the raw data collected from the monitoring system would be translated into another form, which can be used to produce different weight distributions. Secondly, those weight distributions would be simulated to produce a unique variable for the fatigue of a bridge caused after the crossing of one airplane of a given type. Finally, the set of possible operational strategies for the network of the three bridges would be identified. Subsequently, the network model would use the results of those unique variables to find the optimum out of the set of operational strategies. Based on the main research question, the following sub-questions are formulated:

1) *How much does the structural fatigue prediction for bridge 1 differ when using the data from the sensor-based monitoring system compared to the theoretical approach, namely with the assumptions about the weight of the inbound and outbound airplanes (see section 2.1)?*

The first sub-question would be answered by the implementation of a model that exploits the monitoring data of one asset, in that case, bridge 1 was considered, to update its fatigue prediction. After the creation of such a model, the comparison of the cumulative fatigue prediction between the proposed model and the theoretical approach can be achieved.

2) *Given the network of three bridges, how can we optimize the allocation of traffic volume to minimize the total cumulated fatigue across the network?*

Based on the one bridge fatigue prediction model, a network management model will be created to answer the second sub-question. The network model will allocate airplane traffic such that the total cumulative fatigue prediction of the network's assets is minimized.

3) *By comparing the network of the three bridges with and without using the network management model, how does the fatigue prediction for each asset within the network change?*

Subsequently, the comparison of the assets' fatigue prediction between the network model and the one bridge fatigue prediction model will be depicted. The third sub-question will be answered by depicting the fatigue prediction of each asset based on given operational strategies at a time. Namely, the optimum set of traffic rules scenario will be compared to the scenario where no specific strategy is followed.

4) *How sensitive are the results of the monitoring data exploitation, obtained from the one bridge fatigue prediction model to the necessary assumptions made?*

The sensitivity analysis for the fourth sub-question will be limited to three areas. Firstly, the sensitivity of the cumulative fatigue estimation concerning a change in the unique weight distribution of each weight class will be investigated. Subsequently, the analysis will be focused on the volume of the traffic prediction, whereas its final part is dedicated to the A380's assumption.

3. Literature review

3.1 Fatigue and Eurocode

Biondini & Frangopol (2017) surveyed the life-cycle performance of civil structures and infrastructure systems. The type of infrastructure systems in question with the largest appearance rate in this survey was bridges. Aging, fatigue or cyclic loading, and overloading were in the top five hazards for structures as they were rated in the survey. According to this survey, there is a significant gap between research advances and practical implementation in this field since there are no specific regulations, and engineering practices do not utilize life cycle concepts. One of the biggest drawbacks identified in this survey is the lack of data from both existing structures and experimental tests, which is crucial for a successful implementation in the practice of life-cycle methods. Additionally, inspection and monitoring activities are found to be powerful methods for reducing epistemic uncertainty, improving prediction accuracy, and decreasing the level of epistemic uncertainty.

Fatigue is measuring the effect that repeated cycles of stress have on the object. Specifically, fatigue may be defined as a process of progressive and permanent internal damage in a material subjected to repeated loading (H. Li et al., 2007). When the permanent internal damage reaches a critical limit, named fatigue threshold, then the object breaks. Hence, the fatigue performance of concrete slabs is influenced by parameters such as loading conditions, load frequency, number of cycles, and mechanical properties. Fatigue is considered an irresistible consequence for concrete slabs while preventive replacement remains the only way to avoid fatigue failure. Pedersen suggests and explains in detail how the fatigue of an object is highly dependent on many other factors besides just the material (Melters Pedersen, 2018). Those factors include material strength, mean stress, surface roughness, size, and environmental effects. Corrosion is among the environmental effects discussed.

Each bridge is unique based on its geometrical and material characteristics. Eurocode is the source where all standards of design and evaluating structures can be found. The equations that will be used in the thesis were obtained from the Eurocode after the instruction of the civil engineering department of Heijmans. The suitability of the fatigue equations and the stress-to-load relationship were considered out of the scope of this research. Hence, there is no part in this literature review to argue the choices of those equations.

3.2 Single-bridge application of monitored data

Cheng and Frangopol (Cheng & Frangopol, 2021) introduced a decision-making framework for the inspection and replacement of a highway bridge. Their approach was focused on the girders of the bridge. Each girder had its own Markovian degradation process. Matrices of girders states were presented where each state denoted the age and the deterioration of one girder. Their research assumed that the girders would fail at most after 75 years made by AASHTO (2018). The deterioration states were obtained from load rating factors. Those factors reflect the relation between the remaining capacity of the bridge components and its external loads. After the identification of the matrices, the cost minimization of the inspections and replacement was achieved by deep reinforcement learning. The cost of each inspection, the replacement of components, and the operation under the failure state were presented before the analysis of the deep reinforcement learning algorithm used to find a near optimum solution. That solution included the time step for the next inspection. After the inspection, the algorithm would have reidentify the new time step for the next inspection. The goal of this research was the minimization of life-cycle cost of a single bridge and its maintenance.

Peng et al. (2020) conducted research where the multi-objective optimization of maintenance planning for a deteriorating bridge was formulated. The objective functions were separated in maximizing the safety, minimizing the maintenance direct cost, and minimizing the social and environmental impact. The random field theory was selected to identify the performance distribution of the bridge based on the worst performing random field (district component). Then live load effect was formulated as a non-stationary stochastic process followed by Li et al. (2015). The maintenance direct cost included the essential and preventive maintenance. In other terms, the total cost of direct maintenance was the addition of the number of essential and preventive maintenance actions, multiplied by the discounted cost per respective action. The cost of different maintenance strategies was assumed by multiplying the construction cost by a certain proportion. Furthermore, the social impact included the increased running cost, the increased travel time cost, and the increased accident cost due to detours. The state of the bridge due to maintenance, for instance the partial lane closure or full bridge closure, affected the factors of those costs. The goal was the minimization of the summation of those costs. Finally, the environmental impact was formulated as the CO_2 emissions related to the production and transportation process of materials used including the effect of traffic detour. For the multi-objective optimization, the heuristic of non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002) was used followed by a fuzzy analytic hierarchy process and linear programming techniques for multidimensional analysis of preference. Namely, the pareto frontier was identified by NSGA-II. The fuzzy analytic hierarchy process was used to calculate the weight of different objectives. Finally, the linear programming techniques for multidimensional analysis of preference were used to identify the best solution from the pareto frontier based on the Euclidean distance of the infeasible best solution. Altogether, the maintenance policy of the bridge was identified based on the assumed cost factors and assumed social and environmental impacts.

BWIM (Bridge Weigh-In-Motion) systems provide a tool for the collection of statistical data on the weight of the traffic crossing a bridge, introduced by Moses F. (1979). The goal of that tool was to identify the overweight trucks while also estimate the gross weight of any crossing vehicle. Lydon et al. (2017) introduced a power saving sensor based BWIM by using fiber optic sensors. The major drawback of the BWIM systems is the inability to deal with multiple vehicles at the same time. Another, disadvantage lays on the fact that test runs must take place with every type of vehicle. These test runs must include different representative vehicles with known gross weight. Those vehicles cross the bridge in different speeds in order to calibrate the sensors output. Then the least square method is used, with the large number of measurements, to filter out the influence of the bridge’s dynamic oscillation. The increasing academic and managerial attention on sensor systems is the result of the information on traffic loading that can enable efficient and economical management of transport networks. It is the information on traffic loading that can enable efficient and economical management of transport networks that has increased interest in sensor systems among academics and managers. By using BWIM, one can determine if the reduced capacity of deteriorating bridges is still sufficient to allow them to remain operational while minimizing unnecessary replacement and rehabilitation costs and preventing traffic disruptions based on site-specific traffic loading on deteriorating bridges.

Liu et al. (2009) presented a safety evaluation of existing bridges based on monitored data collected from structural health monitoring (SHM) systems. Specifically, they introduced two random variables that correspond to condition and prediction function respectively. The prediction function predicts the future data (values of the two variable) from the SHM system, based on the given SHM data. Specifically, histograms of stresses from different crossing vehicles were created. Then, distributions of estimated bridge stresses were created which were used to predict the future stress on the bridge. One of the key findings of this research was that the monitoring data must cover a period long enough to consider the effects of the deterioration of structural capacity. In any other case, the loading effect may dominate the predicted future SHM data.

As the volume of goods to be carried increases, and bridge owners become increasingly concerned about the loading of bridges, Ghosn (2000) developed a formula to update the truck weight regulations. Specifically, a new approach of estimating the maximum allowed weight of the truck for each bridge was introduced based on the reliability model of that bridge. The type of bridge and its span length were the criteria by which each bridge's safety factor was selected. The output of this research was a new approach to increase the maximum allowed truck-weight while keeping a uniform level of safety over all span lengths for each bridge. The impact of heavy trucks on highway bridges was the scope of research conducted by Zhao et al. (2017). Moreover, Vigh & Kollár (2007) developed an algorithm to determine the safety of bridges subjected to overweight vehicles. The algorithm can also be used within a network of bridges in order to identify the route of an overweight vehicle which maximizes the safety of the bridges within the network.

This chapter contributes to the thesis in a couple of ways. Firstly, just like Liu et al. (2009) unique weight distributions are used to predict future conditions. Secondly, after reviewing this literature, the concepts of monitoring and the uniqueness of each bridge were clarified. Finally, no research was found about bridges crossed by airplanes. Those bridges differ from the highway bridges mainly because the load that they are experiencing is bigger due to the heavier weights of airplanes compared to trucks.

3.3 Bridge Network management

Liu & Frangopol (2006b) developed a decision-making framework that cost-effectively allocates limited budget to the maintenance of a network of highway bridges. They focused on time-dependent structural reliability prediction, highway network performance assessment, and life cycle cost analysis through the optimization of three objective functions, namely maintenance cost, bridge failure cost, and user cost. Thy used genetic algorithms to solve their multi-objective model. They achieved the prioritization of maintenance resources towards the deteriorating bridges by simultaneously minimizing their three objective functions. Other research was focused on the multi-objective optimization based on the average annual maintenance and replacement cost and the percentage area of structural deficient deck (Shim & Lee, 2017). On the other hand, the multi-objective optimization of minimization of bridge repair and reinforcement costs, minimization of disruption to social activities due to bridge maintenance, and maximization of resilience against natural disasters was the goal of another conducted research (Ishibashi et al., 2020). Bocchini & Frangopol (2011) used the uncertain reliability index profiles of bridges in the bridge-network in Santa Barbara, California, USA to identify the in/out states of the network. Afterwards the used genetic algorithms to minimize the total present maintenance cost while maximizing the network performance indicator. Sustainability and maintenance and operations costs can also be used as conflicting criteria of a data driven decision making model (Dong et al., 2015).

Liu & Frangopol (2005) conducted research for a network-level bridge maintenance planning problem. The network of bridges that they investigated is in the northwest metropolitan area of Denver, Colorado. Their problem's definition was the identification of a pareto optimal maintenance planning for the bridge network. The bi-objective function used referred to the value of the network connectivity reliability over the time horizon of 30 years and the present value of total maintenance costs. In other terms, their study aimed to prioritize limited financial resources to maintain the connectivity of the bridge network. The network in question was assumed to have the 13 highway bridges as its only vulnerable elements, in other words the roads connecting the bridges were not included in that research's scope. The connectivity reliability was calculated by an event tree analysis, where each branch was identified as connected or disconnected while having the unique state of every bridge in the network. The states were defined as binary variables, the bridge was either functioning or had failed. Then the network disconnectivity probability was obtained by adding the probabilities of all disconnected branches. The reliability of each bridge was estimated based on performance limit state functions for structural component reliability analysis using the AASHTO specifications (American Association of State Highway and Transportation Officials (AASHTO), 1996). Moreover, it was assumed that there were four different maintenance types. The estimate of each effect and cost were also provided. The optimization of their bi-objective was achieved by using genetic algorithms. This research resulted in many solutions that consisted of a pareto frontier. Each of the solutions had a 30-year maintenance planning for each bridge that would minimize the network disconnectivity probability given a specific budget.

Liu & Frangopol (2006) introduced a mathematical model for probability-based bridge network performance evaluation. Bridge network connectivity, user satisfaction, and structural reliabilities of the critical bridges in the network of fourteen bridges in a regional highway network in Colorado were the criteria out of which a total numerical evaluation for each bridge was obtained. The bridge connectivity was evaluated by an event tree analysis. Each bridge had two possible states ("failure" or "survival") and each branch of the tree had two possible outcomes, either "connected" or "disconnected". The connectivity of the network was developed by identifying some nodes that needed to be connected by "survived" bridges. The numerical output referred to the overall performance of each bridge was recognized as unfitting to be the objective function of an optimization model. On the other hand, the optimization was achieved by maximizing the probability of network connectivity while minimizing the probabilities of unsatisfactory performance of the bridge network in terms of user satisfactory and structural reliability.

No literature was found where the traffic allocation was used to minimize the fatigue of the bridges. However, other optimization parameters were reviewed and discussed. For example, Liu & Frangopol (2006) decided to find the solution to their mathematical problem that minimized the probabilities of network connectivity, user satisfactory, and structural reliability. Whereas Liu & Frangopol (2005) decided to find the pareto frontier of optimal solutions based on the bi-objective function of maintenance present cost and network connectivity reliability. In terms of this thesis, the objective function is the total fatigue of the bridges in the network and it is minimized based on the airplane traffic allocation. The most relevant literature to this thesis's problem was conducted by Vigh & Kollár (2007). They developed an algorithm which can be used within a network of bridges to identify the route of an overweight vehicle which maximizes the safety of the bridges within the network.

4. Data exploitation

In Figure 10, this project's process diagram is depicted. There are three distinct colors within the diagram. The blue textboxes referred to the input data, in other terms the information and data that was provided by Heijmans and Schiphol. Secondly, the white textboxes referred to the research conducted during the project. Finally, the green textboxes referred to the results of the research.

