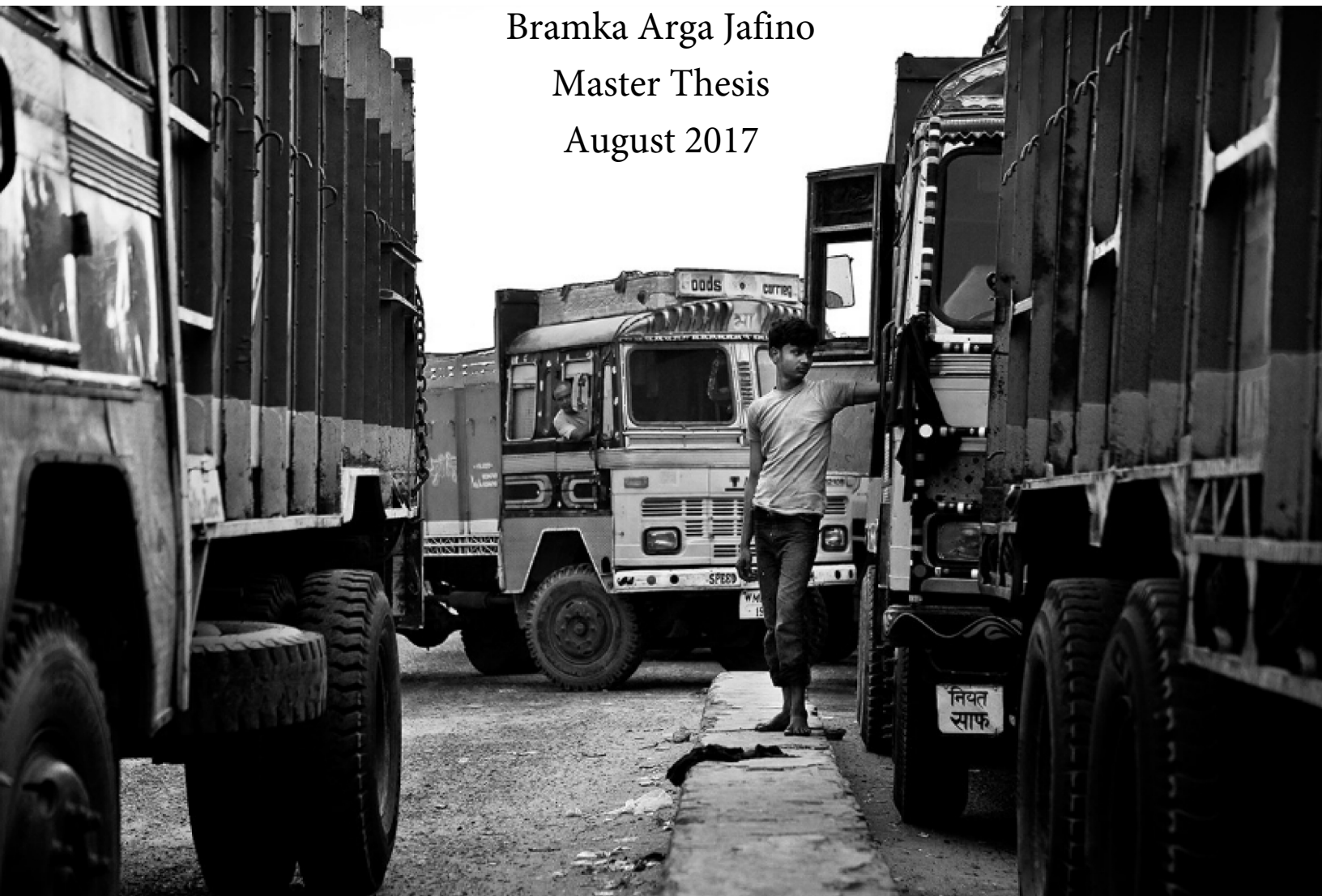


# Measuring Freight Transport Network Criticality

## A Case Study in Bangladesh

Bramka Arga Jafino  
Master Thesis  
August 2017





# Measuring Freight Transport Network Criticality

A Case Study in Bangladesh

by

**Bramka Arga Jafino**

in partial fulfillment of the requirements for the degree of

Master of Science

in Engineering and Policy Analysis,

Faculty of Technology, Policy, and Management,

Delft University of Technology

to be defended publicly on August 15<sup>th</sup> 2017

**Student Number** : 4516516

**Graduation committee**

Chairperson : Prof. Dr. Ir. Alexander Verbraeck, Policy Analysis section

First Supervisor : Dr. Ir. Jan Kwakkel, Policy Analysis section

Second Supervisor : Dr. Jan Anne Annema, Transport and Logistics section

The documentation of all codes used in this thesis can be found at:

<https://github.com/bramkaarga/transcrit>

Cover photo: trucks queueing in Benapole land port, Bangladesh, obtained from:

<http://www.clairelisehavet.com/indexhibit/index.php?/portfolio/benapole/>



# Acknowledgements

After seven months of struggle, this report completes my journey for the final master thesis graduation project. Ultimately, it also marks the end of my adventure as a master student in Engineering and Policy Analysis. Therefore, in this special occasion, I would like to express my deepest gratitude to those who have not only made this thesis possible but also filled my two years of experience in the Netherlands.

First, I would like to truly thank my graduation committee for guiding and supporting me in this project, which is a subset of a professional consultancy project with the World Bank. Jan Kwakkel, who put his trust on me that I would be able to do this work even though we had not been acquainted before and I had zero experience in transport modeling. Alexander Verbraeck, whose attention to details and systematic reasoning had inspired me to always upgrade the quality of my work. Jan Anne Annema, who had been reminding me to not to be drowned in quantitative exercise while forgetting the key points and the lines of argumentation of the whole research.

I would also like to thank the other members of this Bangladesh Transport Network Vulnerability project: Phillip Schwarz, Sibel Eker, and Bahareh Zohoori. The discussions we had for the past seven months have been the most intellectually enriching experience for me. Their help in the technical parts of my thesis, including data collection and code development, is priceless to me.

To my Indonesian friends in daily life as students: Nadia, Templank, Timothy, and Diko. Thanks for the chit chats, laughter, tears, and joys that we shared in these past two years. Those moments have made my life colorful and have crystallized as a precious gem in my memory.

To my fellow EPA colleagues: Yola, Wesley, Kay, Georgios, Rhythima, Duygu, and Pedram. Thanks for making the classroom moments fun (I still have some joke pictures that we shared in our WhatsApp group!). Thanks for all the support throughout the courses. Thanks for all the lunches, drinks, and parties that we did together.

Lastly, to people who are dearest to me. My parents, *Ayah* and *Ibu*, whose patience, love, and care motivate me days and nights. Seeing their smiles and talking with them have been the most emotionally fulfilling activity that I wait for every week. Bitu, whose kindness and understanding have accompanied me through the ups and downs of this wheel of life.

Bramka Arga Jafino

July 2017



# Executive Summary

## Research background

A good transport system is a key prerequisite to a strong economy. Meanwhile, investing in transport infrastructure entails a huge sunk cost. Therefore, when deciding to prioritize their resources for spending on transport infrastructure, a government has to pursue a systematic approach in order to maximize the spending's benefits. For this reason, recent practices of transport infrastructure investment planning use transport network criticality analysis.

Transport network criticality analysis aims at ranking existing transport network elements (e.g. road segments, ports, stations) based on their importance to the serviceability of the transport system. As the focus lies on the existing transport infrastructure, this approach is useful for answering policy relevant questions such as 'which transport network segments should be primarily recovered when disaster strikes?', or 'how should road maintenance budget be distributed among the road segments in a country?'. The approach models the entire transport infrastructure within the study area as a network. Transport segments such as road, waterway, and railway are represented as links in the network while cities, ports, stations, main junctions and intersections are represented as nodes.

This field of study emerged in the early 2000s and had been evolving since then. The loose definition of 'criticality' has resulted in dozens of different metrics and assessment techniques developed by various researchers. They usually develop their own operationalization or adopt an operationalization that they consider to epitomize 'criticality'. Consequently, most studies focus on a narrow definition of criticality and use only a limited number of metrics. On the other hand, using a diverse set of criticality metrics poses a risk of having different criticality outcomes, thus leading to different policy implications. There has been a lack of multiperspective transport network criticality analysis that embraces multiple, diverse plausibility of criticality definitions. Furthermore, some metrics are dependent on the availability of specific data, making them unusable if the same dataset is not available in different study objects. In short, practitioners have been struggling with choosing the best criticality metrics to be used.

Accordingly, this research aims at helping practitioners in transport network criticality to make an informed selection of an appropriate set of criticality metrics to be used that encompasses as many criticality definitions as possible, given the practitioners' problem statement and data availability. The main research question of this study is: *How can a country's multimodal freight transport network criticality be comprehensively assessed?*

## Methodology

In order to answer the main research question, three steps have been taken. First, a semi exhaustive and systematic literature study was conducted in which 78 papers related to transport network criticality were reviewed. Based on these papers, a comprehensive concept map that contains three criticality aspects has been synthesized. A brief literature review on various freight transport modeling approaches was conducted to understand the proper level of simplification for the case study in the next step.

The operationalization of the concept map grounded the second phase of the research, which was a transport network criticality case study. Bangladesh national freight transport was used for the quantitative case study. This

country was chosen because of the relatively limited socioeconomic data availability, while still having sufficient transport network data to account for multimodality. Therefore, this country was suitable for investigating how criticality can still be evaluated comprehensively even when only limited data were available. Moreover, there were ubiquitous rural districts in the southern and western part of Bangladesh, and there were regional imbalances between these rural districts with the core districts located in the central part of Bangladesh. This emphasized the importance of freight transport services to move commodities from/to these districts.

An extensive analysis of Bangladesh's freight transport criticality was done by developing a Bangladesh's multimodal freight transport model in Python (a high-level programming language) and calculating eighteen different criticality metrics from the transport model. The metrics ranged from a simple traffic density metric to a complex change in average accessibility metric. The metrics in principle originated from the operationalization of the criticality aspects. The results were examined on three fronts: individual metrics assessment, metrics robustness to uncertainties, and metrics comparisons. The individual assessment aimed at understanding the statistical distribution of the criticality scores of each metric and visualizing the criticality results geospatially. The robustness analysis observed to what extent the criticality outcomes changed if different parameter settings were applied to the transport model. The metrics comparisons looked for overlapping (i.e. metrics that highlighted the same links as critical) and complementary (i.e. metrics that highlighted different links as critical) metrics. The overlapping metrics were eliminated from the analysis in order to reduce information overload.

The final step of the research was the development of a criticality metrics selection method. The insights gained from the case study, especially the performance of the criticality metrics, grounded the selection method's development. The performance of the metrics refers to the conceptual criticality aspects that the metrics represent, the technical requirements of the metrics, and the complementarity of the metrics.