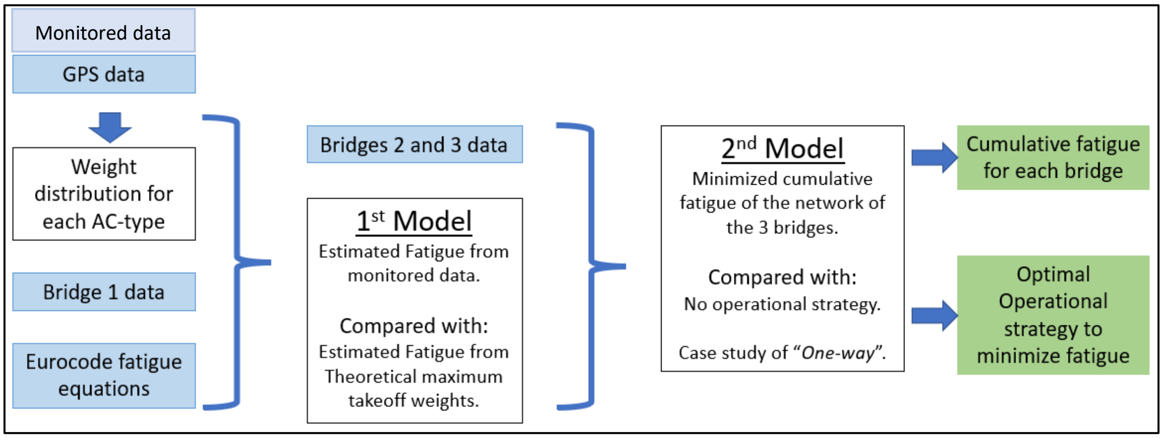


Figure 10 Process diagram of the thesis' project

In this section the process used for translating data from the sensors to useful managerial results and graphs for a given bridge will be given. The aim of this section is summarized in the first part of Figure 10, which was isolated in Figure 11. The first sub-section was aimed to provide the background of the blue shapes in Figure 11, which consisted of the information and data collected and used. The investigation of the suitability of the fatigue equations given by the Eurocode and Heijmans' civil engineering department is out of the scope of this thesis. In the second sub-section, the theoretical approach is explained. The theoretical approach referred to the methodology used by Schiphol before the introduction of the Heijmans monitoring system and its benefits. The rest of the sub-sections explain the methodology, assumptions, results, and results' sensitivity analysis, colored in white in Figure 11.

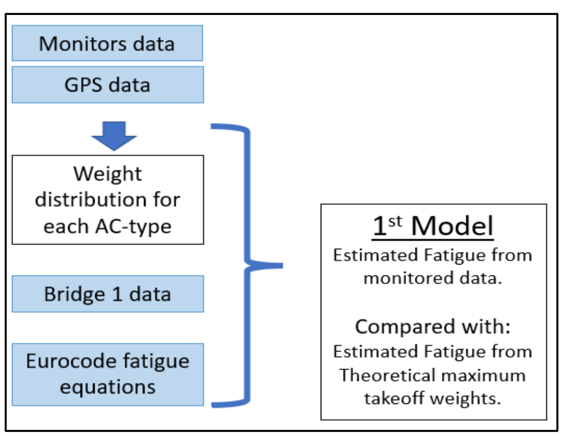


Figure 11 First part of the process diagram

4.1 Given data

As mentioned in section 2, the stress caused to bridge 1 by the weight of each passing aircraft must be calculated. For this purpose, data were collected by the structural engineering department of Schiphol to link the weight of the crossing airplane to the stress of the bridge deck slab. The engineers concluded that the concrete fatigue was governing for bridge's 1 deck slab. This was not the case for bridge 3 which is discussed in section 5.1. The outcome of their endeavor was summarized in the following tables.

AC-type	Max weights (tons)	
	Outbound	Inbound
B767-300	182	137
MD11ER	266	215
B747-400	397	298
B767-8	450	338
A380	600	450

Table 2 Maximum take-off weights of each plane type

In tables Table 2 and Table 3, there are five different aircraft types that were examined. Those aircraft types were selected by the structural department of Schiphol as the representatives of five weight classes respectably. Each airplane type has a unique maximum take-off weight based on the construction manual provided by its manufacturer. The B767-300 represents the lighter aircrafts while A380 represents the heaviest aircrafts departing and landing in Schiphol. Moreover, in Table 2 the distinction between outbound and inbound flights was made. The inbound airplanes are lighter on average compared to the outbound ones. This holds true because the fuel needed for the duration of the flight is still in the airplane before departure, but it has been consumed by the time the airplane has landed. This was the reason for dividing each aircraft type into two categories. After the division, the weight classes were formed. For instance, the outbound airplanes with a maximum take-off weight lighter than 182 tons were categorized in the weight class B767-300 outbound.

In Table 3, the stress factors of bridge 1 are stored. Every representative aircraft type of the weight classes, that were discussed earlier, creates a stress $\left({}^{N}/_{mm^2}, or\ MPa\right)$ within the bridge deck slab as explained in sub-section 1.5. Those stresses are created within the bridge's structure by the weight of the crossing plane. These stress factors were used to translate the estimated weight of a crossing plane to bridge fatigue, as explained later in this thesis. The same stress factors were used for each aircraft within the same weight category. Those stresses were calculated based on the maximum take-off weight of the representative airplanes of each weight class.

AC-type	Stress factor (N/mm2)	
	Outbound	Inbound
B767-300	11	9.5
MD11ER	13	11
B747-400	15.7	13
B767-8	17.4	14.2
A380	18.4	14.8

Table 3 Bridge's stress factor related to each plane type

In Table 4, the historical data and future prediction of bridge's 1 traffic are presented. This figure was part of a big data set provided by Schiphol, where the traffic prediction from the year 1965 until 2083 is divided into ten different weight classes of airplanes. The data from this table was used as the traffic prediction for the rest of the thesis. A noteworthy characteristic of this dataframe in the asymmetry between the inbound and the outbound flights. In other terms, the total predicted the inbound number of flights until 2083 is larger than the total number of predicted outbound flights until 2083. As mentioned in the introduction, Schiphol has six runways and only two of them are connected to the airport hub through bridge 1. Therefore, it is safe to assume that Schiphol decided to use those two runways more frequently as landing rather than take-off runways.

$$Fatigue\ of\ 1\ plane = 10^{-\left(\frac{10}{\sqrt{1-\frac{6.4}{Stress}}} * \left(1-\frac{Stress}{31.88}\right)\right)} \tag{1}$$

Finally, the fatigue equation (1), was provided by Eurocode (*EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings*, 2004). This equation translates the stress within a concrete structure to fatigue for bridge 1. This fatigue equation holds when concrete related fatigue is governing. Moreover, the uniqueness of each bridge results in a different fatigue equation. For example, bridge 2 where also the concrete fatigue is governing has a slightly different equation, see section 5. Alternatively, when the steel fatigue within the deck slab is governing, a different equation must be used to calculate fatigue, as in bridge 3, section 5.1. Fatigue is dimensionless and it ranges from 0% to 100%, where the latest signals the structural fatigue failure.

	OUTBOUND gewicht 100% MTOW					INBOUND gewicht 75% MTOW				
jaar	B767-300 182 ton	MD11ER 286 ton	B747-400c 397 ton	B747-8 450 ton	A380 600 ton	B767-300 137 ton	MD11ER 215 ton	B747-400c 298 ton	B747-8 338 ton	A380 450 ton
1965	5.583	0	0	0	0	7.048	0	0	0	0
1966	6.115	0	0	0	0	7.719	0	0	0	0
1967	6.824	0	0	0	0	8.614	0	0	0	0
1968	7.445	0	0	0	0	9.398	0	0	0	0
2077	61.572	2.437	1.513	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2078	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047
2079	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047
2080	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047
2081	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047
2082	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047
2083	61.572	2.437	1.513	6.810	757	80.077	3.240	2.093	9.419	1.047

Table 4 Airplane traffic volume prediction

4.2 Current approach to fatigue prediction

The used methodology, before introducing the sensor data, assumed that every outbound aircraft's weight would be their maximum take-off weight, while the inbound ones would weigh 25% less than their maximum take-off weight. This approach was based on the weight classes that were introduced in Table 2. Hence, it was assumed that every aircraft that crossed the bridge would weigh as much as the representative aircraft of their weight class. From this point in this thesis, the current approach to fatigue prediction will be mentioned as a theoretical approach.

For example, imagine an airplane with type A320, given a maximum take-off weight of 77 tons, will cross bridge 1 going from the runway to the airport hub, known as inbound. Because it is inbound, one can assume that their maximum weight at that time would be 25% lighter than the maximum take-off weight, or 58 tons. By looking in Table 2, this airplane is listed in the weight category of B737-300 Inbound with a representative maximum weight of 137 tons. Afterward, to calculate the fatigue caused to the bridge's deck slab, from equation (1), one must use the stress of 9.5 MPa from Table 3 looking at the weight category representative B737-300 inbound.

To predict the structural fatigue of bridge 1, Schiphol used the weight representatives of Table 2, with their appointed stresses, Table 3, while translating their stresses to fatigue by equation (1). The result of their method is presented in Figure 12.

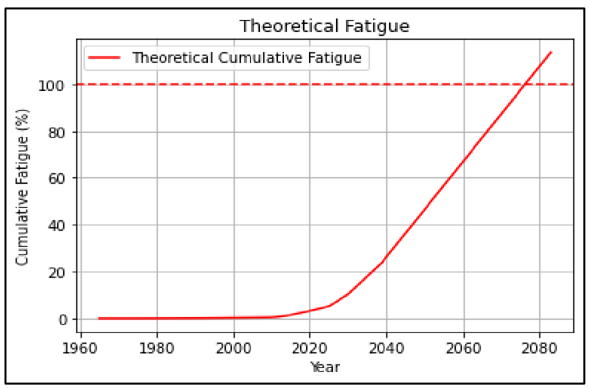


Figure 12 Theoretical Fatigue prediction

Figure 12 represents the prediction of bridge's 1 fatigue from the year 1965 to 2083, based on the prediction of traffic volume by Table 4. By reviewing the result, bridge 1 should be replaced by the year 2077. The dotted red line indicates the 100% fatigue mark, where the structure would be considered unsafe due to fatigue failure.

4.3 Estimating fatigue based on real-time measurement data

In this section, the estimation of the bridge's 1 deck slab fatigue by using the data from the Heijmans monitoring system is explained. Firstly, the data translation process, from monitor data to unique weight distributions for every type of airplane, is discussed. Subsequently, the needed assumptions are listed followed by reasoning and examples. Eventually, the results are presented supported with a comparison with the theoretical approach discussed in the previous sub-section.

4.3.1 Monitoring system and GPS control data

A dataframe is a data structure that organizes data into a 2-dimensional table of rows and columns, much like a spreadsheet. In Table 5, Table 6, and Table 7 parts of two dataframes are presented. The two dataframes in question, which refer to the data from the monitoring system and the air traffic control based on GPS, were provided by Heijmans and Schiphol, respectively.

Table 6 and Table 7 were created by separating the whole dataframe from the GPS air traffic control data into the inbound and outbound flights. The reasons behind this separation were the ease of understanding and the methodology used while modeling the problem at hand. The dataframe has many columns from which most of which are outside the scope of this project. The important, for this project, columns in Table 6 were the “mtow” (maximum take-off weight), “aibt” (Actual In-Block Time), and “aldt” (Actual Landing Time) from the first dataframe that refers to the inbound flights. Additionally, in Table 7 the important columns were “mtow” (maximum take-off weight), “aobt” (Actual Off-Block Time), and “atot” (Actual Take Off Time).

On the other hand, Table 5 contains the information gathered from the sensors. There are only two columns in the table, namely “timestamp” and “weight”. The timestamp is the exact time that the system of sensors has picked the bending moment of the bridge’s deck slab. Whereas the weight column contains the output of the sensors which is an estimation of the crossing airplane’s weight.

Timestamp	Weight
2021-07-01 02:55:11.428Z	119.73
2021-07-01 03:16:25.455Z	258.73
2021-07-01 05:18:19.985Z	138.02
2021-07-01 05:43:28.366Z	59.49
2021-07-01 06:48:34.668Z	51.33
2021-07-01 06:53:07.014Z	22.09

Table 5 Monitor system air traffic dataframe

id	ac_type	des_rwy	mtow	aibt	aldt
5976870	B38M	18R	83	1-7-2021 01:45	1-7-2021 01:32
5976871	B734	18R	69	1-7-2021 02:00	1-7-2021 01:48
5976878	A332	18R	233	1-7-2021 03:00	1-7-2021 02:46
5976882	B748	18R	448	1-7-2021 03:20	1-7-2021 03:02
5976907	A333	18R	233	1-7-2021 05:23	1-7-2021 05:05
5976919	B752	18R	105	1-7-2021 05:45	1-7-2021 05:35

Table 6 Inbound flights from air traffic control GPS dataframe

id	ac_type	dep_rwy	mtow	aobt	atot
5976927	B738	36L	75	1-7-2021 06:42	1-7-2021 06:56
5976979	E75L	36L	37	1-7-2021 06:43	1-7-2021 06:58
5976984	E75L	36L	37	1-7-2021 06:47	1-7-2021 07:01
5976990	B738	36L	76	1-7-2021 06:52	1-7-2021 07:06
5977012	E195	36L	53	1-7-2021 07:12	1-7-2021 07:33
5977037	B748	36L	448	1-7-2021 07:32	1-7-2021 07:50

Table 7 Outbound flights from air traffic control GPS dataframe

After separating the dataframe from air traffic control (GPS) into inbound and outbound flights, the comparison with the monitor system dataframe was achieved. The algorithm used for this comparison is explained in the following paragraph.

The timestamp in Table 5 was used to find potential matches in the air traffic control dataframe. This was achieved by looking at each flight’s needed time to cross the bridge contained in the air traffic control dataframe. This time period is delimited by columns “aldt” and “aibt” in Table 6, and “aobt” and “atot” in Table 7. The potential matches, for each row of Table 5, are the rows of Table 6 and Table 7 which happen to include table’s 4 timestamp within their time period. After identifying those potential matches, the ones with maximum take-off weight smaller than the weight estimation of the sensors, Table 5 column weight, were not considered as potential matches anymore. This is because an airplane cannot weight more than its maximum take-off weight. After identifying the potential matches and confirmed that the weight estimation did not exceed the maximum take-off weight, one potential match would be picked as the final match.

In case there was just one potential match, the algorithm would choose that one as the final match. In case there were zero potential matches found, then that row would be considered as an outlier and would not be used further in this process. Otherwise, when more than one potential matches were found by the algorithm, the one with the smallest difference between its maximum take-off weight and the monitor's weight estimation would get selected. The scenario of multiple potential matches is the result of heavy traffic and overlapping between the time periods in Table 6 and Table 7. The decision of the one match with the smallest difference between maximum take-off weight and weight estimation was based on safety. By taking the smallest difference it was assumed that the airplane was as full as possible within the options that were available. For instance, imagine the weight estimation of a crossing plane to be 350 tons and the potential matches would have been one outbound A380 (mtow is 600 tons Table 2) and one outbound B747-400 (mtow is 397 tons Table 2). The algorithm used would pick the B747-400 as the final match as it would be the smallest difference of mtwo and weight estimation of the two potential matches. By doing so, the crossing plane will be considered to be a B474-400 weighting 350 tons, in other terms nearly full, instead of a A380 weighting 350 tons, in other terms nearly empty. By making this choice, the weight distributions that were created and explained later in the thesis would have been more conservative in favor of safety.

4.3.2 Assumptions

The data set used for this project was collected during the period of the COVID-19 pandemic. During the pandemic, most airlines were facing economic difficulties due to the lack of aviation passengers and regulations aimed to prevent the spread of the virus. That resulted in planes flying half-empty or even empty at times. Most of the airlines decreased the number of flights to the minimum regarding each airport's policy. In Schiphol, A380 was the largest and most heavy airplane that landed and took off by the time this research was conducted. During the period the data was collected, no A380 landed or took off from Schiphol. Therefore, the assumption of considering each A380 weighting as much as their maximum take-off weight was made. For instance, 757 airplanes of type A380 were predicted to be outbound from Schiphol in 2083, Table 4, all of which would be considered weighting as much as their maximum take-off weight of 600 tons, Table 2.

By the time this research was conducted, the only mention of traffic weight estimations using sensors in the literature was the reference to the sensors on the surface of the road. Those sensors measure the weight of a vehicle that is touching vertically, with all its wheels, the surface of the sensor. For the exploitation of the output of those sensors, Eurocode has introduced a safety factor of 15% to be applied to the weight estimation (output) before it is used for structural fatigue or strength calculations (*EN 1990: Eurocode - Basis of Structural Design*, 2002). The same 15% safety factor was used for this research because it was the most similar, to Heijmans's bridge monitoring system, instruction of the Eurocode. The estimated weight of the crossing airplanes was increased by that factor after identifying its final match, as explained in sub-section 4.3.1. Altogether, the weight estimation of the sensors was increased by 15%.

Furthermore, Heijmans provided their estimation of the error in the sensor's output in the form of a table, Table 8. In that table, there are three classes of weight and one column, "95% Interval", which contains the increase of the weight estimation that ensures 95% confidence. For instance, if the weight estimation by the sensors would be 300tons, then increasing that estimation by 9.36% $(300tons * 109.36\% = 328tons)$ would ensure that 95% of the times the estimation would be equal or greater than the actual weight of the plane that crossed the bridge.

Weight Categories	**95% interval**
[0-65 (tons)]	16.06%
[65-200 (tons)]	10.20%
[+200 (tons)]	9.36%
Average	13.83%

Table 8 Error of the sensors

The sensors' error is a random error because it is equally likely for the estimation of the weight of an airplane to be higher or lower than its actual weight. Even though the random error is treated only as added variance in most cases, in this scenario it would not be correct to do so. The sensors are estimating the weight of an airplane, then the weight is translated to the bridge's 1 deck fatigue by equation (1). Due to the exponential nature of the equation, when the error of the sensors is considered random, the transferred error to fatigue is systematic. An example will be used to better understand the sensor error transferred to fatigue. A simulated weight distribution of 2200 airplanes was created. Each of the airplanes' weight is created based on a normal distribution with a mean of 250 tons and a standard deviation of 20 tons. Figure 13 depicts the weight distribution of those 2200 airplanes, while Figure 14 depicts the distribution of the weight difference between each airplane and the mean (250 tons). The mean of the weight error is close to zero, meaning that the weight error is random.

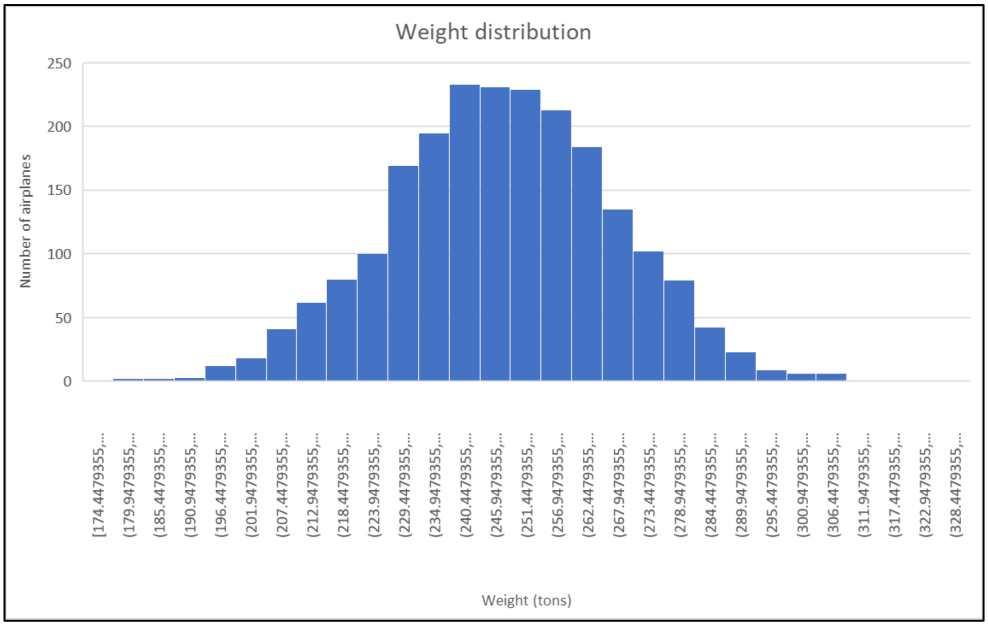


Figure 13 Simulated weight distribution μ=250tons σ=20tons

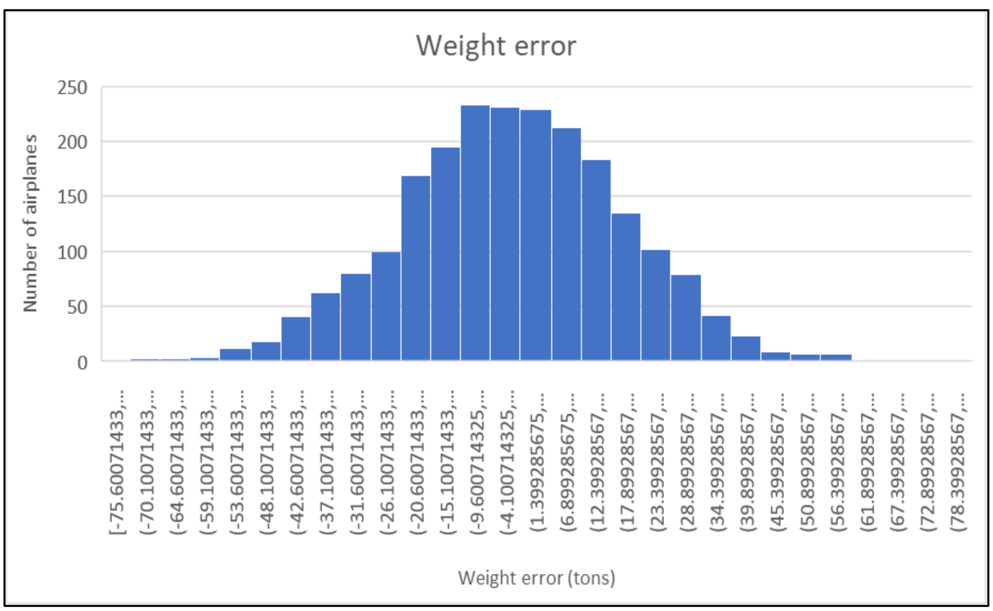


Figure 14 Distribution of error (μ-x)

The weight of the airplanes is then translated to stress (explained in sub-section 4.3.4) and then to bridge's 1 deck fatigue (by equation (1)). By doing so the distribution of the fatigue depicted in Figure 15 was created. An airplane that weighs 250 tons, which is the mean weight of the distribution, would cause an 8.76083E-10 level of fatigue to the bridge's 1 deck. The fatigue error is calculated by subtracting the 8.76083E-10 from the fatigue of each simulated airplane. The result of this subtraction is presented in Figure 16. The mean of the fatigue error is 4.27754E-10 which stands for 32% of the mean fatigue (1.30384E-09). In Figure 16 the zero is pointed with the red line and the mean fatigue error is pointed with the green line. By applying a test hypothesis that the mean of the fatigue error is zero, $\frac{\bar{x}-0}{\sigma-\sqrt{n}} = 15.27$, the p-value is 0. This concludes that the random weight error is translated to systematic fatigue error.

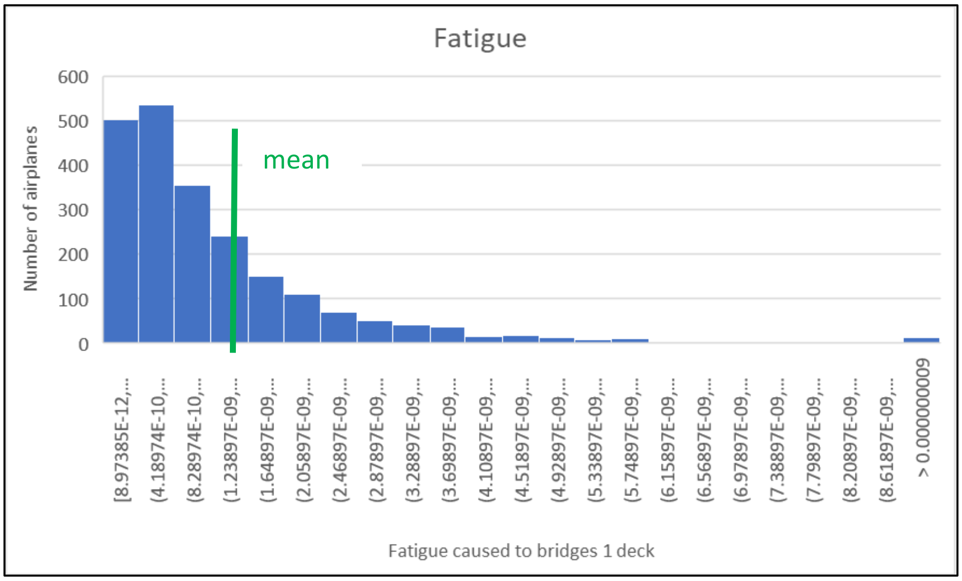


Figure 15 Simulated distribution of fatigue to bridge's 1 deck

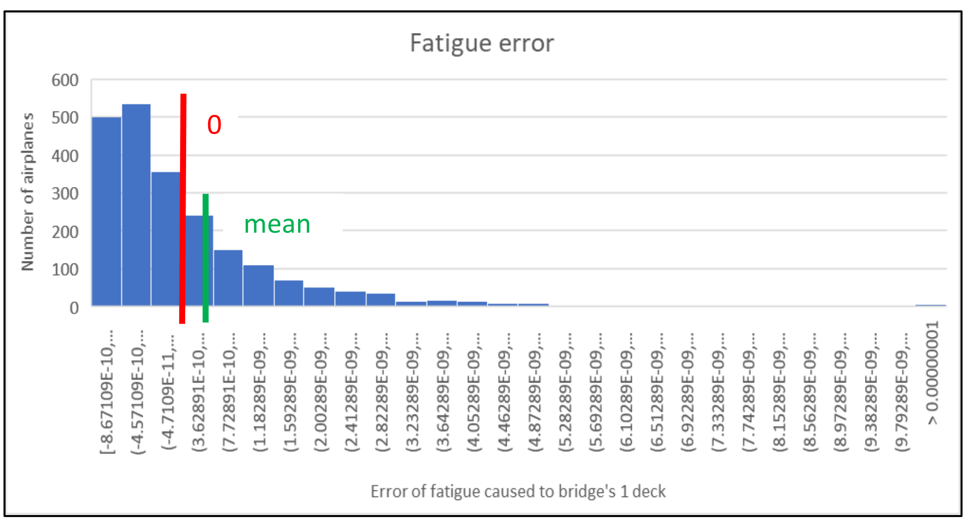


Figure 16 Fatigue error (X_fatigue – μ_fatigue)

It is a widespread practice in structural engineering to apply safety factors in structural calculations. Therefore, the factors of the column "95% interval" were used as increasing factors to the weight estimation provided by the sensors to reduce the probability of a fatigue structural failure before the prediction of the upcoming model.

4.3.3 Weight distribution of aircrafts

In the following graphs, the weight distributions for eight weight classes are presented in histograms. This section was dedicated to the presentation and explanation of the weight distributions of each weight class. However, the last most heavy classes of A380 (inbound and outbound) are missing. As stated in the previous sub-section, the assumption that all the A380s weigh as much as their maximum take-off weight was made. Hence, all the outbound A380s were considered to weigh 600 tons and the inbound A380s 450 tons.

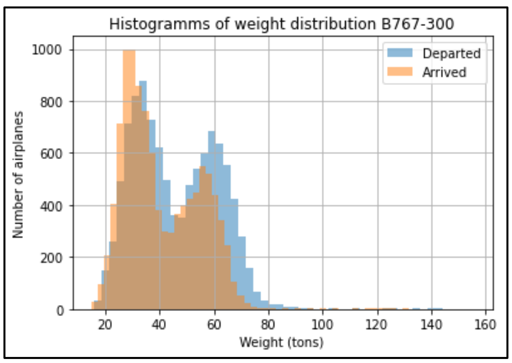


Figure 17 Weight distribution of B767-300

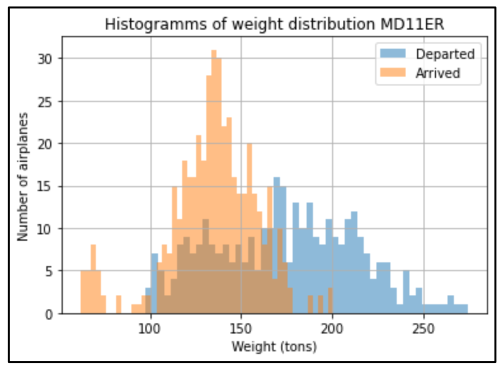


Figure 18 Weight distribution of MD11ER

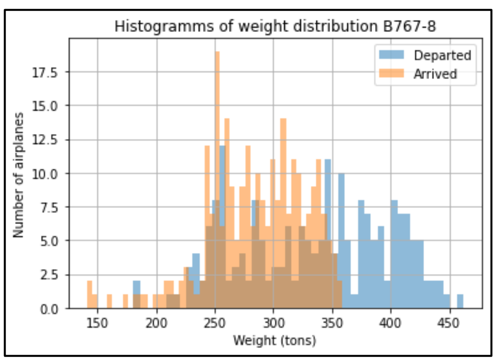


Figure 19 Weight distribution of B767-8

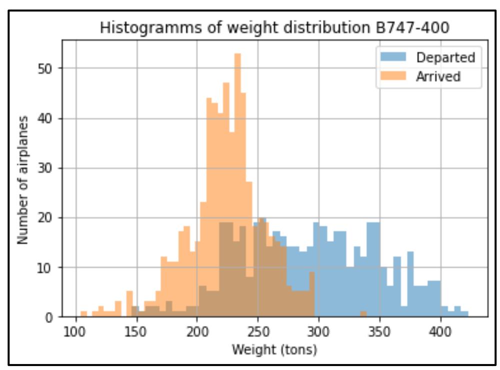


Figure 20 Weight distribution of B747-400

Figures 12-15 depict the weight distribution of eight weight classes. Each figure presents two histograms, with orange color for the inbound/arrived and with blue color for the outbound/departed of each aircraft type. Those histograms represent the number of airplanes and their monitored weight for each weight class. In every figure, the blue histograms tend to be shifted to heavier weights compared to the orange histograms. This was expected as the departed airplanes weigh more due to the fuel not yet consumed. These weight distributions were used to calculate the probability functions of the estimated weight of each airplane of each weight class.

4.3.4 Weight to stress regression

After the creation of the unique weight distribution for each of the ten weight classes (including A380s), the way to translate the weight of a crossing plane to the stress within the bridge's deck slab had to be formulated. Heijmans civil department suggested that the relation of stress and weight could be modeled as linear, but had to be separated into two classes, namely the heavy aircrafts (over 450 tons) and the not-so-heavy ones (lighter than 450 tons). The heavy airplanes' class consisted of the A380s, and the other class was formed by grouping the rest of the aircraft types.