## **Final deliverables**

All in all, this research provides three main deliverables as listed below:

### **1. Conceptualization and operationalization of transport network criticality aspects.**

There are three main aspects to transport network criticality. First, criticality is network component (i.e. links or nodes) centered. This differentiates criticality from other related terms such as transport network vulnerability, robustness, and resilience, as they focus on the network level rather than on the network component level. Second, the criticality of a network component should measure that component's contribution to the serviceability of the transport network. Contributions can be defined on three dimensions: (i) functionality (minimizing total travel cost, improving accessibility, or providing connectivity), (ii) paradigm underlying the contribution measurement (maximizing the overall utility of the transport network i.e. utilitarianism, or giving equal importance to each sub-region under study i.e. egalitarianism), and (iii) spatial aggregation (network-wide or localized). Third, many criticality metrics require disruption of network components in order to assess the components' contribution to the serviceability of the transport system.

The contribution to serviceability aspect can be operationalized into ten different categories of criticality metrics by tailoring the three dimensions of this aspect, while the disruption aspect translates to eight categories of criticality assessment techniques to calculate the metrics. Based on the 78 reviewed papers, an empirical analysis of which metrics categories and which criticality assessment techniques categories were mostly used is also provided. The operationalization and its empirical analysis can guide practitioners in



transport network criticality to advance criticality metrics and techniques, especially those that are rarely used in previous studies.

## 2. **Identification of overlapping and complementary metrics.**

In order to analyze the degree of overlap/complementarity between any two metrics, statistical measures Kolmogorov-Smirnov (K-S) distance and Spearman-rank correlation coefficient were used. If two metrics have a small K-S distance and a high correlation coefficient, they can be considered as overlapping. *Vice versa*, a large K-S distance and a low correlation coefficient between any two metrics imply that the metrics are complementary. Based on the eighteen metrics calculated in the case study, it was discovered that metric categories representing (i) topological, accessibility, and network wide aspects of criticality (coded category M1), (ii) topological, total travel cost, and network wide aspects of criticality (coded category M2), and (iii) system-based, total travel cost, network wide aspects of criticality (coded category M7) have high correlation coefficients for their own within-group metrics comparison. Therefore, in future criticality studies, representing these categories by only a single metric is sufficient. Lastly, a metric representing system-based, accessibility, and network wide aspects of criticality (coded category M6) was found to have coinciding results with metric categories M2 and M7. Consequently, if it is possible to calculate metric M6 in any future criticality studies, M2 and M7 do not need to be assessed anymore as the results can already be well represented by metric M6 alone.

## 3. **Criticality metrics selection method.**

The selection method was formulated in the form of a decision tree. The decision tree can guide practitioners into an appropriate set of criticality metrics, given the problem statement and the data that the practitioners have. There are three questions that practitioners need to answer in selecting the criticality metrics set to be used: (i) is there any initial preference with regard to the functionality (i.e. either minimizing total travel cost, improving accessibility, or maintaining connectivity) of the transport network that wants to be evaluated?, (ii) is sufficient socioeconomic data on the intended aggregation level (e.g. province or district level) available?, and (iii) how much computational expense (e.g. the timespan of the study and the computing power) do the practitioners want to spend? Based on those questions, eighteen sets of criticality metrics that comprehend a broad range of criticality aspects have been identified. By answering the three questions above, the selection method will lead practitioners to a set of criticality metrics that best apprehend as many criticality aspects as possible. Additionally, a preliminary technique to derive conclusions under the presence of distinctive outcomes from multiple criticality metrics is also proposed.

The usefulness of the selection method was demonstrated by performing two criticality analyses on Bangladesh's freight transport network with different hypothetical policy problems and contextual situations. The two illustrative analyses showed that the different settings of the criticality analyses led to different policy implications because different metrics were used, different criticality aspects were covered, and different techniques were employed to derive conclusions from the criticality outcomes.



# Table of Contents

Acknowledgements.....	1
Executive Summary .....	3
List of Figures .....	11
List of Tables.....	13
<b>Part I : Introducing the Research Problem .....</b>	<b>15</b>
<b>Chapter 1: Introduction .....</b>	<b>17</b>
1.1 Trends in transport infrastructure budget prioritization.....	17
1.2 Transport network criticality scientific issues in a nutshell.....	18
1.3 Thesis structure .....	19
<b>Chapter 2: Research Definition .....</b>	<b>21</b>
2.1 Research gaps, questions, and deliverables .....	21
2.1.1 Research gaps .....	21
2.1.2 Research questions .....	22
2.1.3 Main deliverables.....	23
2.1.4 Research relevance.....	23
2.2 Research methods .....	24
2.2.1 Approach to building criticality assessment method .....	25
2.3 Research flow.....	26
<b>Part II : Exploring Freight Transport Network Criticality.....</b>	<b>27</b>
<b>Chapter 3: Transport Network Criticality Analysis Deep Dive .....</b>	<b>29</b>
3.1 Literature review approach.....	29
3.2 Aspects of transport network criticality definition .....	31
3.2.1 Aspect #1: Network components centered .....	31
3.2.2 Aspect #2: Contribution to the serviceability of the transport system.....	32
3.2.3 Aspect #3: Disruption of network component .....	34
3.2.4 Final synthesis of criticality aspects .....	35
3.3 Transport network criticality metrics .....	36
3.3.1 Layer I: Underlying paradigm operationalized .....	36
3.3.2 Layer II: Functionality operationalized .....	37
3.3.3 Layer III: Aggregation operationalized.....	38
3.3.4 Enumeration of the three layers .....	38
3.4 Assessment techniques of transport network criticality .....	40
3.4.1 Layer I: Number of assessment stages .....	40
3.4.2 Layer II and III: Disruption or no disruption.....	41
3.4.3 Layer IV and V: Probability and extent of disruption .....	41

3.4.4 Enumeration of the five layers .....	41
3.5 Chapter 3 Summary .....	43
<b>Chapter 4: Bangladesh Freight Transport Network Case Study .....</b>	<b>45</b>
4.1 A brief review on multimodal freight transport modeling .....	45
4.1.1 General approach to freight transport modeling .....	45
4.1.2 Multimodality of freight transport model.....	48
4.1.3 Approach applied in this case study .....	49
4.2 Contextual background of Bangladesh freight transport.....	51
4.2.1 Geographical features of Bangladesh .....	52
4.2.2 General overview of freight transport infrastructure .....	53
4.2.3 Institutional setting of transport infrastructure .....	55
4.3 Model specification .....	56
4.3.1 Socioeconomic data and O/D matrix calculation .....	56
4.3.2 Transport supernetwork development .....	58
4.3.3 Network assignment .....	60
4.3.4 Interdiction technique implementation .....	61
4.4 Chapter 4 Summary .....	62
<b>Chapter 5: Criticality Analysis Results Evaluation .....</b>	<b>65</b>
5.1 Evaluation framework.....	65
5.1.1 Criticality metrics set selection criteria .....	66
5.1.2 Individual metrics assessment .....	67
5.1.3 Robustness analysis and uncertainties demarcation .....	68
5.1.4 Comparison between metrics .....	71
5.2 Selected metrics and individual assessment.....	72
5.2.1 Brief description of the selected metrics.....	73
5.2.2 Individual assessment of the selected metrics .....	74
5.3 Robustness results.....	76
5.4 Metrics comparison and elimination.....	80
5.5 Generalization of metrics comparison .....	85
5.6 Chapter 5 Summary .....	86
<b>Part III : Designing Criticality Metrics Selection Method.....</b>	<b>87</b>
<b>Chapter 6: Development of Metrics Selection Method for Criticality Analysis .....</b>	<b>89</b>
6.1 Insights from literature review and case study .....	89
6.1.1 General insights .....	89
6.1.2 Insights related to the metrics employed in the case study.....	90
6.1.3 Insights related to the assessment techniques used in the case study .....	94
6.2 An informed criticality metrics selection method .....	95
6.2.1 Complete functionality specific choice sets .....	96
6.2.2 Topological-based functionality specific choice sets .....	97
6.2.3 Comprehensive choice sets .....	98
6.2.4 Topological-based comprehensive choice sets .....	99

6.2.5 Dealing with multiple criticality outcomes.....	100
6.3 Demonstration of the selection method.....	103
6.3.1 Illustrative case study 1 .....	103
6.3.2 Illustrative case study 2 .....	105
6.4 Chapter 6 Summary .....	107
<b>Chapter 7: Conclusion and Reflection.....</b>	<b>109</b>
7.1 Revisiting research questions.....	109
7.2 Policy recommendations from the illustrative case studies.....	111
7.3 Limitations and future research.....	112
7.4 Beyond the research: Some retrospective critiques.....	113
<b>References .....</b>	<b>117</b>
<b>Appendix A : Software Packages Used.....</b>	<b>123</b>
<b>Appendix B : Socioeconomic Figures Geovisualization .....</b>	<b>124</b>
<b>Appendix C : Mathematical Formulation of Criticality Metrics.....</b>	<b>125</b>
<b>Appendix D : Metrics Density Overlaps.....</b>	<b>130</b>
<b>Appendix E : Spearman-rank Analysis for Subnetworks.....</b>	<b>131</b>
<b>Appendix F : Summary of the Metrics Choice Sets.....</b>	<b>133</b>



# List of Figures

Figure 1 Possible budget prioritization schemes.....	18
Figure 2 Thesis outline.....	20
Figure 3 Research flow diagram .....	26
Figure 4 Conceptual flow of Chapter 3.....	29
Figure 5 Literature review flowchart.....	30
Figure 6 Hypothetical transport network, the number represents the economic weight of the nodes.....	33
Figure 7 Concept map of criticality aspects .....	36
Figure 8 Layered approach to criticality metrics.....	37
Figure 9 Sorted criticality metrics distribution from 78 reviewed papers .....	39
Figure 10 Layered approach to assessment techniques.....	40
Figure 11 Sorted assessment techniques distribution from 78 reviewed papers .....	42
Figure 12 Four-step modeling (Ortuzar & Willumsen, 2011) .....	46
Figure 13 Options for freight modeling approach.....	47
Figure 14 Multimodal supernetwork illustration.....	49
Figure 15 Overview of modeling approach for this study.....	49
Figure 16 Geographical highlights of Bangladesh.....	52
Figure 17 Evolution of cargo modal share, obtained from Smith (2009) .....	54
Figure 18 Relevant institutions to freight transport system .....	55
Figure 19 O/D matrix heatmap on division level (units in tonnage) .....	58
Figure 20 Road Network preprocessing scheme.....	59
Figure 21 Supernetwork development.....	60
Figure 22 Network flow .....	61
Figure 23 Illustration of technical implementation of interdiction technique .....	62
Figure 24 Metrics evaluation framework .....	65
Figure 25 Possible distribution of criticality values .....	67
Figure 26 Robustness analysis scheme.....	70
Figure 27 Distribution scores from each metric.....	75
Figure 28 Multiple metric-rank combinations from individual geovisualization tool.....	76
Figure 29 Heatmap of spearman correlation between each replication for topological metrics.....	77
Figure 30 Heatmap of spearman correlation between each replication for system-based metrics.....	78
Figure 31 Kolmogorov-Smirnov distance between each replication for topological metrics.....	79
Figure 32 Kolmogorov-Smirnov distance between each replication for system-based metrics.....	79
Figure 33 Value sensitivity of all metrics.....	80
Figure 34 Kolmogorov-Smirnov distance between metrics distribution .....	81
Figure 35 Spearman-rank correlation coefficient between metrics.....	82
Figure 36 Geovisualization panel of the remaining metrics .....	84
Figure 37 Comparison of assessment techniques .....	94
Figure 38 Criticality metrics selection decision tree - First layer.....	96
Figure 39 Criticality metrics selection decision tree - Second layer category A1 .....	97
Figure 40 Criticality metrics selection decision tree - Second layer category A2 .....	98
Figure 41 Criticality metrics selection decision tree - Second layer category A3 .....	99
Figure 42 Criticality metrics selection decision tree - Second layer category A4 .....	100