Linear regression was applied to formulate the equation needed to translate all weight estimations, except A380s, to stress within the bridge's deck slab, as depicted in Figure 21. The regression was a result of eight points within the axis. Those points came from Table 3. Specifically, each point in the figure represents the maximum weight of a weight class with the corresponding stress applied within bridge 1. Owing to the fact that the sample size of this regression was small one can conclude that this regression is one of the limitations of this research. Even though the sample size was small, in Figure 21 the result of the regression is depicted as well as the equations used to translate the weight of crossing airplanes to stress within bridge's deck slap. The results of this regression can be found in Figure 41 in the appendix.

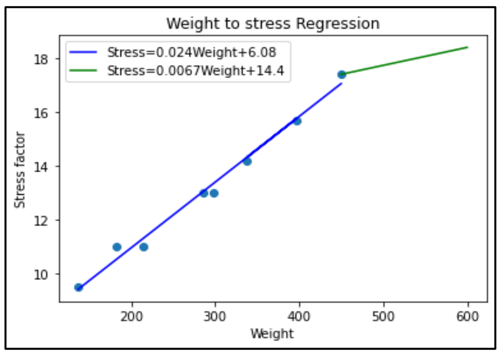


Figure 21 Weight to stress regression

4.3.5 Fatigue of a single-plane variable

After identifying the unique weight distributions and the equations for translating airplanes' weight to stress within the bridge's deck slab, the introduction of a variable to denote the fatigue caused to the bridge's deck slab was the next step. This variable stands for the estimated fatigue within the bridge's deck slab caused by one crossing airplane of a given weight class. There are ten different weight classes identified in Table 2. The weight distribution of each of the weight classes was explained in sub-section 4.3.3. The equations for translating the weight to stress were created by the linear regression in the previous sub-section. Finally, equation (1) was used to translate the stresses at the bridge's 1 deck slab to fatigue.

The mean and variance of the fatigue variable, fatigue caused to the bridge's deck slab by a single airplane passing for each weight class, were estimated by a Monte Carlo simulation. Particularly, one million airplanes for each weight class were simulated based on the weight distribution of that weight class. The weight of each of the one million planes was translated to stress and then to fatigue by equation (1). Hence, after simulating all eight weight classes, excluding A380s, eight new variables were created for the expected fatigue caused to the bridge's deck slab by a random airplane from each of the eight weight classes. Those variables' means and variances were calculated.

The A380 outbound and inbound are the two classes that have a mean but no variance. By assuming that all A380s would weigh as much as their maximum take-off weight, the variance in their weight distribution is zero and the mean is their maximum take-off weight. Therefore, the fatigue variable for the weight classes inbound A380s and outbound A380s had no variance, and their means were calculated by translating their maximum take-off weight to stress and that stress to fatigue.

4.4 Results

As a concise summary of the methodology used and assumptions made so far, one could say that the process from input data to the unique distributions and identification of fatigue variables was explained. The next step of the project was to combine the constructed fatigue variables with the traffic prediction of bridge 1, Table 4.

Each crossing plane causes fatigue to the bridge. The bridge fatigue caused by a plane is a random variable with known mean and variance, which are dependent on the weight class of that plane. Moreover, the number of planes was given in Table 4. Central Limit Theorem states that when independent random variables are summed up, their sum tends toward a normal distribution even if the variables are not normally distributed. Moreover, the larger the sample size, the closer to a normal distribution the sum of the independent random variables is. In this case, Table 4, the sample size was more than 130 million independent flights for the year 2083. Therefore, by using the Central Limit Theorem, the cumulative estimated fatigue of the bridge's deck slab was calculated.

Let us define:

x_i: Independent variable indicating the fatigue caused to bridge's 1 deck slab by a random crossing airplane of weight class i (there are 10 different weight classes).

n_{iz}: The total number of all planes that crossed the bridge by time z.

$$E(x_i)_z = \frac{\sum_{j=1}^{n_{iz}} x_{ij}}{n_{iz}}$$

$E(x_i)_z$: The mean of the fatigue variables at time z.

$$V(x_i)_z = \frac{\sum_{j=1}^{n_{iz}} \left(x_i - E(x_i)\right)^2}{n_{iz} - 1}$$

$V(x_i)_z$: The variance of the fatigue variables at time z.

$$Cumulative\ fatigue_z \sim N\left(\sum_{i=1}^{10}\sum_{j=1}^{n_{iz}} E(x_i)_z, \sum_{i=1}^{10}\sum_{j=1}^{n_{iz}} V(x_i)_z\right)$$

$Cumulative\ fatigue_z$: The cumulative fatigue of the deck slab at time z.

4.4.1 Comparison

In Figure 23, the comparison of the Theoretical approach explained in sub-section 4.2, and the estimated cumulative fatigue is depicted. The red continuous line refers to the cumulative fatigue of the bridge's 1 deck slab calculated by the theoretical approach. The dotted red line indicates the 100% fatigue point, also known as the estimation of the structural fatigue threshold. The green continuous line specifies the estimated cumulative fatigue calculated as explained in the previous subsection. The blue and light blue dotted lines hint at the 99% confidence interval of the estimation. The green continuous line and the blue and light blue dotted lines are hard to distinguish. The hard distinction is the consequence of the big sample used in the simulation for identifying the variance of each fatigue variable. Finally, the green dotted line points out the estimated fatigue level of bridge's 1 deck slab in the year 2083, which is the last year of the available prediction dataframe (Table 4). In this figure, one can notice that the bridge's 1 replacement would not be mandatory by the year 2083 by using the estimated cumulative fatigue. In contrast with the theoretical approach, which indicates that bridge 1 must be replaced by the year 2077 because the cumulative fatigue level in that year would pass the 100% mark.

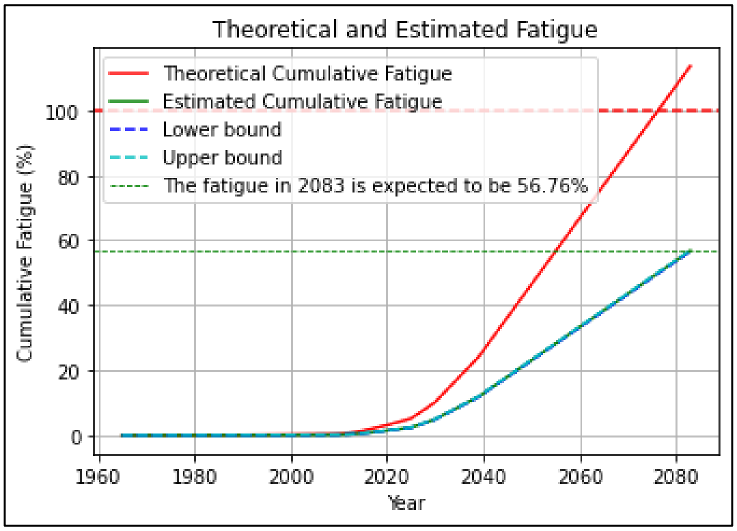


Figure 23 Theoretical vs Estimated cumulative fatigue

To better understand the results, an assumption was made to increase the traffic prediction data. It was assumed that from the year 2083, a yearly growth factor of 1% was applied to the predicted number of airplanes of each weight class. In Figure 22 the comparison between the Estimated cumulative fatigue and cumulative fatigue by the Theoretical approach is depicted. Moreover, another assumption was made, stating that before the cumulative fatigue passes the 100% level, the bridge would be instantly replaced by an identical bridge with 0% cumulative fatigue, in both cases. By following the theoretical approach bridge 1 would have to be replaced five times until the year 2200, yet only twice by using the estimated cumulative fatigue approach introduced by this thesis.

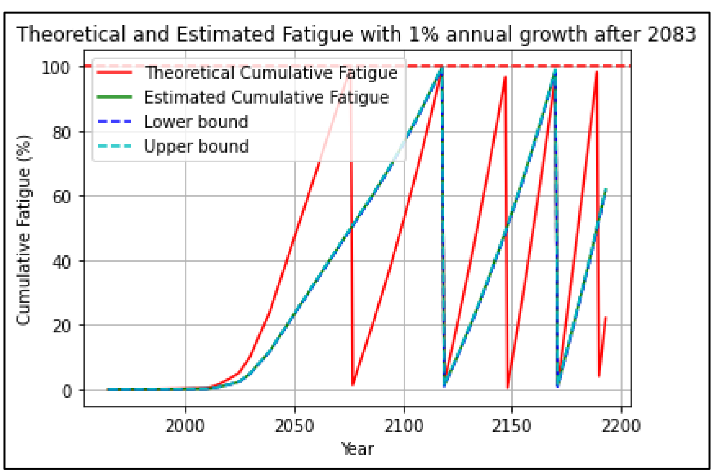


Figure 22 Estimated vs Theoretical fatigue until 2200 growth assumption

4.4.2 Sensitivity analysis

This sub-section provides the sensitivity analysis of the results presented previously. The sensitivity analysis consists of three parts. The first part illustrates the sensitivity of the cumulative fatigue estimation with respect to a change in the unique weight distribution of each weight class. The second part is focused on the volume of the traffic prediction, whereas the third part is dedicated to the A380's assumption.

4.4.2.1 Weight change

The question asked for this sub-section was how much the cumulative fatigue of the bridge's 1 deck slab would change if the average weight of the planes within a weight class would increase by a factor. Due to the COVID-19 pandemic impact, it was taken into consideration that the available data would consist of lighter airplanes in general than usual. Figures from Figure 25 to Figure 27 depict the answer to that question. For each of the following figures, the average weight of that specific weight class was increased by a factor (1%,2%,5%,10%, and 25%). It is noticeable, by looking at the figures, that the change in the three lighter weight classes (simultaneously increase in inbound and outbound) was not impactful to the cumulative fatigue of the bridge's 1 deck slab. Conversely, the effect of the increased average weight of the airplanes within the B767-8 classes (inbound and outbound) was significant. This result was expected due to the exponential relationship between stress and fatigue, see equation (1). As a result, the same increase in stress has a different impact on fatigue depending on the values of stress. For instance, the increase of 1 point in stress from 6 to 7 (Mpa) would have a lower impact on fatigue compared to the same increase from 10 to 11 (Mpa). Moreover, the weight to stress relation was assumed to be linear for the airplanes with a maximum take-off weight lower than 450 tons. Subsequently, the heavier the aircraft the bigger the impact on the bridge's 1 deck slab's fatigue. Altogether, the same increase in the weight for different weight classes was expected to have a different impact on fatigue, as confirmed by figures from Figure 24 to Figure 27.

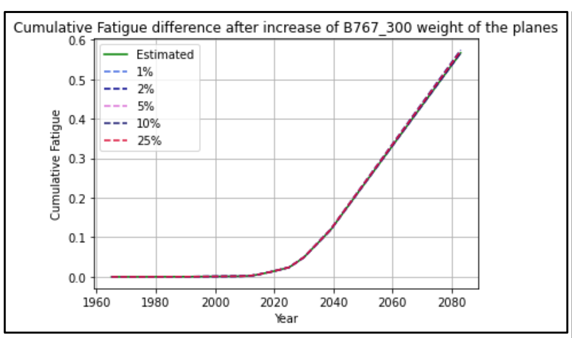


Figure 24 Sensitivity of weight increase B767-300

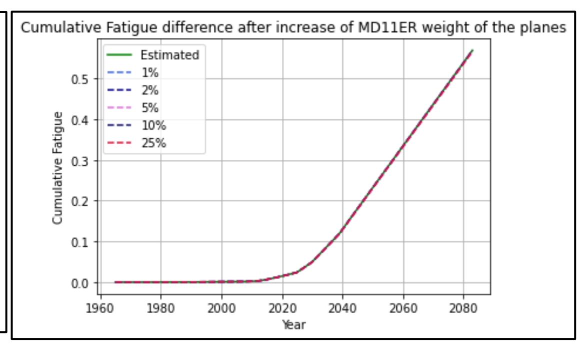


Figure 25 Sensitivity of weight increase MD11ER

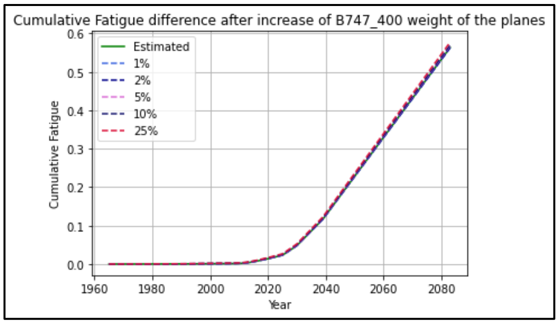


Figure 26 Sensitivity of weight increase B747-400

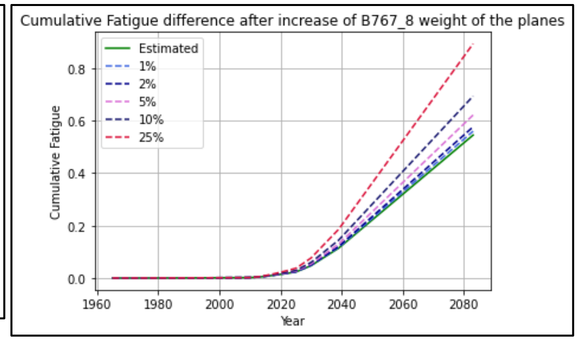


Figure 27 Sensitivity of weight increase B767-8

Figure 28 was created to better understand the increase in weight introduced in figures from Figure 25 to Figure 27. Specifically, the 25% increase in weight was tested for the B767-8 weight classes (inbound and outbound). Namely, when the weight of each of the airplanes in those weight categories was increased by 25%, new weight distributions had to be created. Following the same procedure as explained in sub-section 4.3.3, two histograms were created for inbound and outbound flights, respectively. The difference in that scenario was that every airplane's weight was increased by 25%. However, the maximum weight of those planes was limited by their maximum take-off weight. For example, if an airplane after the 25% increase to its weight estimation was weighing more than its maximum take-off weight, then the maximum take-off weight would be picked as its weight. In Figure 28 one can notice four columns dominating the two histograms. Those columns represent the maximum take-off weight of the two aircraft types within this weight class. The 25% increase in weight results in most of the airplanes reaching their maximum take-off weight limit.