Figure 43 Proposed procedure for dealing with multiple metrics.....	101
Figure 44 Spearman-rank correlation coefficients and K-S distances between metrics in case study 1 .....	104
Figure 45 Geovisualization of top 100 most critical links for case study 1 .....	105
Figure 46 Spearman-rank correlation coefficients and K-S distances between metrics in case study 2 .....	106
Figure 47 Geovisualization of weighted average criticality score for case study 2 .....	107
Figure 48 Socioeconomic figures distribution of key factors .....	124
Figure 49 Illustration of number of alternative links.....	127
Figure 50 1 in 75 Fluvial defended flood map of Bangladesh.....	129
Figure 51 Density overlap for all metrics .....	130
Figure 52 Spearman-rank correlation heatmap for subnetworks (1).....	131
Figure 53 Spearman-rank correlation heatmap for subnetworks (2).....	131
Figure 54 Spearman-rank correlation heatmap for subnetworks (3).....	132
Figure 55 Spearman-rank correlation heatmap for subnetworks (4).....	132



# List of Tables

Table 1 Research methods.....	24
Table 2 Adaptation of conceptual framework building .....	25
Table 3 Assessment object of related terms comparison .....	32
Table 4 Criticality metrics categories.....	39
Table 5 Assessment techniques categories .....	42
Table 6 IWT classification, acquired from Mahmud et al. (2007).....	54
Table 7 Commodities selected in this study.....	57
Table 8 Freight modal share comparison.....	60
Table 9 Requirements for selecting set of criticality metrics .....	66
Table 10 Transport model uncertainties .....	69
Table 11 Selected metrics set.....	72
Table 12 Uncertainties review.....	76
Table 13 Metrics with high correlations.....	83
Table 14 Metrics with high correlations in general for all (sub)networks.....	85
Table 15 Comparison of criticality metrics performance .....	91
Table 16 Case study 1 contextual situations .....	103
Table 17 Case study 2 contextual situations .....	105
Table 18 Python libraries utilized in this study .....	123
Table 19 Metrics sets technical aspects summary .....	134
Table 20 Criticality aspects conceptual level representation of metrics sets summary .....	135
Table 21 Criticality aspects representation of metrics sets summary.....	136

*This page is intentionally left blank.*

# Part I : Introducing the Research Problem

*“If we knew what it was we were doing, it would not be called research, would it?”*

*– Albert Einstein*

*This page is intentionally left blank.*

# Chapter 1: Introduction

A good transportation system has been widely acknowledged as a prerequisite to strengthen a nation's economy. Increasing transport infrastructure supply will have a multiplier effect on the productivity of other economic sectors both at a regional and a national level (Rietveld, 1994). This makes investments in transport infrastructure very valuable. However, the critical role of transport systems usually comes with a huge sunk cost for its infrastructure investment. Therefore, a comprehensive transport infrastructure planning should maximize the societal benefits of the incurred investment (Banister & Berechman, 2003). This chapter introduces the research by describing the trends in transport infrastructure investment and how transport network criticality has become a prominent tool for studying transport infrastructure investment. Furthermore, the scientific issues surrounding transport network criticality are elaborated.

## 1.1 Trends in transport infrastructure budget prioritization

Traditionally, transport infrastructure project appraisal is guided by a multi criteria cost benefit analysis (CBA) of the proposed investment (Hayashi & Morisugi, 2000). The CBA study comprises transport-related indicators such as expected saving in travel time, increase in traffic safety and forecasted traffic flow, economic-related indicators such as impacts on regional economic and return on investment, and other externalities such as environmental impact. These metrics, however, are localized in scale. For instance, economic impacts are calculated by estimating the number of workers during the construction process, and the transport supply surplus to cities around the investment project. Weights are then put on the indicators based on the stakeholders' preference. The resulting benefit-cost ratio is used to prioritize multiple transport infrastructure project candidates.

The localized metrics of transport infrastructure project miss a fundamental aspect of a transport infrastructure system. Transport infrastructure systems are networked in nature (Lin & Ban, 2013), and localized CBA overlooks this. From a network theoretical perspective, road, waterway, and railway segments can be represented as links while junctions, intersections, stations, ports, and cities can be represented as nodes. Due to the interconnectedness of links and nodes, transport infrastructures should not be treated independently. A disruption in one road segment does not only affect cities adjacent to it since the behavioral change of that road segment's users will perturbate to other road segments, which in turn disrupts other road segments' users. The same principle applies to improvement in transport infrastructure; increasing the number of lanes on a specific road segment will attract more transport users to go through that road segment, altering the overall travel behavior of a larger group of road users in the entire network.

Accepting that a transport system is a network in nature calls for a new approach of project appraisals that embraces wider aspects of an infrastructure element's contribution. This is especially important during *ex-ante* evaluation when decision makers want to prioritize their budget. Specifically, there are four distinguished situations on budget allocation as schematically shown in Figure 1. The localized CBA approach is only suitable for prioritizing over a set of predefined infrastructure candidates, both for the existing ones or the new ones (e.g. several predefined new bridges to be built, or several predefined existing road segments to be paved). However, it should be emphasized that localized CBA is still not enough because it does not incorporate the network effects.

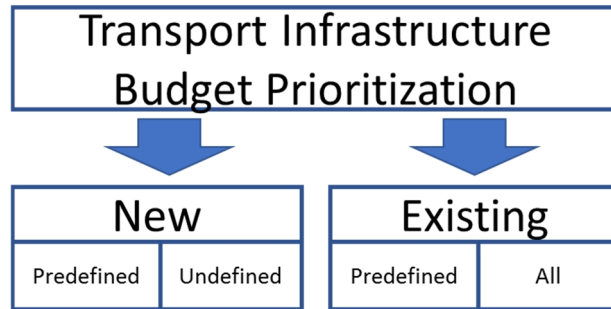


Figure 1 Possible budget prioritization schemes

Identifying the most economically sound places for undefined new transport infrastructure has not been extensively studied. Nevertheless, several concepts such as spatial economic resilience and transport links redundancy have been argued to be helpful for this purpose. Spatial economic resilience combines spatial-economic profiles of regions with accessibility and transport supply availability (Östh, Reggiani, & Galiazzi, 2015). Regions that have potential economic activity but low accessibility and low transport supply can benefit from transport infrastructure investments. Transport links redundancy simply measures the excess of transport supply in a region (e.g. kilometers of road per area, or kilometers of road per capita) (E. Jenelius, 2009).

As for ranking all existing transport infrastructures, transport network vulnerability and criticality analysis is becoming a more prominent approach (Mattsson & Jenelius, 2015). Put differently, vulnerability and criticality analysis is of utmost relevance as a decision support tool to prioritize resources for protecting, maintaining and improving the serviceability of the current transport network.

## 1.2 Transport network criticality scientific issues in a nutshell

The first definition of transport network vulnerability was introduced by Berdica (2002) as a two-fold concept: susceptibility of the transport network to disruption and substantial degradation in transport network serviceability. Accordingly, a network is more vulnerable if it is more exposed to disruption (e.g. flood) and if its disruption causes a considerable impact on the functioning of the transport system (e.g. disconnecting several cities).

Whereas transport network vulnerability introduced by Berdica is a system-level concept, Erik Jenelius, Petersen, and Mattsson (2006) proposed the term ‘criticality’ for transport network vulnerability assessment on network component level (i.e. links or nodes). They argue that a component is critical if it is both ‘weak’ (it is likely to be exposed to disruption) and ‘important’ (the consequences of the disruption is substantial). With the primary aim of identifying the most critical infrastructure in the existing transport network, criticality study fits the need of decision support tool for budget prioritization over all existing transport infrastructure.

As the field of study grows, the concept of criticality has deviated from the original idea proposed by Erik Jenelius et al. (2006). For instance, Pant, Hall, Blainey, and Preston (2015) in their research do not use the ‘weak’ aspect of transport infrastructure to define criticality. Rather, they use the ‘important’ aspect plus the traffic flow on a particular transport infrastructure in a no disruption scenario. As a matter of fact, dozens of other methods (i.e. criticality metrics and assessment techniques) have been employed to quantify the criticality of transport network elements. These methods range from simple measurement of road length (J. L. Sullivan, Novak, Aultman-Hall, & Scott, 2010) to a fuzzy logic based combination of some metrics (El-Rashidy & Grant-Muller, 2014). Reflecting back

to the initial meta problem, this phenomenon occurs because researchers have been struggling with the exact definition of criticality itself.

The numerous different definitions of criticality force practitioners to struggle with selecting the appropriate methods to assess a transport network's criticality. Eventually, in practice, practitioners only use few criticality metrics that they think epitomize the criticality definition. As an example, a World Bank study on Peru's road network criticality uses three metrics to assess criticality: (i) the least-cost routes between all pairs of economic nodes, (ii) the roads' traffic level, and (iii) the increase of total travel cost when a road segment is removed from the network (Rozenberg, Garmendia, Lu, Bonzanigo, & Moroz, 2017). Whereas, as explained in the previous paragraph, the study could have employed other dozen metrics to analyze the road network's criticality. However, it has to be realized that using a different set of metrics may lead to different criticality results. Consequently, there is a risk that the criticality analysis could have resulted in a very different policy implication.

Practitioners are left with the question whether a single best metric is present, or whether all metrics should be used simultaneously. In the first case, which metric is the best one and how can one determine the best metric? In the other case, how can an informed choice on a set of metrics to use be made? The situation where practitioners are faced with numerous indicators fits the third definition of deep uncertainty as coined in the box below (Lempert, 2003).

*“.....that is, **where analysts do not know, or the parties to a decision cannot agree on**, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) **how to value the desirability of alternative outcomes.**” (Lempert, 2003)*

To further complicate matters, different metrics and assessment techniques require different input data. As an example, increase in total travel cost due to disruption requires information about the number of trips on the network (Rodríguez-Núñez & García-Palomares, 2014). This information may not be needed if criticality is defined as the contribution of transport infrastructure to maintain connectivity between places, as measured by minimum edge cut centrality (Yang, Tu, & Chen, 2009). The data dependency nature of the methods in previous studies makes some transport network criticality studies irreproducible in different contexts if the same type of data is not available.

For that reason, the ultimate aim of this research is to develop a metrics selection method to assess transport network criticality with emphasize on nation-wide multimodal freight transport. By comprehensive, it is expected that the method will be able to guide practitioners to the best set of criticality metrics that captures a broad range of plausible definitions of criticality while relaxing the dependency on data inputs.

### **1.3 Thesis structure**

This thesis is divided into three parts as outlined in Figure 2: introduction of the research problem, exploration of freight transport network criticality, and design of selection method to assess nation-wide freight transport network criticality.

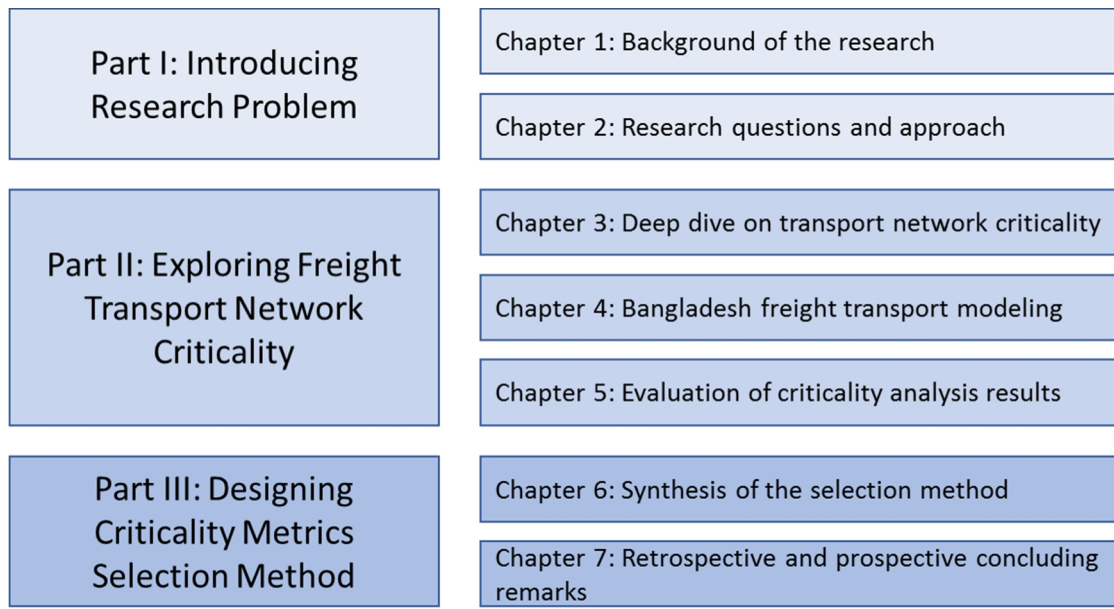


Figure 2 Thesis outline

Part I describes the background of the research, research gaps to be addressed, and approaches used for addressing the research questions. In chapter 2, the research questions are introduced and the final deliverables are explained. Following the deliverables is the overview of the research approach used throughout the thesis. The specific approach used to design the metrics selection method is elaborated in detail as it guides the flow of the overall research.

Part II presents building blocks from which insights will be generated for developing the metrics selection method. Both literature study and case study are exhibited in this part. The part begins with Chapter 3 where transport network criticality is discussed theoretically in depth. Main concepts surrounding the notion are synthesized and their operationalization thereof is elaborated. Chapter 4 introduces Bangladesh freight transport that becomes the subject of a test-case of transport network criticality operationalization. The Chapter also explicates scientific approaches of freight transport modeling and the specific approach used in the case study. Chapter 5 operationalizes criticality concepts upon the case study and explores plausible ways of extracting insights from the criticality analysis.

Part III ends the research by developing a metrics selection method based on the insights gained from the previous chapters. Lastly, Chapter 7 elaborates retrospective conclusions from the study and prospective reflections for future research.



## Chapter 2: Research Definition

The ultimate aim of this research is to develop a criticality metrics selection method that can encompass a broad range of criticality aspects given the data availability of the study object. To achieve this objective, the research gaps should firstly be made explicit. Research question and its corresponding sub-research questions are then elaborated in Section 2.1. Further, the research methods for answering each question are explained in Section 2.2. Lastly, the research flow describing the interconnectedness of the different chapters in this study is presented in Section 2.3.

### 2.1 Research gaps, questions, and deliverables

Based on a preliminary literature study, the research gaps tried to be addressed by this thesis are found. The research gaps translate to a general research question that can be answered by solving the sub-research questions. Lastly, the key deliverables of the thesis are enlisted.

#### 2.1.1 Research gaps

Previous studies in transport network vulnerability and criticality focus on advancing assessment techniques (e.g. Burgholzer, Bauer, Posset, & Jammernegg, 2013; D. Z. W. Wang, Liu, Szeto, & Chow, 2016; Zhang et al., 2014) and developing new metrics that capture different features of the transport system (e.g. Knoop, Snelder, van Zuylen, & Hoogendoorn, 2012; Soltani-Sobh, Heaslip, & El Khoury, 2015; Su, Hua, Lan, & Yang, 2012). Different authors usually develop their own metrics or adopt metrics that they consider to characterize 'criticality'. In practice, some of these metrics may highlight the same network segments as critical. Other metrics may be complementary as they represent different aspects of criticality. To date, the extent to which the use of multiple metrics influences the result of the criticality analysis has not been explored. Therefore, the first research gap identified is:

**Research gap #1: Lack of multiperspective transport network criticality analysis method that embraces diverse criticality aspects.**

Furthermore, reliance on specific data for several metrics jeopardizes the metrics' reusability in other contexts. This calls for a generalized method that enables analysts to enlist the criticality metrics and assessment techniques that are calculable given the case specific data availability of the study object. Additionally, the implication of data availability toward the final conclusion of the criticality study has not been well addressed. Therefore, the second research gap can be encapsulated as:

**Research gap #2: Lack of a systematic understanding on the data requirements of various transport network criticality metrics and assessment techniques.**

## 2.1.2 Research questions

The contextual background and the two scientific gaps lead to the following main research question:

***How can a country's multimodal freight transport network criticality be comprehensively assessed?***

The key element of the research question that differentiates this study with previous studies is the 'comprehensiveness' of the method. Since there are various methods (i.e. metrics and techniques) available to assess criticality, a systematic understanding of these methods should be tailored: the criticality aspects they represent, the operationalization requirements (including the data requirements), and the way in which the conclusions are derived.

The main research question can be solved by answering five sub-questions. As a first step, a meta-level understanding of transport network criticality should be established. To achieve this purpose, the general aspects of transport network criticality have to be synthesized based on the various definitions of the transport network criticality itself.

**Sub RQ #1: What general aspects of transport network criticality can be synthesized from the diverse criticality definitions?**

Next, the way in which criticality can be operationalized should be assessed. A coherent operationalization framework should be made by deriving from the criticality aspects synthesized in sub-research question #1. The term operationalization refers to the metrics used to represent criticality, the assessment techniques to quantify the metrics, and the associated data requirements.

**Sub RQ #2: How can the criticality aspects be operationalized in practice?**

Several metrics may highlight a similar set of road segments as critical. Thus, they are overlapping with each other. On the other hand, other sets of metrics are complementary if they illuminate different road segments as critical. Accordingly, the (dis)similarities among the metrics should be investigated.

**Sub RQ #3: When applied to a real-world network, how do different metrics overlap and complement one another?**

In network theory, it is widely noted that the structure and characteristics of a network determine its performance (Newman, 2010). Therefore, the (dis)similarities result from the previous sub-research question may not hold for different network structures. Whether this is also the case for freight transport networks should be examined. Furthermore, regardless of the network structures, several criticality metrics depend on abstract parameters which observation in the real world is either difficult or impossible. The robustness of the metrics (dis)similarities has to be assessed, especially for testing the possibility of generalizing the conclusion in sub-research question #3.

**Sub RQ #4: How robust are the metrics and their complementarity and overlap when faced with uncertainty?**

## in parameters and network structure?

After synthesizing the conceptualization and operationalization of transport network criticality, as well as understanding the performance of the metrics, the final step is designing a method for selecting the most relevant set of criticality metrics based on the contextual situation of the criticality study. The method should be able to guide people involved in criticality study in making an informed selection of an appropriate criticality metrics set given the criticality study objective and the technical constraints (e.g. limited computation power or limited data availability). The insights gained from answering the preceding research questions feed into this method development process.

## Sub RQ #5: How can an informed selection of an appropriate set of transport network criticality metrics be made?

### 2.1.3 Main deliverables

Answering the aforementioned questions results in four main deliverables:

1. **A conceptualization of transport network criticality and its operationalization;** this deliverable provides an overview of the various aspects of transport network criticality and how they are operationalized by different metrics and different assessment techniques to calculate the metrics, and what their subsequent data requirements are. An empirical observation of which aspects were mostly used in previous studies is also provided. This deliverable is presented in Chapter 3.
2. **An empirical analysis of criticality metrics (dis)similarities;** this deliverable explores which of the eighteen metrics employed in this study provide similar results and which of them produce noticeably different results. The generalizability of the (dis)similarities in different transport network structures is tested as well. This deliverable is presented in Chapter 5.
3. **A metrics selection method for network criticality analysis;** grounded upon the insights derived from the previous deliverables, this deliverable provides an informed selection method for selecting an appropriate set of criticality metrics that embraces as many criticality aspects as possible, given the study objective and the technical limitations of the criticality study. This deliverable is presented in Chapter 6.
4. **A criticality analysis for Bangladesh;** as a proof of concept of the selection method, this deliverable investigates the criticality of Bangladesh's multimodal freight transport network based on two different hypothetical policy problems. This deliverable is presented in Chapter 6.

### 2.1.4 Research relevance

This study provides both scientific and societal relevance. From a scientific point of view, this study tries to close the knowledge gap of single-perspective and data-dependence nature of criticality studies. The final outcome, a metrics selection method, is intended for this purpose by providing a complete picture of the possible sets of metrics that embrace a broad range of criticality aspects to be used given the contextual data availability. In achieving this, this study also develops a concept map of transport network criticality aspects which future criticality studies can be grounded in.

From a societal point of view, the research can be useful for the Bangladeshi Government and multinational organizations concerned with this issue such as the World Bank. First, the results from the case study of

Bangladesh’s multimodal freight transport network can help the Government in prioritizing their budget for investments in the existing transport infrastructure. Reflection on the freight transport modeling exercise, which is integral to the criticality analysis, can aid the Government in determining unavailable data to be collected for future transport modeling studies. Second, this is also the case for multinational organizations. The reflection can guide them in helping especially data-poor countries to collect relevant data for criticality studies. Furthermore, this research urges such organizations to move from a single-perspective to a multiperspective criticality analysis by providing a proof of concept of the idea.

## 2.2 Research methods

The sub-questions are answered with different methods presented in Table 1. To tackle the different challenges in this research, a combination of qualitative and quantitative methods is employed. The qualitative methods consist of literature review, desk research, and conceptual framework building while the quantitative methods consist of freight transport modeling and statistical analysis.

*Table 1 Research methods*

Sub-RQ	Method	Deliverables
General aspects of criticality	Literature review	Criticality aspects and operationalization
Operationalization of the aspects		
(Dis)similarities of criticality metrics	Transport modeling case study + Statistical & robustness analysis	Criticality empirical assessments based on the case study
Robustness of criticality metrics		
Generalized method development	Conceptual framework building	Informed criticality metrics selection method

The first two sub-questions involve capturing and systematizing the richness of transport network criticality properties from previous studies. Thus, a literature review is conducted for this. The literature study is carried out in two stages; the aim of the first stage is to develop an initial idea of the general aspects of transport network criticality while the objective of the second one is to support and finalize the criticality aspects synthesis. This approach will be further detailed in Section 3.1.