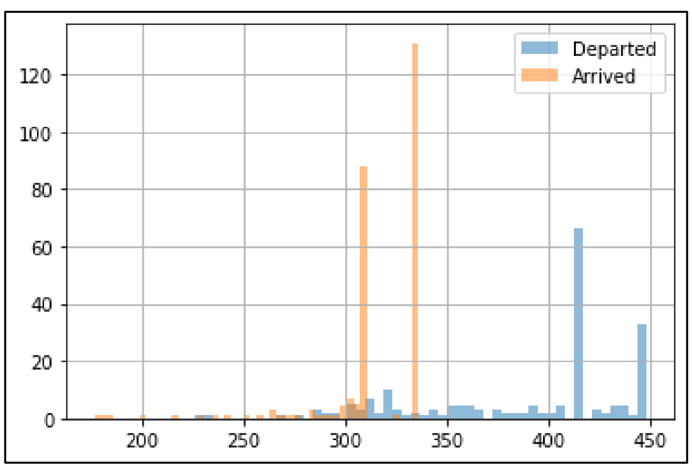


Figure 28 Weight distribution after 25% increase in weight for B767-8

4.4.2.2 Traffic volume change

The question asked for this sub-section was how much the cumulative fatigue of the bridge's 1 deck slab would change if the traffic volume of all different airplanes would increase by a factor. In Figure 29, the answer to the previous question is depicted. All the values of the dataframe presented in Table 4 were changed by a factor. Specifically, the values of the factor were -25%, -10%, 10%, and 25%. The negative values represent a decrease in the volume of traffic, whereas the positive represents an increase. As expected, by increasing the volume of traffic the cumulative fatigue of the bridge's 1 deck slab increases. This sensitivity analysis could be used as a predictive visualization tool for a change in traffic prediction. For instance, if Schiphol aims to increase their flights (inbound and outbound) by 25%, this figure will provide a visualization of the impact on the bridge's 1 deck slab's fatigue.

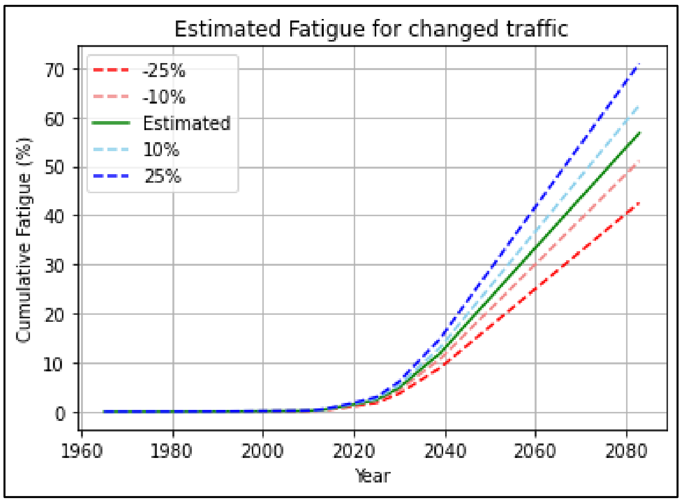


Figure 29 Sensitivity analysis for traffic volume

4.4.2.3 A380s

The A380 was, by the time this research was conducted, the heavier aircraft type flying in and taking off from Schiphol. In this research, the assumption that every A380 would weigh as much as its maximum take-off weight was made due to a lack of data from the sensors during the COVID-19 pandemic. However, it was highlighted that this lack of data is one of the main limitations of this research. Therefore, this sub-section aims to provide insight into how this assumption affects the results.

Figure 30 depicts the estimated cumulative fatigue of the bridge's 1 deck slab when the mean of the fatigue variable of the A380's weight classes (inbound and outbound) is decreased. Specifically, the values 99%, 95%, 90%, 75%, 50%, and 25% refer to the new mean of the fatigue variable for the A380's weight classes. For instance, the 99% scenario means that the new fatigue variable has a mean value equal to 99% of the fatigue caused by an A380 weighing its maximum take-off weight. As depicted in Figure 30, any change in the mean of A380s' fatigue variable has a significant impact on the cumulative fatigue of the bridge's 1 deck slab. That was expected since A380 is the heavier aircraft type within the given dataset and the exponential relation between stress and fatigue.

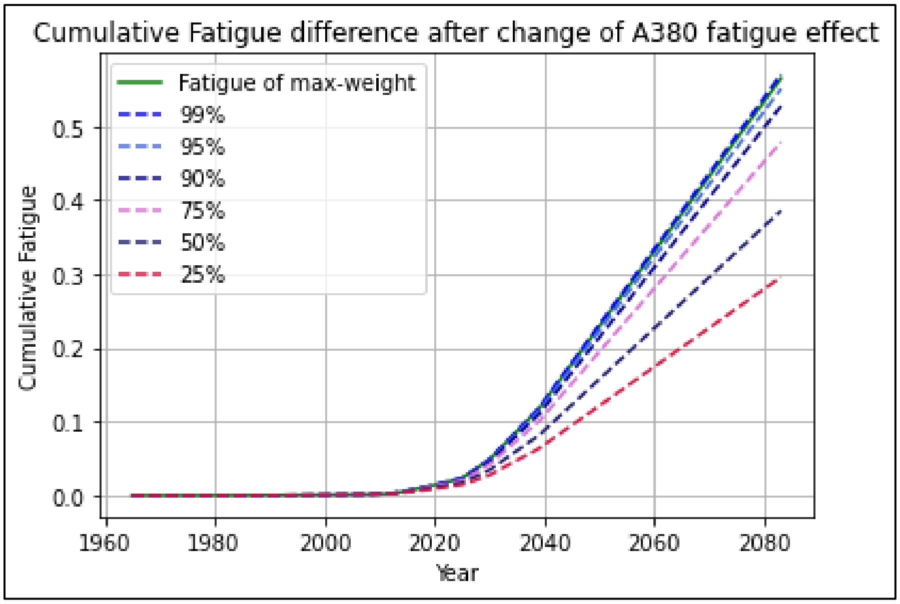


Figure 30 A380's assumption analysis

To better understand the change in fatigue variable, Table 9 was formulated. The first column of the table refers to the change in A380s' fatigue variable's mean while the second column presents the change in the average weight of the A380s. Specifically, if the average weight of all A380s was 99.8% of their maximum take-off weight, then the fatigue variable's mean would be approximately 99% of the mean obtained when all A380s weigh their maximum take-off weight. In contrast, when looking at the weight class of B767-8 outbound, the fatigue variable's mean was approximately 40% of the value obtained when all B767-8 are considered to weigh as much as their maximum weight.

Fatigue variable change	**Average weight compared to the mtow**
99%	99.8%
95%	98.8%
90%	97.6%
75%	93.3%
50%	84.1%
25%	68.8%

Table 9 Fatigue variable change translated to average weight of A380s changed

After looking at this analysis, one can conclude that the impact of A380s on the cumulative fatigue of the bridge's 1 deck slab is the most significant compared to all other weight classes. Moreover, the lack of data on the A380s' weight distribution was responsible for the conservative assumption made that all A380s would be considered to weigh as much as their maximum take-off weight. Finally, more data is needed to relax this assumption and obtain even better results compared to the theoretical approach.

5. Traffic allocation network model

The previous part of this thesis explained the chosen way to exploit the data gathered by Heijmans's monitoring system. Furthermore, by comparing the fatigue predictions between the proposed estimated approach and the theoretical approach, it is shown that the estimated approach ensures a bigger lifespan expectancy to bridge 1. This increase in life expectancy comes as a result of the less conservative estimation of bridge's 1 cumulative fatigue. The next part of this thesis is aimed to use the insight gained from this thesis's findings so far in order to apply it in a network approach. By creating a traffic allocation network model, the cumulative fatigue across the monitored assets can be further decreased. By understanding the uniqueness of each bridge within the network, creating unique weight distributions for the traffic of each bridge, and estimating the fatigue of each bridge using the estimated fatigue based on real-time measurement data the traffic of the network can be allocated such that the cumulative fatigue across the bridges of the network be minimized.

This section explains the second part of this thesis process diagram, Figure 10. The focus of this section is summarized in the isolated second part of this thesis process diagram depicted in Figure 31. The blue textbox represents the input data used which was bridges' 2 and 3 structural behaviors and their stresses. This input data was used combined with the first model (the cumulative fatigue estimation of one bridge, explained in section 4) to create the 2nd model (the traffic allocation network model, which is explained in this section). Moreover, the green textboxes refer to the output of the 2nd Model as well as the final results of this thesis.

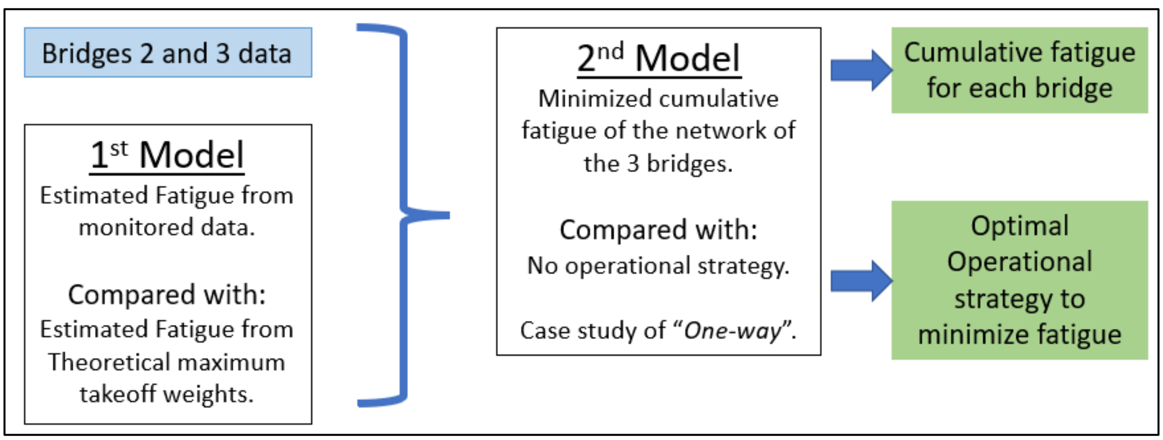


Figure 31 Latter part of this thesis process diagram

5.1 Introduction of the assets

Figure 32 illustrates the relative position and connectivity of the bridges in question-related to each other. Specifically, bridge 3 was constructed parallel to the other two bridges which are connected in series. As a result, any airplane, while getting ready for take-off or after landing in Schiphol, that crossed bridge 1 would cross bridge 2 as well but would not cross bridge 3. Alternatively, if it would cross bridge 3, then it would not cross bridges 1 and 2.

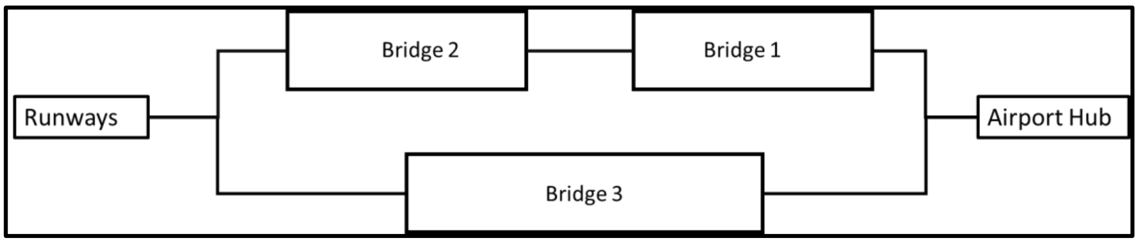


Figure 32 Bridge network connection

As discussed in sub-section 1.3, each bridge is unique. The type of material used the geometry and the ground characteristics below the bridge are some of the many parameters that differentiate each bridge. Thus, bridges 2 and 3 unique characteristics are presented and discussed in this sub-section.

Bridge 2, which is connected in series with bridge 1, has concrete fatigue governing. That means that the methodology and equations used for the estimation of its deck slab's fatigue were similar to bridge 1. Table 10 represents the stress factors (MPa) for each of the weight classes in like manner Table 3 presented the stress factors for each weight class for bridge 1. Equation (2) was constructed by the structural department to translate the stress to fatigue for the bridge's 2 deck slab. One can notice differences by comparing equations (1) and (2). Those differences are the result of different types of concrete used for the construction of each of the two bridges, even though both bridges were constructed in 1965. The differences in the two tables and the two equations result in the same airplane affecting differently the two bridges.

AC type	MTW	outbound stress	inbound stress
B767-300	182	7.3	6.2
MD11ER	266	9.9	8.1
B747-400	397	13.2	10.1
B767-8	450	15.2	10.8
A380	600	20.9	13.7

Table 10 Bridge's 2 deck slab stress factors

$$\textbf{Fatigue of 1 plane} = 10^{-\left(\frac{10}{\sqrt{1-\frac{5}{Stress}}}*\left(1-\frac{Stress}{39}\right)\right)} \qquad (2)$$

On the other hand, bridge 3 was constructed in 2021. The type of concrete and construction process was different from the other two bridges. Therefore, the stresses and fatigue equations used to calculate the fatigue were also different. The steel fatigue inside the bridge's 3 deck slab is governing instead of the concrete fatigue that governs bridges 1 and 2.

Figure 33 represents the relation between the stress of the bridge's 3 deck slab and the weight of the crossing plane. The graph consists of three parts denoted by distinct colors. The blue and orange dotted lines were provided by the structural department of Schiphol, whereas the continuous black line represents an assumption made within the scope of this project. The assumption was made, in terms of the feedback from the structural department of Heijmans, to fill the lack of data. Namely, any airplane with a maximum take-off weight between 350 tons and 450 tons could not be translated to stress. The graph in Figure 33 was used to translate the weight of a crossing airplane to stress within the bridge's 3 deck slab by allocating it to one of the three parts of the graph based on its maximum take-off weight. The phenomenon where a lighter plane causes bigger stress within bridge 3 is explained by the wheel distribution of the plane. Heavier airplanes have more wheels than lighter airplanes. This is the case due to safety because each wheel can carry up to a certain weight. Furthermore, the points of contact between the airplane and the bridge are the airplane's wheels. When an airplane has more wheels the distribution of its weight causes the stress within the bridge deck to spread wider. This phenomenon is depicted by the discontinuous function of the dotted lines in Figure 33.