Sub-question 3 and 4 require a quantitative assessment of criticality metrics. For this, a case study of the Bangladesh’s freight transport network is performed. This country is selected for two reasons. First, from practicability point of view, Bangladesh has sufficient transport network data to account for multimodality. However, the socioeconomic data availability is limited. This is suitable for assessing how criticality can still be evaluated comprehensively even when only limited data is available. Second, there are ubiquitous rural districts in the southwestern and the western part of Bangladesh. There are regional economic imbalances between these periphery districts and the core districts in the central part of Bangladesh. This phenomenon emphasizes the importance of freight transport services to transfer goods from/to the rural areas. Furthermore, it calls for a comprehensive assessment of the transport network criticality, as focusing transport investment solely on the transport segments in the busiest region may deepen the inequality.

As a start of the case study, a review of various multimodal transport modeling approaches is presented in Chapter 4. Next, the results from the modeling exercise are analyzed by using statistical and robustness analysis techniques.

Sub-question 5 is the capstone of this study and draws upon the answers of the other sub-questions. Therefore, the approach for answering it is discussed in the following section as it establishes the overall structure of the research.

### 2.2.1 Approach to building criticality assessment method

The approach followed to build the criticality metrics selection method is the methodology of conceptual framework development presented by Jabareen (2009). Conceptual framework development is a qualitative method that was originally designed for building a new conceptual framework based on an extensive literature review. However, as this research is aimed at developing a method based on not only literature review but also a quantitative case study, the steps are slightly modified. Table 2 presents the adaptation and the relevant sections in this thesis.

*Table 2 Adaptation of conceptual framework building*

<b>Phase</b> (based on Jabareen (2009) )	<b>Adaptation to this research</b>	<b>Relevant section</b>
Mapping selected data sources	Two main building blocks: transport modeling and transport network criticality	Section 3.1 and 4.1
Extensive reading and categorizing of the selected data	1. Literature review 2. Case study	1. Chapter 3 and Section 4.1 2. Section 4.2, 4.3 and Chapter 5
Identifying and naming concepts	Deriving insights from case study and literature review	Section 6.1
Deconstructing and categorizing the concepts		
Integrating the concepts	Development of the criticality metrics selection method	Section 6.2
Synthesis		
Validation	Proof of principle: examples of the method's use	Section 6.3
Rethinking the conceptual framework	Reflection on the developed method	Chapter 7

The building blocks for developing the generalized assessment method are transport modeling and transport network criticality analysis. Thus, there is no dedicated section for mapping the selected data sources (Phase 1). Rather, the two building blocks are presented in Chapter 3 and 4. The second phase, which originally is extensive reading to build the new conceptual framework, is adapted to literature review and case study. The insights (Jabareen (2009) denotes them as 'concepts') gained from these are made explicit in Section 6.1. The insights are then integrated into an informed criticality metrics selection method, and the detailed description of the method is elaborated in Section 6.2. As the term validation was originally relevant for testing a 'conceptual framework', it is not applicable for testing a 'method'. Therefore, in this research, this phase is substituted with a proof of principle of the method. Two case studies based on the developed method and drawn upon Bangladesh's freight transport network is presented in Section 6.3 to demonstrate the usefulness of the method. Lastly, the developed method is reflected in the final chapter.

## 2.3 Research flow

Figure 3 shows the conceptual flow of the entire research. The study begins by conducting the literature review and preparing relevant data for the case study. The literature review is performed for two building blocks: transport network criticality and multimodal freight transport modeling. Since the focus of this research is the former one, a deeper and more critical review is conducted for it. A custom-tailored freight transport modeling approach based on the available data is specified for the Bangladesh case study. The literature review of transport network criticality results in a concept map of criticality aspects and its operationalization. Together with the developed Bangladesh freight transport model, the criticality metrics are computed and evaluated.

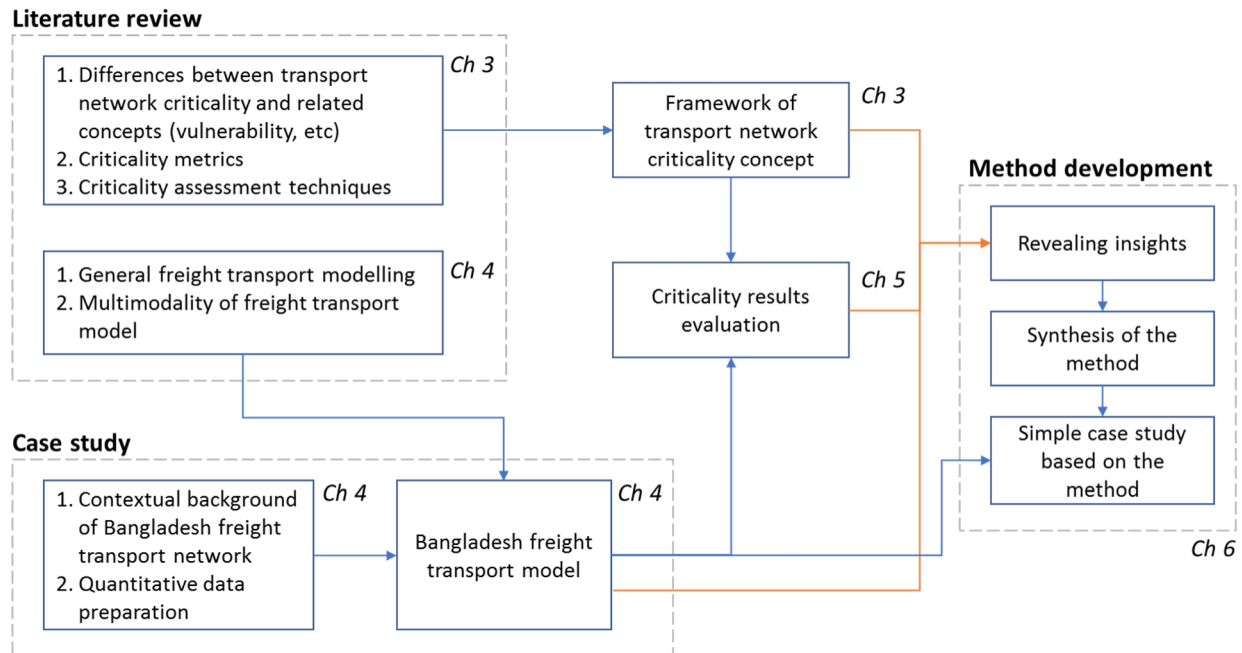


Figure 3 Research flow diagram

The final stage of the study starts by collecting insights from Chapter 3 through Chapter 5 (purposefully illustrated by orange arrows in Figure 3). Building upon these, the informed criticality metrics selection method is formulated. Finally, using the same freight transport model, a proof of principle of the method is demonstrated by addressing two distinctive policy problems.

## **Part II : Exploring Freight Transport Network Criticality**

*“At the same time that we are earnest to explore and learn all things, we require that all things be mysterious and unexplorable, that land and sea be indefinitely wild, unsurveyed and unfathomed by us”*

*– Henry David Thoreau*

*This page is intentionally left blank.*



# Chapter 3: Transport Network Criticality Analysis Deep Dive

As discussed in the introduction, there is still no consensus on the exact definition and best indicators of transport network criticality. This chapter enriches the discussion of transport network criticality by trying to provide a complete picture of the concept. This chapter conceptually follows the framework presented in Figure 4. First, various aspects of transport network criticality definition are discussed and a concept map is developed in Section 3.2. These aspects can be viewed as the building blocks of the criticality concept. From these aspects, the criticality metrics and the assessment techniques to calculate them are operationalized in Section 3.3 and 3.4 consecutively. Before discussing the main findings, this chapter starts with an explanation of the approach used for the literature review in Section 3.1.

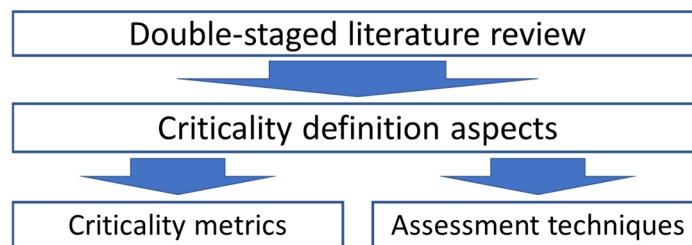


Figure 4 Conceptual flow of Chapter 3

## 3.1 Literature review approach

Figure 5 shows the double-stage literature review conducted in this research. The intention of conducting double-stage literature review is to first grasp the general idea of transport network criticality from a relatively small number of papers, then enhancing the initial general idea afterward. Therefore, the preliminary aspects of criticality obtained from the first stage of the literature review are a foundation that remains to be completed by the second stage of the literature review.

In the first stage, semi exhaustive literature review is conducted. The literature review starts by looking for (i) seminal papers and (ii) recent review papers on transport network vulnerability and criticality. Based on the first few papers, prominent researchers and other interesting papers are identified. The process continues and eventually twenty papers are found. Content analysis is conducted on these papers in order to synthesize the preliminary ideas of criticality aspects.

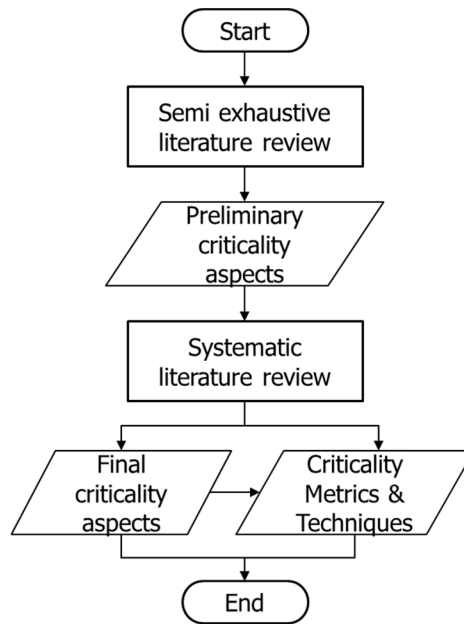


Figure 5 Literature review flowchart

The second stage is a systematic literature review conducted by extracting relevant papers from Scopus and ScienceDirect databases. The syntaxes for each database are presented in the following text box. In short, the terms ‘transport’, ‘road’ and/or ‘freight’ along with ‘critical’, ‘vulnerable’ and/or ‘important’ are used for the systematic search. The topics are limited to transportation study, as there are also other subjects such as physics and biology that have similar terms.