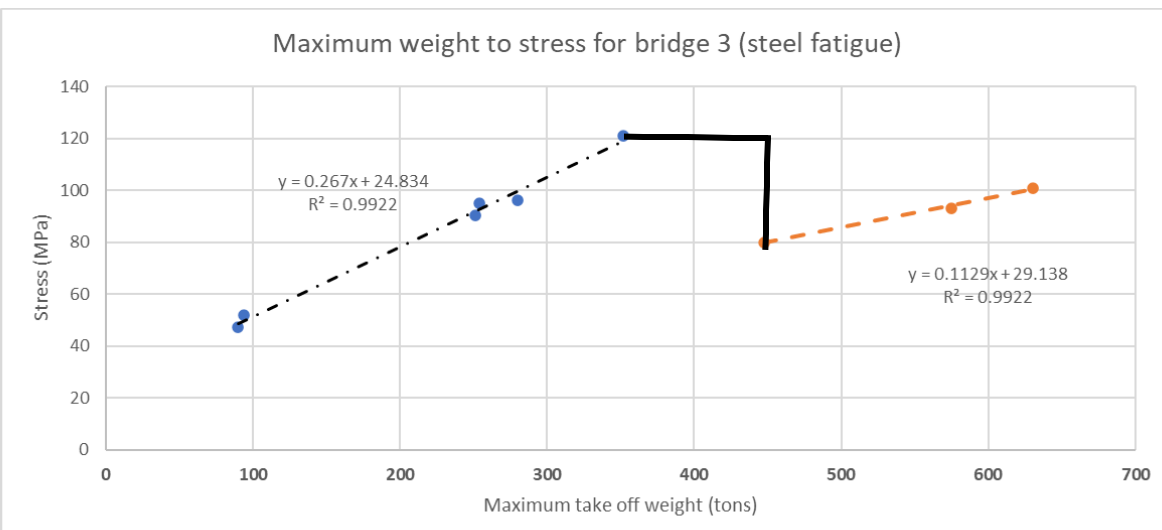


Figure 33 Bridge's 3 stress to weight relation

For instance, imagine an outbound MD11ER (mtow 266 tons) weighing 200 tons crossing bridge 3. Based on its maximum take-off weight (mtow), that plane would belong to the first part of the graph, namely the blue dotted line. Then to calculate the stress within the bridge's 3 deck slab one would use the equation of that line to calculate the stress. However, the limits of that line, namely [50,120], would be the minimum and maximum of the calculated stress respectively. Thus, in that example, the stress would have been:

$$stress_{MD11ER(200tons)} = 0.267 * 200\ tons + 24.834 = 78.234\ MPa$$

After the translation of airplane weight to the bridge's stress the methodology, already explained for bridge 1, continues to the calculation of the fatigue. In the case of bridge 3, where the steel fatigue is governing, equation (3) was used for the calculation of steel fatigue, obtained by Eurocode 3 (*EN 1993-1-1: Eurocode 3: Design of Steel Structures - Part 1-1: General Rules and Rules for Buildings*, n.d.).

$$\boldsymbol{fatigue\ of\ 1\ plane} = \mathbf{10}^{-\left(\mathbf{6}+\mathbf{9}*\mathbf{log}_{\mathbf{10}}\left(\frac{\mathbf{162.5}}{\mathbf{1.15}*\boldsymbol{Stress}}\right)\right)} \tag{3}$$

5.2 Traffic volume assumption

The traffic volume was the next thing to be determined after the introduction of the assets of the network and their stress and fatigue calculations. Table 4 contains the predicted traffic volume for bridge 1 from 1965 until 2083. Bridge 2 is connected in series with bridge 1. Therefore, the bridge 2 traffic volume prediction would be the same as bridge 1. However, for bridge 3 there was no prediction available, as a result, an assumption was made. Bridge 3 was built in 2021, so a new dataframe was created based on the one represented in Table 4. The new dataframe would contain the same predictions from 2021 until 2083 as the old dataframe. The new dataframe would then be named the predicted traffic volume for bridge 3.

5.3 Mathematical model

After identifying the assets of the network in the previous sub-sections, the mathematical model used to minimize the cumulative fatigue of the network's bridges was formulated and is explained in this section. Firstly, the sets used for the model are presented and explained, followed by the decision variables. Subsequently, the objective function and the constraints are presented and discussed in detail. After the mathematical model, the heuristic used to solve the model is presented in the form of a pseudo code. Finally, the results are presented followed by a case study.

The network in question consists of three bridges arranged as shown in Figure 32. Moreover, the project was focused on ten different weight classes and their representative aircraft types, Table 2. The prediction of traffic volume for bridges 1 and 2 was received as a dataframe and is detailed in Table 4 (section 4.2). However, the prediction of traffic volume for bridge 3 was assumed. Therefore, the traffic volume prediction of the network was the summation of the two dataframes. For instance, in the year 2050, it was estimated that the network would have a traffic volume equal to the number of flights within the bridge's 1 dataframe for each aircraft type, plus the number of flights within the bridge's 3 dataframe for each aircraft type.

It is assumed that the yearly traffic volume for a given plane type can be "allocated" to a bridge either fully, partially, or not at all. The aim of the optimization model is to allocate the traffic volume of each aircraft type to a bridge such that the overall cumulated fatigue for the network of bridges throughout the considered time window is minimized. The following notation is introduced before the formulation of the optimization model:

$B = \{B_1, B_2, B_3\}$: *The set of Bridges.*

$A = \{A_1, A_2, \dots, A_{10}\}$: *The set of aircraft types (weight classes).*

$T = \{1965, 1966, \dots, 2083\}$: *Set of time (years).*

$P_{i,j} \quad \forall i \in A, \forall j \in T$: *Prediction of traffic volume for aircraft type i at time j.*

$F_{i,b}$: *The fatigue caused to bridge b by 1 aircraft of type i.*

$C = \{C_1, C_2, C_3\}$: *The set of the yearly traffic capacity of the bridges.*

$$x_{i,b} = \begin{cases} 0, & type\ i\ wont\ cross\ bridge\ b \\ 0.5, & half(on\ average)traffic\ of\ type\ i\ will\ be\ allocated\ to\ bridge\ b\,, \\ 1, & all\ trafic\ of\ type\ i\ will\ be\ allocated\ to\ bridge\ b \end{cases} \qquad i\forall \in A, b\forall \in B$$

If the decision variable associated with the pair of MD11ER-outbound and bridge 1 takes value 0, then it means that MD11ER-outbound is not allowed to cross that bridge. The 0.5 state represents the situation where the traffic of that type is allocated on average half of the time to that bridge. The weight type with the smaller predicted total number of airplanes throughout the time period of traffic prediction is A380 outbound, namely a total of around 42.000 airplanes. This means that all other weight types have a greater number of airplanes predicted to cross the network. If the traffic of a specific weight type is not allocated 100% or 0% towards one bridge then any airplane entering the network has a 50% chance to cross bridges one and two (in series) and a 50% chance to cross bridge three. Thus, the occurrences of a crossing airplane of a weight type that does not have a traffic rule of 1 or 0 can be described as a binomial distribution with $p = 0.5$. In that case, the 99.9% confidence interval of the average percentage of the traffic of A380 outbound that crosses bridge three is:

$$C.I._{99.9\%} = p \pm 3.3 * \sqrt{\frac{p*(1-p)}{n}} = 0.5 \pm 3.3 * \sqrt{\frac{0.5^2}{42000}} = [0.492, 0.508]$$

The rest of the weight types, which have a larger number of airplanes, have a smaller 99.9% confidence interval. So, the assumption that the traffic rule state of 0.5 relates to half of the traffic of a weight type crosses that bridge can be made. In other terms, the probability of the percentage of the traffic of any weight type being more than 51% is always less than 0.01%.

The calculation of each bridge's fatigue caused by each aircraft type was described in the previous sections. Namely, by identifying weight distributions, then translating weight to stress, and finally by using the fatigue equations, the fatigue of each bridge by any airplane was calculated. Finally, the restrictions were formulated and explained.

Each decision variable can be interpreted as a traffic allocation rule defined for each pair of aircraft type and bridge. Therefore, the vector of decision variables X (10 components), is the vector of traffic allocation rules.

The objective function of the model calculates the cumulative fatigue of the three bridges within the network in question. This objective function will be minimized by the heuristic explained in sub-section 5.5.

Network

$$\sum_{b=1}^{B}\sum_{i=1}^{A}\sum_{j}^{T}\left(F_{i,b} * P_{i,j} * x_{i,b}\right)$$

Subject to:

$$\sum_{i}^{A} P_{i,j} * x_{i,b} \leq C_b, \quad \forall b \in B, \forall j \in T \qquad (1)$$

$$x_{i,1} - x_{i,2} = 0, \quad \forall i \in A \qquad (2)$$

$$x_{i,3} + \frac{x_{i,1} + x_{i,2}}{2} = 1, \quad \forall i \in A \qquad (3)$$

$$x_{i,b} \in \{0, 0.5, 1\}, \quad \forall i \in A, \forall b \in B \qquad (4)$$

1. The capacity constraint forces the model to comply with the yearly maximum traffic allowed across each bridge
2. Bridge 1 and bridge 2 are in series. Hence, the traffic crossing each of the bridges must be the same as the other.
3. Bridge 3 is in parallel with bridges 1 and 2. Hence, the traffic must either go through one of the possible ways or be divided into both ways.

Each solution of the mathematical model is a combination of traffic rules. Specifically, each of the three bridges has ten traffic rules, one for every airplane weight type. Such, each solution consists of thirty traffic rules, $x_{i,b}$. So, each solution is a vector of thirty discrete variables, the traffic rules.

The network's traffic restrictions were stored in Table 11. It was assumed that each bridge could handle 180.000 crossing airplanes per year. This assumption was made to ensure the feasibility of the model's solution. The values were assumed since the prediction dataframe provided, Table 4, had a growth pattern. The growth pattern changed when the cumulative yearly prediction of airplanes reached the approximated limit of 180.000. For the upcoming years, the prediction remains the same for bridge 1. As a result, the assumption was made to limit each bridge's yearly traffic volume to 180.000 airplanes.

Bridge	Maximum yearly bridge's capacity (number of airplanes)
Bridge 1	180000
Bridge 2	180000
Bridge 3	180000
Bridge	**Year of construction**
Bridge 1	1965
Bridge 2	1965
Bridge 3	2021

Table 11 Network restrictions

5.4 Mathematical problem optimization using Gurobi

One standard way to solve discrete optimization mathematical problems is by converting them to integer problems. In this case the decision variable $x_{i,b}$ is a discrete variable that takes the values $(0, {}^{1}/_{2}, 1)$. One way to convert this discrete variable to an integer is by introducing the new $x_{i,b}$ which will take the values (0,1,2), in other words, it will be doubled. In order to achieve that, the mathematical model has to be changed as follows:

Decision variables:

$$x_{i,b} = \begin{cases} 0, & type\ i\ wont\ cross\ bridge\ b \\ 1, & half\ (on\ average)\ traffic\ of\ type\ i\ will\ be\ allocated\ to\ bridge\ b\ , \\ 2, & all\ trafic\ of\ type\ i\ will\ be\ allocated\ to\ bridge\ b \end{cases} \quad i\forall \in A, b\forall \in B$$

The objective function to be minimized:

$$\sum_{b=1}^{B}\sum_{i=1}^{A}\sum_{j}^{T}\left(\frac{F_{i,b} * P_{i,j} * x_{i,b}}{2}\right)$$

Subject to:

$$\sum_{i}^{A} P_{i,j} * x_{i,b} \leq 2 * C_b, \quad \forall b \in B, \forall j \in T \qquad (1')$$

$$x_{i,1} - x_{i,2} = 0, \quad \forall i \in A \qquad (2')$$

$$x_{i,3} + \frac{x_{i,1} + x_{i,2}}{2} = 2, \quad \forall i \in A \qquad (3')$$

$$x_{i,b} \in \{0,1,2\}, \quad \forall i \in A\ , \forall b \in B \qquad (4')$$

The new constraints are similar to the constraints of the previous model (with the discrete decision variables) but there are some differences. In constraints (1') and (3') the right side of the inequalities is multiplied by a factor of 2 compared with the constraints (1) and (3). This multiplication is necessary because the integer decision variables of constraints (1) and (3) are also multiplied by 2 when compared to the discrete decision variables.

The integer mathematical model was solved by using the gourbi software. Gurobi is a mathematical optimization solver. The mathematical model was written in python to be optimized by the gurobi software. The computational time needed to find the solution to this integer mathematical problem was 1.4 seconds. The computer used to obtain the solution had a single DDR3 8GB memory stick and an Intel Core i7 6700HQ 4-core CPU @ 2.60GHz.

The solution depicted in Table 12 was obtained by the optimization by gurobi. The objective value of 22.45% total cumulative fatigue across the bridges by the year 2083 would be achieved by following the traffic rules as presented. Moreover, Figure 35 was created to depict the cumulative fatigue of the bridges when the optimum traffic rules are followed.

Objective value		**22.45%**	
x(b,i)	Bridge 1	Bridge 2	Bridge 3
B767 out	1	1	1
MD11ER out	2	2	0
B747-400 out	2	2	0
B767-8 out	0	0	2
A380 out	0	0	2
B767 in	1	1	1
MD11ER in	2	2	0
B747-400 in	2	2	0
B767-8 in	2	2	0
A380 in	0	0	2

Table 12 Optimum Solution integer network model by gurobi

5.5 Description of greedy algorithm (heuristic)

After installing more sensors to bridges in Schiphol airport, Heijmans can extend the network traffic allocation model. The increased number of bridges within the network will increase the complexity of the model, thus the computational time needed by gurobi to locate the optimum solution. For this reason, the following heuristic was created. In the current scenario, the total number of possible traffic rules combinations for each bridge was 59049. Therefore, the option of enumeration would be computationally intensive and time consuming. Enumeration, which is the scenario that all combinations are tested before deciding the best, is an approach used when the number of all possible combinations is manageable. However, that is rarely the case in practice where the number of all possible scenarios is big. For those cases many heuristics were used by researchers to solve efficiently and effectively mathematical problems. Heuristics such as tabu search, genetics algorithms, greedy heuristics, and local maximum are used to provide a near optimum solution to the problem with less computational stress. In this sub-section the greedy heuristic created and used to solve the mathematical model will be explained.

1. Start point: A random solution (combination of traffic rules) is chosen as the start point.
2. Neighbor point: Identify the neighbor points. Each neighbor point is a solution (traffic-rule combination) that has only 1 different traffic rule compared to the start point. Traffic rules were explained in sub-section 5.3. Each point has a total of 60 neighbors. Each solution has ten traffic rules for each of the three bridges, so thirty traffic rules in total. Each neighbor point is another solution with one different traffic rule, while each traffic rule can be in one out of three states. So, for each traffic rule there are two neighbors, meaning that any solution has a total of 60 neighbors ($(30 * 2 = 60)$
3. After identifying the neighbor points, the cumulative fatigue of the network for each of the neighbor points and the start point is calculated. In case the solution is unfeasible, because the traffic volume constraint is violated, then the cumulative fatigue of the network from that traffic rule takes a large number as its value.
4. Terminate: In case the start point gives the smallest network cumulative fatigue out of all 61 solutions (60 neighbors + 1 start point) stop the heuristic. Moreover, if the difference between the network cumulative fatigue given by the start and the neighbor points with the lowest network cumulative fatigue among the 60 neighbors in question stands at 0.001%, then stop the heuristic. If none of the above criteria is met, then continue to next step.
5. Appoint new start point: The new start point would be the solution with the lowest network cumulative fatigue among the 61 solutions that were investigated the previous steps. After identifying the new start point, go to step 2.

By applying this greedy heuristic, the solution to the mathematical problem would be a feasible optimum or near optimum traffic rule. The 0.001% difference terminate option, was introduced to decrease the computational stress of the model. This difference was considered small enough, especially after taking into consideration that more conservative assumptions were made throughout this project. Furthermore, there is no start point which all each neighbor points including itself would lead to infeasible solutions. Even if the start point is the traffic rule which forbid any airplane to cross a bridge, which is infeasible solution, there is at least one neighbor point which ensures a feasible solution.