#### **Scopus**

```

TITLE ( ("transport*" OR "road*" OR "freigh*") AND ("critical*" OR "vulnerab*" OR "importan*") ) AND
KEY ( ("transport*" OR "road*" OR "freigh*") AND ("critical*" OR "vulnerab*" OR "importan*") ) AND (
LIMIT-TO ( SUBJAREA , "ENGI " ) OR LIMIT-TO ( SUBJAREA , "SOCI " ) OR LIMIT-TO ( SUBJAREA ,
"MATH " ) OR LIMIT-TO ( SUBJAREA , "BUSI " ) OR LIMIT-TO ( SUBJAREA , "MULT " ) OR LIMIT-TO
( SUBJAREA , "ECON " ) ) AND ( LIMIT-TO ( PUBYEAR , 2017 ) OR LIMIT-TO ( PUBYEAR , 2016 ) OR
LIMIT-TO ( PUBYEAR , 2015 ) OR LIMIT-TO ( PUBYEAR , 2014 ) OR LIMIT-TO ( PUBYEAR , 2013 ) OR
LIMIT-TO ( PUBYEAR , 2012 ) OR LIMIT-TO ( PUBYEAR , 2011 ) OR LIMIT-TO ( PUBYEAR , 2010 ) OR
LIMIT-TO ( PUBYEAR , 2009 ) OR LIMIT-TO ( PUBYEAR , 2008 ) ) AND ( EXCLUDE ( SUBJAREA ,
"PHYS" ) OR EXCLUDE ( SUBJAREA , "MATE" ) OR EXCLUDE ( SUBJAREA , "MEDI" ) OR EXCLUDE (
SUBJAREA , "CENG" ) OR EXCLUDE ( SUBJAREA , "CHEM" ) OR EXCLUDE ( SUBJAREA , "PSYC" ) OR
EXCLUDE ( SUBJAREA , "BIOC" ) OR EXCLUDE ( SUBJAREA , "NEUR" ) OR EXCLUDE ( SUBJAREA ,
"NURS" ) )
  
```

#### **ScienceDirect**

```

TITLE((transport* OR road* OR freight*) AND (critical* OR vulnerab* OR importan*)) AND
KEYWORDS((transport* OR road* OR freight*) AND (critical* OR vulnerab* OR importan*)) AND LIMIT-
TO(topics, "transport,transport critical,road,network")
  
```

The initial search results in a total of 397 papers (249 papers from Scopus and 148 papers from ScienceDirect). A quick scan of the abstracts is performed on all papers to decide if they are relevant for this study. This step reduces the total number of papers to 112. However, 25 papers could not be found on the internet. Most of these non-downloadable papers are published in Chinese conferences that are not publicly accessible. Lastly, content analysis is performed, focusing on the criticality and/or vulnerability metrics as well as the assessment techniques. This results in 66 usable papers, of which eight of them have been found in the first stage of the literature review. Together with the semi exhaustive literature review, 78 papers are reviewed.

From the second stage of the literature review, the criticality aspects are completed further. The criticality metrics and techniques are categorized based on the aspects they represent.

## **3.2 Aspects of transport network criticality definition**

There are three aspects to a transport network criticality study extracted from the literature review: (i) network component centered, (ii) contribution to the serviceability of the transport system, and (iii) disruption of network components. These aspects are not only derived by how the papers explicitly define criticality but also inferred from the way they operationalize criticality (i.e. how they quantitatively assess criticality). By understanding how the papers specify and calculate the metrics, the implicit definition of the criticality based on the authors' views can be recognized.

### **3.2.1 Aspect #1: Network components centered**

Since the aim of the criticality analysis is to rank network components, criticality should be assessed on network component level (i.e. nodes or links). At the end of the analysis, a value should be attached to each network component so that the components can be ranked based on their values. This aspect distinguishes criticality from other related transport network terms such as vulnerability, resilience, and robustness. Transport network resilience measures the capacity of a transport network to maintain its function (Cox, Prager, & Rose, 2011). Transport network robustness has a larger context as its assessment consists of incident prevention, links redundancy, network compartmentalization, network resilience, and flexibility (Snelder, van Zuylen, & Immers, 2012). Vulnerability, on the other hand, is also originally defined as a concept to measure the performance of the entire transport system (Berdica, 2002). Although, as the term evolves, several authors have extended the definition to the susceptibility and importance of transport network components (Erath, Birdsall, Axhausen, & Hajdin, 2009; Maltinti, Melis, & Annunziata, 2012; D. Z. W. Wang et al., 2016; Zhiru Wang et al., 2014; Yin & Xu, 2010).

As can be seen in Table 3, the primary object of study of transport network criticality is limited to network components. This strict limitation differentiates criticality from resilience, robustness, and vulnerability where assessment can be done on the network level. While network level centered assessment is useful to compare the characteristics of two different networks (inter-network comparison), network components assessment enables prioritization of components within a network (intra-network comparison) (J. Sullivan, Aultman-Hall, & Novak, 2009). Moreover, since criticality can be deemed as a subset of transport network vulnerability study from this scope definition, some authors reason that criticality is an element of vulnerability (E. Jenelius & Mattsson, 2015).

Table 3 Assessment object of related terms comparison

Related Terms	Assessment Object	
	Whole Network	Network Components (e.g. links and nodes)
Resilience	✓	
Robustness	✓	
Vulnerability	✓	✓
Criticality		✓

### 3.2.2 Aspect #2: Contribution to the serviceability of the transport system

The most controversial discussion of transport network criticality definition falls on the way in which ‘contribution’ is specified because it acts as a basis to operationalize the criticality metrics. Generally, authors do not explicitly present comprehensive semantical discussions of network component contributions in their papers. They do, however, discuss the deficiencies of other criticality metrics and how their new metric overcomes the limitation of the other metrics (Jansuwan & Chen, 2015; Liu, Agarwal, & Blockley, 2016; Qi, Zhang, Zheng, & Lin, 2015; Zhang et al., 2014). By reflecting on the diverse criticality metrics, a generic definition of contributions can be derived.

Specification of contributions can be observed from three different angles: the underlying paradigm of contribution measurements, the functionality of contribution measurements and the aggregation level of contribution measurements. The focus of the first one lies in the ethical values of transport studies. Specifically, ‘underlying paradigm’ angle talks about the dilemma between total-performance and user-equality preference in transport investments. Discourses of ‘functionality’ angle lie on the operational bases and the utility specification of network component contribution measurements. ‘Aggregation level’ angle discusses if contributions are measured on a system-wide level or on a localized scale.

#### *Underlying paradigm angle: Utilitarianism, Egalitarianism, and Sufficiencyarianism*

When deciding the parts of the transport network that should be improved, decision makers are faced with a dilemma. They have to choose between improving the performance of the transport network for all users collectively (total-performance preference) and improving the performance with an ultimate goal to promote equality among user groups (user-equality preference) (Van Wee & Roeser, 2013). In a freight transport context, the user groups normally refer to different regions in a country. It is only in rare cases that both goals result in identifying the same transport network component as the most critical one, such as the case of the Jamuna multipurpose bridge case in Bangladesh (Anam, Sohel-Uz-Zaman, & Anam, 2005; Bayes, 2007). From an ethical standpoint, total-performance preference adopts utilitarianism paradigm while user-equality preference adopts either egalitarianism or sufficiencyarianism paradigm.

In economics science, utilitarianism is a view of social welfare that wants to maximize the collective happiness (utility) of the society (Posner, 1979). If decision makers adopt this view as the underlying paradigm of their investment decision, the prioritization should incorporate the actual traffic flow and/or the economic activities of the economic nodes that the transport network connects. This perspective is gaining more popularity in recent transport network criticality studies, as increasing computational resources enables researchers to incorporate more data (in this case the actual traffic flows) into the analysis (Mattsson & Jenelius, 2015). Illustratively shown in Figure

6, a utilitarianism-based decision making allocates more resources to link AB that connects node A and B. This is because the total economic weight of node B, B1 and B2 is higher than the economic weight of node C, C1, and C2.

In the field of transport and spatial planning, one major critic of this paradigm is that the policy implication of the investment tends to benefit the ‘core’ economic regions at the expense of the ‘periphery’ economic regions, as the core economic regions get higher priority. This in turn may widen regional disparities between the core and the periphery (Keeble, Owens, & Thompson, 1982). Therefore, in his thesis, Posner (1979) criticizes the utilitarianism paradigm by inquiring whether the ultimate goal should be to maximize the total or the average utility of the society. If the goal is the latter, then utilitarianism is moving outwards to egalitarianism.

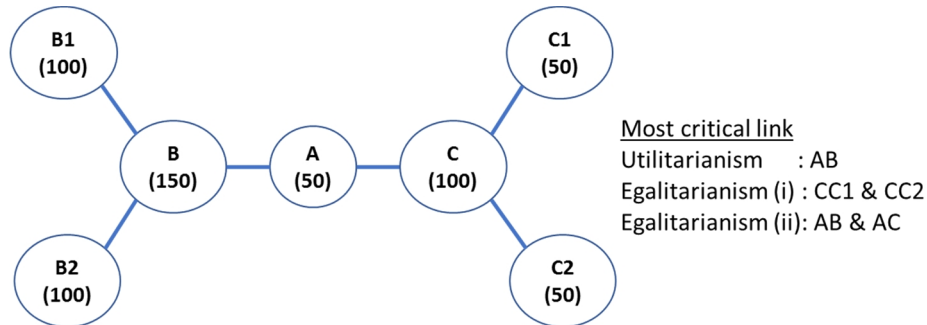


Figure 6 Hypothetical transport network, the number represents the economic weight of the nodes

Originally, egalitarianism promotes equal opportunity to the society to answer the problem of distributive justice. In its extreme form, Rawls (2009) in his second principle of justice argues that in egalitarianism paradigm social and economic policy should be arranged “so that they are to be of the greatest benefit to the least-advantaged members of society”. The main idea behind this is that helping the least-advantaged members is expected to reduce the inequality between them and the most-advantaged members. Reflecting back to the illustrative case study in Figure 6, link CC1 and CC2 that connect node C to node C1 and node C2 are the most critical ones.

In most transport network criticality and vulnerability studies, however, egalitarianism is practiced by giving equal weights to all economic nodes (Kurauchi, Uno, Sumalee, & Seto, 2009; J. L. Sullivan et al., 2010; Taylor & Susilawati, 2012). These practices are influenced by Rawls’ first principle of justice which states that “each person is to have an equal right to the most extensive basic liberty”. In the illustrative example above, all nodes will have same economic weights (e.g. 1). Consequently, both link AB and link AC are the most critical components as they connect the left nodes cluster with the right nodes cluster.

The last paradigm which also promotes user-equality preference is sufficientarianism. This paradigm puts emphasis on providing economic resources in such a way that all members of the society live in at least the minimum agreed standard of living. While the practice of this paradigm in transport network study is still minimal, it has been argued that one way to operationalize this paradigm is by ensuring that all user groups in the transport network study scope have an adequate level of accessibility (Lucas, van Wee, & Maat, 2016). However, the way in which the most critical links can be identified from this paradigm has not been researched.

Functionality angle: accessibility, total travel cost, and connectivity

Functionality angle zooms further into the operational roles of the transport infrastructure. The functionality of a transport component can be observed from three viewpoints: providing accessibility (the ease to reach a particular

location), reducing the total travel cost of the system, and maintaining connectivity (the availability of connections between all economic nodes).

First, accessibility functionality measures the ease by which users from a specific location partake in activities that take place in other locations by using the transport service (Taylor, 2004). The accessibility based contribution examines the decrease of a network's or of a particular region's accessibility due to disruptions of network components (Hernández & Gómez, 2011; Taylor & D'Este, 2007). A network component is considered to be more critical if its removal from the transport network causes a significant reduction to the accessibility of the overall network. Accessibility index that uses the economic potential of two nodes and the distance between them is normally utilized for this purpose (Demirel, Kompil, & Nemry, 2015; Ouyang, Pan, Hong, & He, 2015; Rozenberg et al., 2017; Taylor & D'Este, 2007).

Total travel cost-based measures accumulate the total distance traveled of all centroid pairs (i.e. economic nodes) in the network. The higher the increase of the total distance traveled when a network component is disrupted relative to its business as usual state, the more important that network component is (de Oliveira, Portugal, & Porto Junior, 2016; Ibrahim et al., 2011; Ukkusuri & Yushimito, 2009). When assessed from the total-performance preference, the total distance traveled is weighted by the magnitude of the traffic flows between the centroid pairs. It is typically measured in vehicles-kilometer traveled or monetary units. User-equality preference on the other hand does not give different weights to each centroid pair (Schuchmann, 2010; Su et al., 2012). It assumes that the traffic flow of all centroid pairs to be equal.

Connectivity-based measures promote the preservation of connections between all centroids in the system (Kurauchi et al., 2009; Reggiani, Nijkamp, & Lanzi, 2015). While the other two viewpoints are often labeled as the functional perspective of transport networks, this point of view epitomizes the structural perspective of transport networks (Zhou, Fang, Thill, Li, & Li, 2015). In a complex transportation network, the degree of interconnectivity is usually high. However, simultaneous removal of several network components may still create immediate disconnections (Pant et al., 2015; Snelder et al., 2012; Tu, Yang, & Chen, 2013). A network component is critical if its disruption potentially causes disconnection between one or more centroid pairs.

#### Aggregation angle: system-wide assessment and localized assessment

The last angle examines the scale of the assessment. That is, whether contributions are assessed for the whole network or for a particular localized subset of the network. The term localized subset may refer to two different things: localized measures of contribution (B. Y. Chen, Lam, Sumalee, Li, & Li, 2012), or local characteristics of network components (Nourzad & Pradhan, 2016). The former refers to calculating the contribution of a network component only until the level of a particular geospatial subset of the whole transport network. As an example, the contribution of a particular road segment can be assessed by the impact of the removal of that road segment to the total travel time of the city where that road segment resides, rather than the total travel time of the whole country. The latter refers to the static characteristics of the network component. The number of culverts and bridges on a particular road segment and the observed average annual daily traffic of that road segment are few examples of this category.

### **3.2.3 Aspect #3: Disruption of network component**

Although it is still debatable whether disruptions of network components should be incorporated in a criticality assessment, most papers in fact use interdiction techniques (removing network elements such as nodes or links, then recalculating the metrics of interest and comparing them with the business as usual performance) for ranking

network components (Murray, Matisziw, & Grubestic, 2008). Therefore, it is important to include the concept of disruption as an aspect of a criticality study. There are three sub-aspects within this concept: the probability of disruptions, the severity of damages caused by disruptions, and the spatial extent of disruptions. The technical implementation of interdiction technique will be explained later in Section 4.3.4. There are also several criticality studies that do not necessitate interdiction techniques, although the number is relatively small in comparison to the ones that use interdiction techniques.

#### Sub-aspect probability

Proponents of inclusion of probability in criticality root back to Berdica (2002)'s seminal paper on road vulnerability where she argues that vulnerability is "a susceptibility to incidents that can result in considerable reductions in road network serviceability". Historical natural hazard maps of the study area such as flood map and earthquake map are the most frequently used data to indicate the probability of network components disruptions. This is done by overlaying the hazard map on top of the transport network (Du, Kishi, & Nakatsuji, 2015; Erath et al., 2009). Furthermore, the physical condition of a network component such as its soil type, pavement type, and the presence of bridges may be attributed to the calculation of disruption probability (Kermanshah & Derrible, 2016).

#### Sub-aspect severity

Disruption events can either completely remove or partially reduce the functionality of a network component. Complete failure of network components is more widely practiced due to its ease of operationalization and its ease of results interpretation (J. Sullivan et al., 2009). However, complete removal might not fully capture real-world phenomena such as mild flooding where cars can still go through the road with a reduced speed. In this case, the road segment is not completely inoperative, but is operating at a reduced capacity.

#### Sub-aspect spatial extent

Spatial extent sub-aspect talks about the number of network components and the selection of network components that will be simultaneously disrupted. In general, disruptions can be done either to a single component individually, to multiple components at random, or to spatially-related multiple components. One important note to be made is that using single component disruption may lose the interdependency nature of the transport components. Therefore, disrupting multiple components simultaneously may produce nonlinear effects to the network performance (O. Cats & Jenelius, 2016), leading to different results of the criticality study.

### **3.2.4 Final synthesis of criticality aspects**

The overview of the criticality aspects can be seen in Figure 7. Every transport criticality study has all aspects embedded in its analysis. It can be reflected from the assessment techniques or from the metrics used to calculate criticality. For instance, Oded Cats and Jenelius (2015) identify links criticality by adopting total-performance paradigm, with total travel cost functionality, assessed on both system-wide and localized level. They apply exhaustive (without probability) single component interdiction technique to all links in the network. Criticality analysis that does not use interdiction technique may not have disruption aspect in its study.

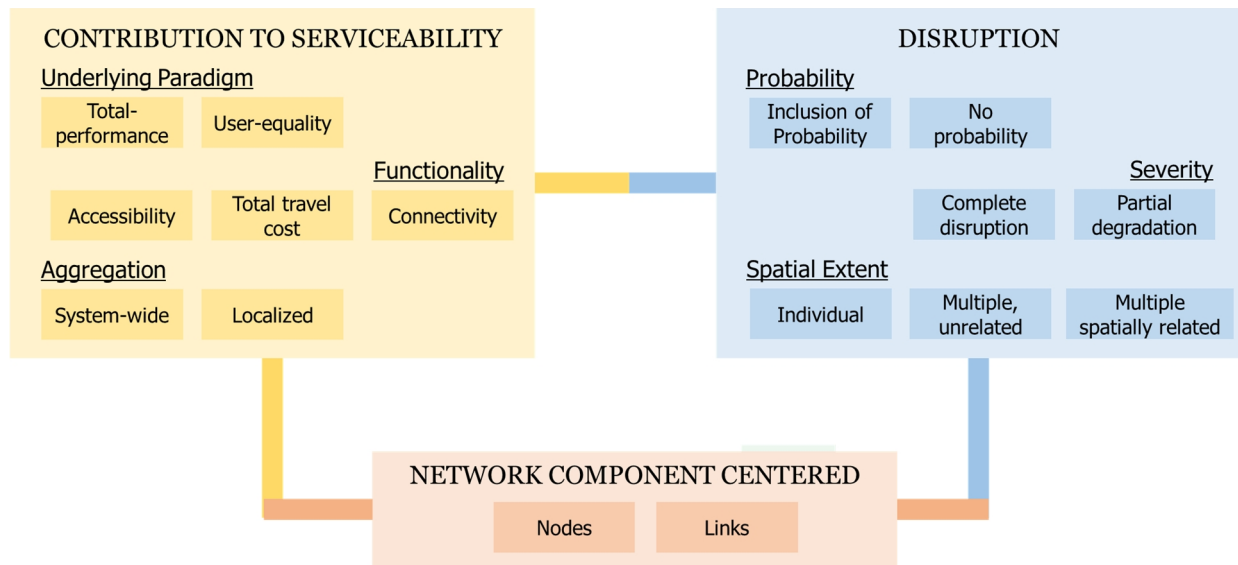


Figure 7 Concept map of criticality aspects

In view of the fact that using different configurations of criticality aspects is likely to result in different criticality outcomes, the concept map can be used at the early stage of a study or at the latter stage of a study. Before deciding on which assessment techniques and metrics to be employed, the concept map can help practitioners to first think about the criticality aspects that they want to consider. This concept map is also useful at the latter stage of the study once the criticality analysis results have emerged in order to reflect on the conceptual completeness of the analysis. Deliberating back the incorporated criticality aspects can provide valuable insights for the final policy implication of the criticality study. Lastly, by tailoring different aspects of criticality, the concept map can aid researchers to define new assessment techniques and criticality metrics.

### 3.3 Transport network criticality metrics

A network component can be deemed more critical if it plays a larger role in the transport network. Therefore, the ‘contribution to serviceability’ aspect of criticality is suitable to be used as a starting point to explore criticality metrics. Figure 8 presents the layered approach of criticality metrics classification. Each layer in the figure is an operationalization of the sub-aspects within the ‘contribution to serviceability’ aspect.

#### 3.3.1 Layer I: Underlying paradigm operationalized

The first layer is based on the underlying paradigm sub-aspect, where the total-performance preference is represented by system-based metrics while the user-equality preference is represented by topological metrics (Erik Jenelius et al., 2006). The main difference between topological and system-based measures is that the latter requires socioeconomic data while the former sees the transport network as an unweighted graph (Mattsson & Jenelius, 2015). System-based metrics put more demand-side information of the transport system such as the traffic flow between cities. Consequently, system-based metrics also demand higher computational cost to process the data. In defining criticality metrics, this layer is the most accountable layer for determining the data requirements of the criticality study.



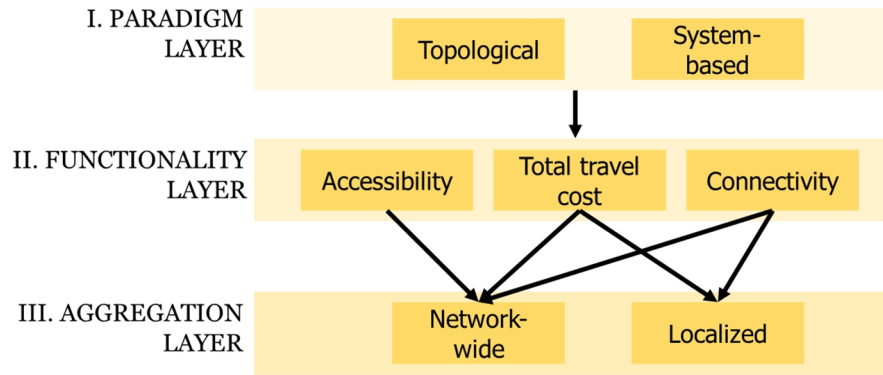


Figure 8 Layered approach to criticality metrics

### 3.3.2 Layer II: Functionality operationalized

The second layer talks about the specific real-world functionality of the transport network component and how they can be operationalized mathematically. The general idea of each functionality’s operationalization is presented below while several examples of specific mathematical formulations that have been used in previous transport network criticality studies can be found in Appendix C.

#### *Accessibility*

Hansen’s accessibility index is the most commonly used measure for accessibility assessment in transport studies (Hansen, 1959). The accessibility of a particular region is the sum of the division between the economic potentials in all other regions and the travel cost to those regions. Originally, the economic potentials of a region are characterized by the number of jobs (employment), annual retail sales (shopping opportunities), and population (residential activity) in that region. Another way to measure the economic potentials is by using the region’s GDP (Demirel et al., 2015). The total travel flow between a region from/to another region has also been utilized as an economic potentials measure (Luathep, Sumalee, Ho, & Kurauchi, 2011).