5.6 Results

In this sub-section the results of the network optimization will be presented. To better understand the results of the optimization, the scenario of no strategy has to be shown. In case Schiphol airport does not specifically allocate airplane traffic within the network of those three bridges, the set of traffic rules that would describe that scenario would be all traffic rules equal to 0.5. In other terms half of the network's traffic volume on average would cross bridge one and two and the other half would cross bridge three. The fatigue of each bridge within the network by the "no specific strategy" scenario is depicted in Figure 34. By year 2083 bridge one would have reached approximately 50% of its fatigue tolerance level, while bridges two and three would be at the 20%. It is important to note that the dotted lines represent bridges' one and two fatigue before the construction of bridge three. It was important to distinguish the period before and after construction of bridge three. Before bridge's three construction all the traffic was crossing bridges one and two. So the model cannot allocate any traffic to bridge three as it was not built yet.

Network

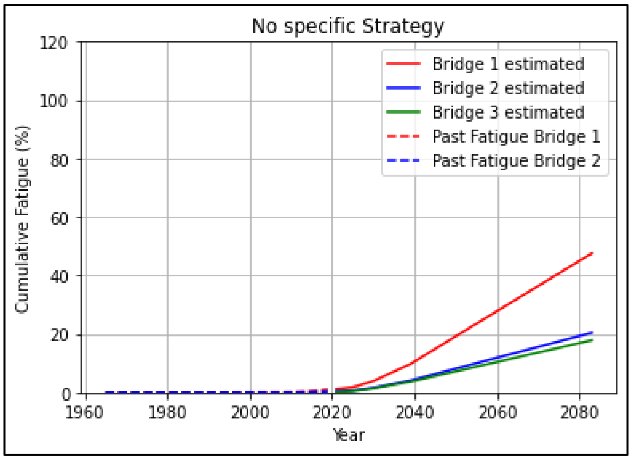


Figure 34 No specific network allocation strategy

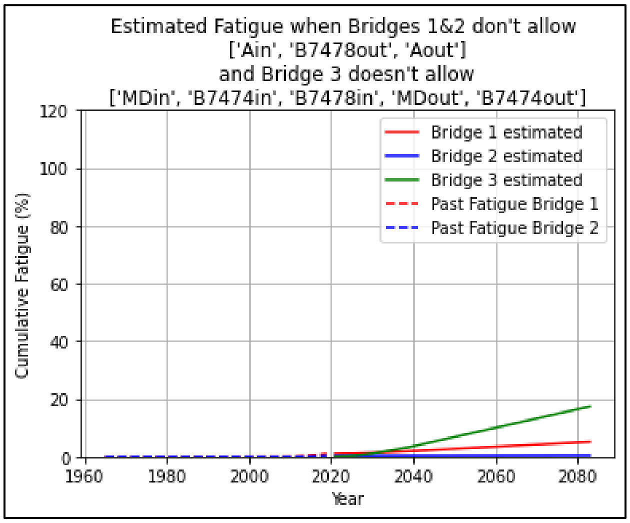


Figure 35 Network model optimum solution by Gurobi

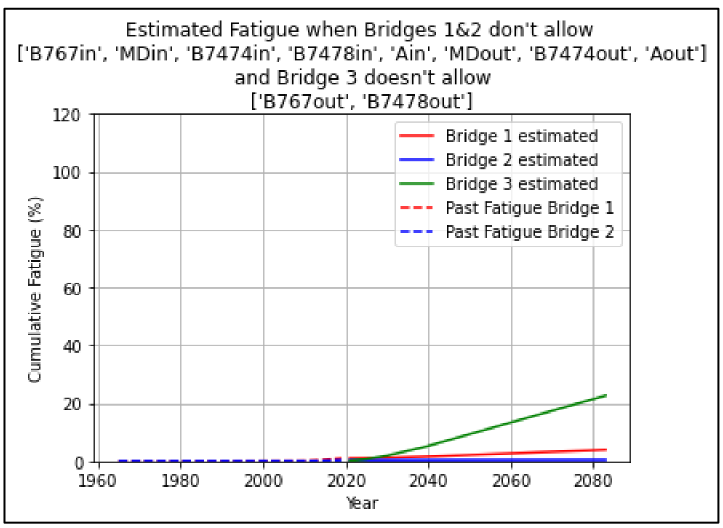


Figure 36 Heuristic solution to network traffic allocation model

After solving the model, with gurobi, Figure 35 was created to depict the cumulative fatigue of each of the three bridges. The optimum solution, as shown in Table 12, finds the majority of inbound airplanes to cross only bridges 1 and 2. Only the A380s inbound are banned to cross those bridges, while the traffic of B747-300 inbound is shared in half on average between bridges 1 and 2 and bridge 3. On the other hand, the outbound airplanes, which are heavier than the inbound, are shared more evenly across the available routes of the network. As before, the traffic of the lighter B747-300 outbound is divided between the bridges. However, the two heavier classes of A380s and B747-800 outbound are allocated only through bridge 3, while the two remaining less heavy classes (MD11ER and B747-400 outbound) are allocated only through bridges 1 and 2. This solution, a set of traffic rules, is predicted to accumulate a total of approximately 22.5% cumulative fatigue for the network. More specifically, bridges 1, 2, and 3 will reach around 0.7%, 5%, and 16.8% of their fatigue threshold, respectively.

After applying the heuristic to solve the mathematical problem, Figure 36 was created. In this figure, the result of a near-optimum traffic rule is presented. The created heuristic produces near-optimal solutions regardless of the starting point. The selected traffic rules allocate all airplanes with weight type within the weight classes B767-300 outbound and B747-8 outbound to cross only bridges 1 and 2, while the rest of the airplanes were allocated to cross only bridge 3. In other words, the solution (combination of traffic rules) found by the heuristic that minimizes the cumulative fatigue is [0,0,0,0,0,1,0,0,1,0] for bridges 1 and 2 while [1,1,1,1,1,0,1,1,0,1] for bridge 3. By applying those traffic rules to the traffic prediction until 2083, bridge 3 is estimated to accumulate approximately 23% fatigue while bridges 1 and 2 are less than 5%. The total cumulative fatigue across the network would reach around 26%.

The comparison of the results of the heuristic and the solution obtained by solving the mathematical model will be discussed here. The near-optimum solution found by the heuristic produces 15% more fatigue than the optimum solution. Due to the size of the mathematical model, the exact solution is better the choice. The computational time needed to solve the integer problem with gurobi and the one needed to find a near-optimum solution by the heuristic is small, in both cases. However, as the complexity and the size of the model are increased, the computational time needed for gurobi to solve the model will increase as well. If the computational time needed becomes problematically large, then the heuristic can be used to obtain a near-optimum solution.

5.7 Case study "One-way"

Schiphol understood the complexity of the application of this traffic allocation network model. The difficulty in applying those traffic rules lies in the fact that each airplane would have to wait for the air traffic control to determine the weight class of that airplane and the appropriate way to follow. That extra workload would add to the already complicated work of the air traffic control personnel. This extra workload was considered an unwanted risk for Schiphol based on the current work process. Before this network optimization traffic rules can be used as intended, Schiphol identified that more changes needed to be made. As a result, it was discussed that the introduction of a simpler traffic rule would be easier to implement in the current work process Schiphol. The proposed, easier to apply, traffic rule will be discussed in this sub-section under the name "one-way case study".

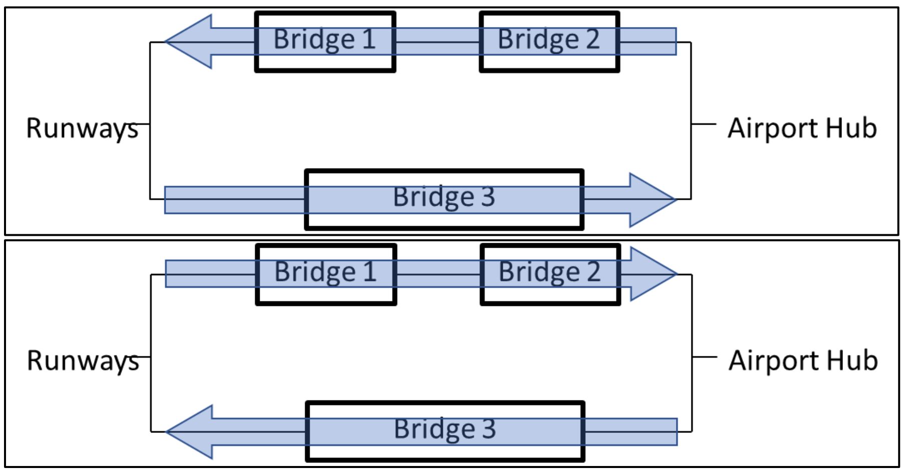


Figure 37 Presentation of two possible traffic rules for the "One-way"

By limiting the traffic of each bridge to crossing one way, it was determined by Schiphol to be easily applied in their current processes. The question that arises is which of the two possible combinations of traffic rules that enforce the one-way would be better regarding the cumulative fatigue of the bridges. The two possible solutions are depicted in Figure 37. The first solution suggests that all the outbound flights would cross bridges 1 and 2, while the inbound flights would cross bridge 3. Alternatively, the other solution suggests the opposite. Those two solutions constitute the set of possible combinations of traffic rules that imply that the bridges will be used as "one-way streets". In Figure 39 and Figure 38, the cumulative fatigue of the bridges is depicted for those two combinations of traffic rules.

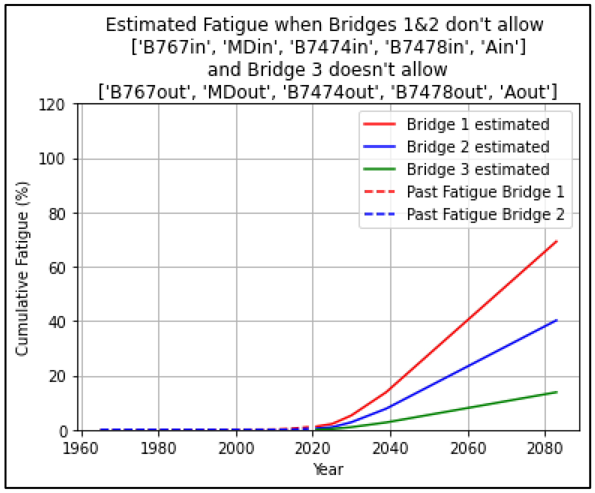


Figure 38 One-way: Inbound flights via bridge 3

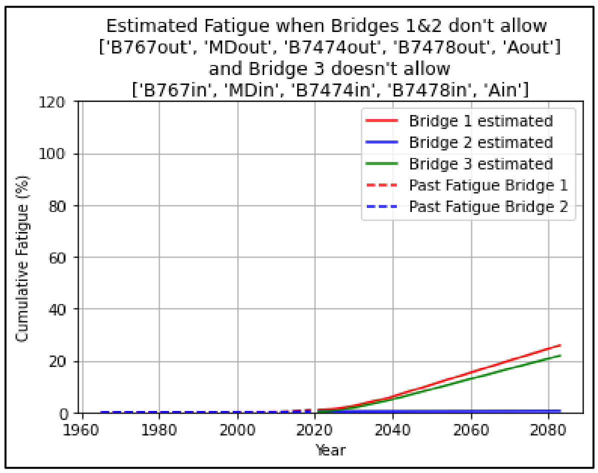


Figure 39 One-way: Inbound flights via bridges 1&2

In sub-section 4.1, the asymmetry of the inbound and outbound flights was noticed. Since the inbound flights crossing the network in question are predicted to be more than the outbound, one could argue that the increased traffic should cross bridge 3 as it is the newest bridge of the network. On the other hand, the optimum combination of traffic rules was presented in the previous sub-section. That optimum solution indicated that most of the heavy traffic would be allocated to bridge 3 in order to obtain lesser cumulative fatigue across the network. Thus, one could argue that in the "one-way" case study, the outbound flights should be crossing bridge 3. Even though the inbound flights crossing the network are predicted to be more than the outbound ones, Figure 39 and Figure 38 suggest that when the outbound flights cross bridge 3 the cumulative fatigue of the network is lowered. The increased weight of the outbound flights had a higher impact on the fatigue of the network compared to the impact of the higher volume of inbound flights. This result might seem contradicting considering the fatigue is a result of a circling repetition of load, although the exponential relationship between fatigue and stress indicates that the weight of the crossing airplanes is the main factor of fatigue. Altogether, the smaller traffic of heavier airplanes is causing more fatigue than the larger traffic of lighter airplanes in the "one-way" case study.

6. Conclusions

In the final section of this thesis, the results will be summarized whereas the identified limitations and made assumptions will be discussed.

6.1 Overview of the results

6.1.1 Overview of estimating fatigue model (first part)

Before the introduction and implementation of the proposed models presented and discussed within this thesis, the structural department of Schiphol was calculating the fatigue of each bridge based on the "theoretical approach", sub-section 4.2. Via this approach, each airplane was estimated to weigh as much as its maximum take-off weight as it was crossing each bridge. Then this weight was translated to stress and subsequently, the stress was translated to fatigue. The traffic prediction, Table 4, was used to calculate the repetition of load for each bridge. After calculating the theoretical approach for each bridge, Figure 40 was created. In this figure, the cumulative fatigue estimation based on the theoretical approach for each bridge is presented. Approximately by the year, 2077 bridge 1 should be replaced while the estimation of the cumulative fatigue for bridges 2 and 3 would stand at approximately 20%. This is the reason that the given traffic prediction was until the year 2083 and not later. The structural department would have considered that it was unnecessary to include traffic prediction after that year because it would not provide any insight as the estimated remaining useful lifetime of bridge 1 was already determined.

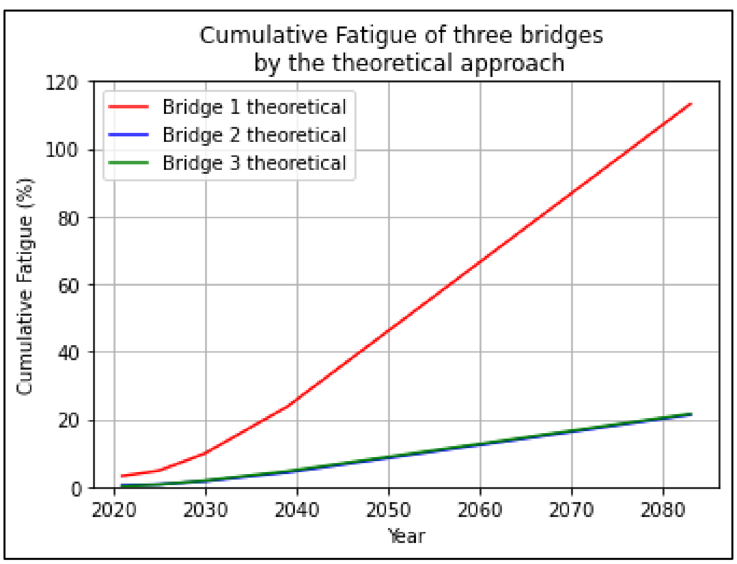


Figure 40 Cumulative fatigue from theoretical approach for all bridges

The difference in the bridge's deck's cumulative fatigue between bridge 1 and bridge 2 could be considered unexpected. Those two bridges were built during the same time, concrete fatigue is governing in both structures, and they support the same traffic because they are connected in series. However, the difference in their geometry and shape are the factors that affect their unique fatigue equations. Hence, the outcome that bridge's 1 deck is more susceptible to the weight of the crossing planes than bridge's 2 deck is explained. This phenomenon is evident in all cases that were examined during this thesis. For instance, the theoretical approach concludes to Figure 40, where bridge's 1 deck is expected to reach 100% fatigue by the year 2077. Following the same principle, after the application of the traffic allocation model and the case study of "one way", bridge's 1 deck always suffers more fatigue compared to bridge's 2 deck.

Heijmans introduced their monitoring system with its capability to estimate the load of the bridge, or in other terms the weight of the crossing planes. Those estimations were used for the development of model 1 presented in this thesis. Before using those estimations, error and safety factors were applied to the estimations to ensure the credibility and confidence of the first model's results. This model used the updated estimations for the weight of the planes to determine weight distributions for each airplane type. Then the translation of airplane weight to bridge's stress took place by assuming a linear relationship between the two variables, followed by the fatigue equations obtained from the Eurocode. The outcome of the first model indicates that the theoretical approach used before was conservative regarding the future lifetime of the assets. Specifically, bridge 1, which would have to be replaced by the year 2077 via the theoretical approach, was estimated to have accumulated approximately 50% of fatigue by 2083 via model 1, as depicted in Figure 23. In other terms, by using the theoretical approach the bridge would have been replaced, but by the first model, it is shown that the bridge's 1 predicted remaining useful lifetime would not be over after 2077. The first part of the main research question was answered by the introduction of model 1, while the implementation of the first model answered the first sub-question.

Following the first model, a sensitivity analysis was conducted. This analysis assessed the sensitivity of the results regarding three topics. The first topic was the weight of the monitored crossing airplanes. Since the data gathered by the monitors during the COVID-19 pandemic, the change in the airplanes' weight had to be analyzed. This analysis concluded that even if the average monitored airplane would weigh up to 10% more, the results would not differ much especially when the other assumptions made are considered. Moreover, the increase in the weight of airplanes with heavier maximum take-off weight would lead to a larger increase in fatigue compared with the same increase in weight of airplanes with lighter maximum take-off weight. In view of the non-linearity of the fatigue equations used in the thesis, one could have seen that the impact on the fatigue of the bridge by increasing the weight of heavy aircraft would be larger than the one of a lighter aircraft. Furthermore, after increasing the average weight of the airplanes by 25%, which would lead to most of the airplanes weighing as much as their maximum take-off weight, the estimated cumulative fatigue of bridge 1 would significantly increase from approximately 55% to 90% level of fatigue in 2083, Figure 27.

The next topic analyzed was the sensitivity of traffic prediction. In Figure 29, the sensitivity of the estimated cumulative fatigue of bridge 1 to the traffic volume was depicted. It is noticeable that if the traffic volume increases, the bridge's 1 cumulative fatigue increases as well. As stated in the introduction, fatigue is the result of a cyclic repetition of load, or in this case the number of airplanes. Hence, it was foreseen and confirmed that traffic volume and bridge fatigue are positively related.

The final topic refers to the assumption made for the weight distribution of A380. Since no data for A380 airplanes was gathered, the assumption made by the theoretical approach was used for the A380s of the first model. Namely, all the A380s from the traffic volume prediction dataframe were considered to weigh as much as their maximum take-off weight. Based on the output of the monitoring system, each of the rest of the weight classes has a unique weight distribution. By identifying those weight classes, the assumption that all airplanes weigh as much as their maximum take-off weight can be considered a conservative assumption. Hence, the assumption for the weight of the A380s is conservative as well. However, the lack of data is responsible for the necessity of this assumption. The impact of the weight distribution of A380 on the future prediction of bridge's 1 cumulative fatigue was depicted in Figure 30. Since the A380 is the heaviest aircraft type in Schiphol, its fatigue impact on bridge 1 would be the highest among the different aircraft types. Even a slight decrease in the average weight of crossing A380s would lead to a significant decrease in the cumulative fatigue of bridge 1. Therefore, in order to relax the conservative assumption, more data must be gathered. Altogether, the sensitivity analysis conducted answers the third sub-research question.

6.1.2 Overview of network traffic allocation model (second part)

It was shown from the first part of this thesis that the fatigue predictions currently used for the bridges did not consider the weight distribution of the airplanes. The current approach, or "theoretical approach", assumes that all planes are weighted as much as possible. In the first model, the first part of this thesis, unique weight distributions were identified. Those weight distributions present a more realistic interpretation of the load of the bridges. On top of the first model, the second model of the network traffic allocation model was built. The second model considered the three bridges network and their connectivity as much as the unique weight distributions of all airplanes. By allocating the total traffic between the bridges, a set of traffic rules could be identified to minimize cumulative fatigue across the three bridges. Those traffic rules were introduced by the mathematical model presented in sub-section 5.3. The mathematical model was converted to an integer problem before solving it with the gurobi optimization software. The solution of the mathematical model is a set of traffic rules for all the bridges and airplane weight types. The implementation of such an operation strategy would result in the minimization of the total cumulative fatigue across the bridges. The network traffic allocation model was created to answer the second part of the main research question as well as the second sub-question, while the results depicted in Figure 35 and Figure 34 provide the comparison requested by the third sub-question.

Another way to locate a near-optimum solution for the mathematical model was also presented in the form of a greedy heuristic. That heuristic evaluated combinations of traffic rules based on a given starting point. Then, by changing one variable at a time, a new point would be selected in every iteration, such the cumulative fatigue across the network would be further decreased. The solution that could not be improved after changing any traffic rule was named the near-optimum combination of traffic rules. The result of this heuristic was depicted in Figure 36. Using this heuristic, one can obtain a set of traffic rules that reduces the cumulative fatigue of the network if the network becomes too large for an exact solution to be computed in a reasonable amount of time. The solution obtained from the heuristic will not always be the optimum one, rather it will be a near optimum.

However, the implementation of such an operational strategy would require several changes in Schiphol's current air traffic control work process. Based on the approach of traffic rules, the case study of "one-way" was conducted to provide a feasible improvement of the assets' operational management. Specifically, the two scenarios of having a one-way road for each bridge were compared. The result of that comparison suggests that all outbound flights should be allocated to bridge 3 while all inbound flights should be allocated to bridges 1 and 2.

To conclude, Schiphol used the theoretical approach to calculate bridges' remaining useful lifespan. This project introduced a way to capitalize the data from Heijmans's monitoring system, model 1. In this way, even though safety factors were applied to make model 1 more conservative, the useful remaining lifespan of a bridge was extended, compared to the theoretical approach. Subsequently, the network traffic allocation model illustrates the minimization of cumulative fatigue across the network of the three monitored bridges. The exact solution of that model is a combination of traffic rules that minimizes the cumulative fatigue across the network of the three bridges. Furthermore, a greedy heuristic was developed to locate a near-optimum combination of traffic rules that decreases the cumulative fatigue across the network of the three bridges if the computational time for an exact solution gets too much.

The results of this project indicate that the monitoring of the assets provides value that has not yet been extracted. By the time this research is conducted, Schiphol's strategy team is not taking into consideration that extra remaining useful lifespan of their assets as input for their strategy-decisions. For instance, based on the theoretical approach bridge 1 should have been replaced by 2077, which results in expenses for Schiphol. That would not be the case when the insights of this project will be shared to Schiphol. As a result, the replacement of bridge 1 would be postponed and the money needed for its early replacement would be used elsewhere.

6.2 Limitations

The conducted research was based on input data gathered by Heijmans and Schiphol. This data was received in the form of various dataframes, for example the traffic volume prediction of bridge 1 by Schiphol, the monitored air traffic by Heijmans, and the air traffic control data based on GPS by Schiphol. Each of this input data will be discussed separately.

The traffic volume prediction is a dataframe with number of airplanes per year per weight class until 2083. The theoretical approach of calculating fatigue results in a mandatory replacement of bridge 1 by year 2077. As a result, the predictions until 2083 was considered to be enough, because the characteristics of the bridge that would have replace the bridge 1 by the year 2077 are unknown. Hence, there was no need or did not make sense to predict bridge's 1 traffic for a longer period. This research concluded that the remaining useful lifespan of each bridge is longer than the one calculated via the theoretical approach. Therefore, the current prediction dataframe is not enough to extend the scope of the research in order to calculate the estimated remaining useful lifespan of the bridges.

Moreover, as the input data is concerned, the dataframe containing the monitored estimation of airplane weights was created by data gathered during the COVID-19 pandemic. The impact of COVID-19 on aviation in general was highlighted throughout this research. It is known that most of the airplanes monitored at that period had to be less crowded, in other terms weigh less than usual. Following the research of Iacus (Iacus et al., 2020) several forecasting models of the economic impact of the COVID-19 pandemic on the aviation were introduced. However, there is no available research on the actual weight reduction of the airplanes during COVID-19 pandemic. Hence, the provided dataframe of monitored weights was not an unbiased sample.

Throughout this research, multiple assumptions were made which could be potential limitations. Firstly, the biased dataframe of monitored weights did not provide any data for the heavier weight class of A380s. During the COVID-19 pandemic, no A380s crossed bridge 1. Moreover, this research highlighted that due to the exponential relationship between fatigue and stress, heavier airplanes are causing exponentially more fatigue than lighter ones. Owing to the lack of data on A380s and the fact that A380 represents the heavier weight class in this research, a conservative assumption had to be made. Following the assumption made in the theoretical approach, all A380s were considered to weigh as much as their maximum take-off weight. On one hand, this assumption deals with the lack of data, but on the other, it is conservative.

The introduction of the weight class in Table 2 was an assumption made by the structural department of Schiphol. The incentives and assumptions behind the identification of those classes were not in the scope of this research. The weight distributions created during this research were based on those weight classes. Finally, the cumulative fatigue of each bridge was calculated by combining those weight distributions and the traffic volume predictions. Hence, any change in the approach of creating those weight classes will impact the results of this thesis. Moreover, the representative weights of those weight classes were used to create a linear relationship between weight of a crossing airplane and stress within the bridge. The assumption of linear relationship between the two variables was made due to the lack of data. The existence of a non-linear relationship between these two variables would raise doubts about the validity of this study's findings.

Another assumption made during this research concerns the relation between the strength, durability, and fatigue of a bridge. It is a common practice that those three features be considered independent. Based on the insights gained by this research, the lifespan of each asset is found to be larger than the one when the fatigue was calculated by the current (theoretical) approach. It is still assumed that strength, durability, and fatigue remain independent, regardless of the increase in predicted lifespan.

6.3 Recommendations and further study

After identifying the limitations of this research, this section provides recommendations to relax some of the assumptions made. Moreover, suggestions for potential directions for future research are also discussed.

Firstly, a more comprehensive traffic volume prediction dataframe could be created by extending the years of prediction. This dataframe could be created via the Schiphol’s airport traffic prediction. Schiphol airport traffic prediction is a superset of the traffic volume prediction of bridge 1. In other terms, the traffic of the whole airport contains the traffic of bridge 1, but the traffic of bridge 1 does not contain the whole of Sciphol’s traffic. This is the case because Schiphol has runways that are connected to the airport hub without crossing bridge 1. In addition, Schiphol’s forecast department constantly updates the traffic forecast of the airport. New laws and regulations are some examples that influence the traffic volume. Altogether, the estimation of the remaining useful lifespan of Schiphol's bridges (all the models presented by this thesis) would benefit from the update of the traffic prediction of each bridge.

Secondly, to deal with the fact that the data from Heijmans monitoring system was gathered during the COVID-19 pandemic, more data must be gathered during the after-COVID era. Financial performance in all regions, including aviation, is expected to improve in 2023 (*Travel Recovery Hints at Profitability in 2023 | Airlines.*, n.d.). This implies that airplanes will not be forced by regulations to be less crowded while the number of flights will increase throughout the globe. Thus, the sample of monitored airplanes during 2022 and 2023 will be unbiased to COVID in contrast with the sample used in this thesis.

The final recommendation concerns the objective function used for the network traffic allocation model, sub-section 5.3. The objective function includes the cumulative fatigue across the bridges. This approach does not offer much insight regarding the asset's cost. This approach was not in the scope of this research because there is no cost data for replacing a similar bridge due to fatigue in the Netherlands. Moreover, the replacement of an old bridge is most of the times a bridge with different attributes due to different materials and technology. Most of the big bridges in the Netherlands were built after 1965. As a result, no bridge has reached its fatigue threshold limit in order to be replaced. Hence, the objective function of the network traffic allocation model was decided to not include costs.

However, the research in bridge replacement cost would be the steppingstone in the realization of an objective function about cost. If the missing data can be assumed, then the proposed model can be adjusted. The decision variables will remain the same (traffic rules) joined by maintenance decision variables. The objective function will include the cost of bridge replacement and the depreciation value of the investment of each bridge based on the new lifespan of the bridges as predicted by the solution of the model. In other words, by changing the traffic allocation and the maintenance decisions (in this case the replacement of the bridge deck) the model would offer the optimum solution that would achieve the minimum present value of the asset investment throughout its life cycle.

Another potential direction for future research would include the relationship between weight of a crossing airplane and the stress of the bridge. The assumption made for this thesis, that the relation is linear, was based on empirical feedback from the structural department of Heijmans. Finally, the relationship between fatigue, strength, and durability of a bridge is another potential direction for future research. It is empirically considered that the three attributes are independent, based on the fatigue calculations prior to the exploitation of the monitoring data. However, based on the insights gained from this research, the proposed estimation of a bridge's useful remaining lifespan results in a bigger lifespan compared to the prediction prior to the exploitation of the monitoring data. It might be the case that this increase in the predicted lifespan of the bridge influence the assumption of the independent relationship between the three attributes of the bridge. For example, after an amount of time and an accumulated amount of fatigue, the strength of the bridge might have decreased such the fatigue will not be the only safety concern anymore.

Heijmans can further develop the models presented by this thesis. The next steps that they need to follow are to include more bridges to the network by first installing under them their monitoring system. By adding more bridges to the network, the amount of traffic would increase as well. This holds true, because the network that this thesis was focused on serves a portion of the whole airplane traffic within Schiphol airport. Subsequently, the network traffic allocation model could include all the bridges of Schiphol in order to optimize all the airplane traffic to minimize the fatigue on the bridges. As far as Schiphol is concerned, the insights gained from this thesis would be the starting point for them to reconsider the airplane traffic allocation. Schiphol must incorporate this thesis's decision-making parameters into its traffic allocation model in order to minimize their asset cumulative fatigue.

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8. Appendix

```
                            OLS Regression Results
==============================================================================
Dep. Variable:                      y   R-squared:                       0.987
Model:                            OLS   Adj. R-squared:                  0.985
Method:                 Least Squares   F-statistic:                     472.8
Date:                Mon, 30 May 2022   Prob (F-statistic):           6.18e-07
Time:                        16:19:04   Log-Likelihood:                -1.0218
No. Observations:                   8   AIC:                             6.044
Df Residuals:                       6   BIC:                             6.202
Df Model:                           1
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const          6.0781      0.342     17.779      0.000       5.242       6.915
x1             0.0244      0.001     21.745      0.000       0.022       0.027
==============================================================================
```

Figure 41 Results of the regression