#### *Total travel cost*

The total travel cost in a transport network is the summation of the multiplication between the travel cost of all centroid pairs and the magnitude of flows between the pairs. The simplest form of travel costs is the total distance (normally in kilometer) of the shortest route between two nodes (Dehghani, Flintsch, & McNeil, 2014; Ham, Kim, & Boyce, 2005; Moruza et al., 2017). A more accurate measure of travel costs in transport study can be represented by the travel time (de Oliveira et al., 2016; Ibrahim et al., 2011; D. Z. W. Wang et al., 2016). Several studies even capture a more realistic representation of travel costs. O. Cats and Jenelius (2016) calculate the generalized cost function of public transport network users as the combination of the number of transfers, the waiting time, the in-vehicle time, and the walking time. In multimodal logistics, Du et al. (2015) develop a detailed breakdown of highway and railway costs.

While the examples above provide direct measures of total travel cost, there are also several indirect measures available. As an example, link betweenness centrality can indicate the contribution of a link to the total travel cost since the more flows pass through a particular link, the higher the role of that link to minimize the system’s travel cost (Z. Wang, Chan, & Li, 2014). Empirical data of traffic and congestion level can represent the link’s betweenness centrality, thus the link’s contribution to the system’s travel cost (Zhou et al., 2015). This is because as stated in Wardrop’s second principle of road traffic, the total travel time in equilibrium condition is minimal since all users

try to maximize their utility by choosing the least cost routes (Wardrop, 1952). Lastly, network efficiency measures can also indicate a transport network's total travel cost. A higher network efficiency leads to lower travel cost incurred to all users. Network average efficiency and N-Q efficiency measures have been used to identify subnetworks where decision makers should focus on (Balijepalli & Oppong, 2014; Dehghani et al., 2014).

#### *Connectivity*

Similar to travel cost, connectivity can be measured both in direct and indirect ways. Direct measurements of connectivity adopt minimum cut set computation of network theory (Newman, 2010). A minimum cut set between two nodes is the set of minimum links which if simultaneously removed from the network will cause a disconnection to the nodes. A link is considered to be more critical to the network's connectivity if it appears in a lot of centroids pairs' cut set (Snelder et al., 2012). If it is assessed from the total-performance preference, the number of the disconnected centroid pairs is weighted by the magnitude of flow between the disconnected centroids (Muriel-Villegas, Alvarez-Uribe, Patiño-Rodríguez, & Villegas, 2016; Soltani-Sobh et al., 2015). Indirect measurements of connectivity also use metrics from network theory body of knowledge. For instance, network density, which is a ratio between the total length of links in a particular region and the region's area, has been used to understand the transport supply inequalities among regions (E. Jenelius, 2009). The higher the network density of a particular region, the lower the disconnection probability is.

### **3.3.3 Layer III: Aggregation operationalized**

The final layer determines the aggregation level of the criticality metrics; that is, whether the metric is calculated by considering the full network or by considering only a subnetwork. Aggregating on the network level means calculating the contribution of the network component to the entire network, such as calculating the increase of the total travel time of the entire system when a network component is removed. Several researchers have argued that network-wide aggregation level is the most appropriate way to measure criticality since it captures full interdependencies between network components (Scott, Novak, Aultman-Hall, & Guo, 2006).

Despite the growing popularity of network-wide assessments, it is computationally burdensome if the transport network is too complex. Therefore, it has been argued that calculating only localized contribution of network components is sufficient to understand the network-wide contribution (B. Y. Chen et al., 2012). Localized measures, especially those related to the static performance of the network component such as traffic congestion and betweenness centrality, have been used to signify criticality (Scott et al., 2006; Z. Wang et al., 2014).

While total travel cost and connectivity functionalities can be assessed from both the network-wide and the localized level, it is not the case for accessibility. This is because accessibility index essentially invokes calculation of values (e.g. economic potentials and distance) between all economic elements in the system (Hansen, 1959). Moreover, in the context of national freight transport, it is important to incorporate all economic nodes in the system since freight may move from/to two farthestmost places in the country to transport vital commodities.

### **3.3.4 Enumeration of the three layers**

Combinations of elements in the three layers shown in Figure 8 result in ten criticality metrics categories as presented in Table 4. It should be noted that there is no restriction in using only a single metric in a criticality study. Some studies use one criticality metric (Al Khaled, Jin, & Li, 2011; Ibrahim et al., 2011; Sunghoon Kim & Yeo, 2016; Schuchmann, 2010; Su et al., 2012) and others compare the result of multiple metrics (Guo & Xiong, 2014; E. Jenelius & Mattsson, 2015; Kermanshah & Derrible, 2016; Rozenberg et al., 2017).

Table 4 Criticality metrics categories

Type	Layer I	Layer II	Layer III
M1	Topological	Accessibility	Network-wide
M2	Topological	Total travel cost	Network-wide
M3	Topological	Total travel cost	Localized
M4	Topological	Connectivity	Network-wide
M5	Topological	Connectivity	Localized
M6	System-based	Accessibility	Network-wide
M7	System-based	Total travel cost	Network-wide
M8	System-based	Total travel cost	Localized
M9	System-based	Connectivity	Network-wide
M10	System-based	Connectivity	Localized

The distribution of each categories' use in transport network criticality study based on reviewing 78 papers is shown in Figure 9. Metrics category M7 and M8 are the two most frequently used metrics. Specifically for category M7, the total increase in network's travel costs due to the removal of network components has been used in a large number of studies. This metric is favored for two reasons. First, the interpretation of the metric is straightforward and is easy to be understood by a broad audience (i.e. not only transport experts). Second, it can indicate the distance of an alternative route to the disrupted link. If an alternative route is located quite far from the disrupted one, disruption of that link will cause a substantial increase in the total travel cost. As for category M8, traffic density and congestion are used to understand the component's importance in minimizing the network's travel cost.

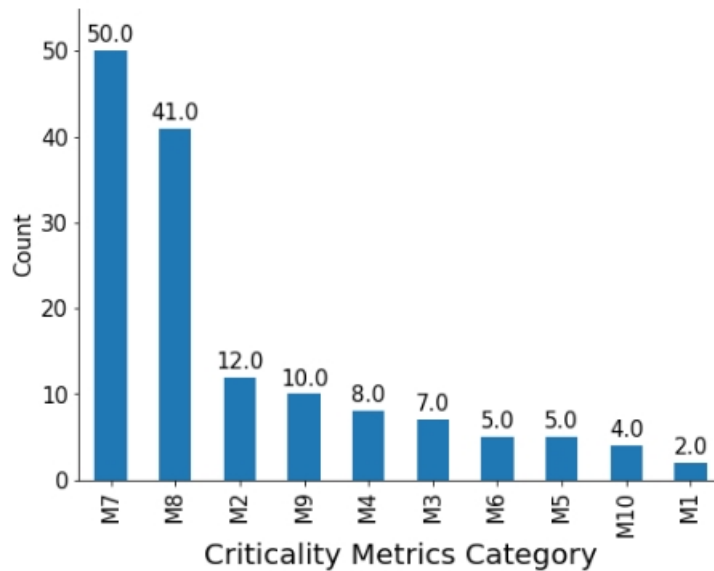


Figure 9 Sorted criticality metrics distribution from 78 reviewed papers

Another interesting finding from the literature review is that system-based measures are more widely used compared to topological measures. In total, system-based measures (category M6-M10) have been used for 110 times while topological measures (category M1-M5) have only been used for 34 times. This threefold difference shows that more

researchers adopt total-performance preference (utilitarianism paradigm) rather than user-equality preference (egalitarianism paradigm), thus putting emphasize on collective efficiency rather than on inequality reduction.

### 3.4 Assessment techniques of transport network criticality

While the contribution to serviceability aspect of criticality definition is suitable for defining metrics categories, the disruption aspect fits for exploring plausible assessment techniques categories. Figure 10 shows the five layers on which assessment techniques can be categorized. The first layer determines whether only a single calculation is exercised in order to gain the final result, or more than one consecutive calculations are needed. The second layer differentiates assessment techniques that require disruptions of transport network elements and those that do not. The third, fourth and the fifth layers represent the three sub-aspects of disruptions discussed in Section 3.2.3.

#### 3.4.1 Layer I: Number of assessment stages

Network-wide metrics such as increase in total travel cost require only one stage of computation. System-based localized metrics, however, sometimes require more than one computation stage. For instance, J. Sullivan et al. (2009) proposes a two-stage criticality analysis approach. First, the most vulnerable subnetwork/region is identified. Expected and worst-case user exposure metrics (Erik Jenelius et al., 2006) as well as accessibility metric (Luathep et al., 2011) can be employed for this. Afterward, the most critical network components in the most vulnerable subnetwork/region are identified. By using this approach, comparison of criticality between all network components is not possible since the focus is put only on the most vulnerable region.

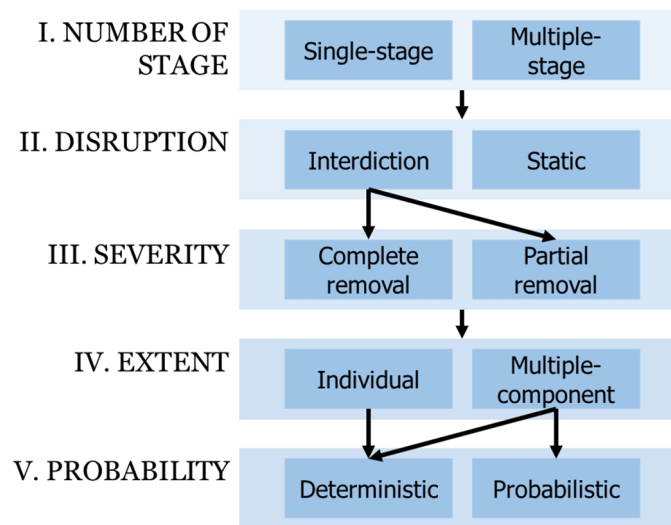


Figure 10 Layered approach to assessment techniques

Another two-stage approach for identifying criticality is done by Guo and Xiong (2014); Hsieh and Feng (2014); and Xi (2013). They apply fuzzy methods in order to combine multiple criticality metrics. The first stage is calculating several criticality metrics for all network components, and the second stage is applying fuzzification to the resulting metrics scores. This approach provides a single fuzzy criticality value for each network component, enabling comparisons of all network components.

### **3.4.2 Layer II and III: Disruption or no disruption**

Several metrics require removal of network components (Interdiction in Figure 10's second layer) in order to quantify the components' criticality while other metrics do not require such removal (Static in Figure 10's second layer). Metrics such as increase of total travel cost and unsatisfied travel demand require disruption of network elements (E. Jenelius & Mattsson, 2015; S. Kim & Yeo, 2017; Muriel-Villegas et al., 2016). Empirical traffic level, betweenness centrality, and network density do not require removal of any network components as they are assessed in the business-as-usual situation (Bagloee, Sarvi, Wolshon, & Dixit, 2017; Fang, Shaw, Tu, Li, & Li, 2012; Hernández & Gómez, 2011; Knoop et al., 2012).

If interdiction technique is selected, layer III determines whether the disrupted component is completely removed from the network or if it is only partially disrupted. Partial disruption reduces the operational capacity of the network component, thus limiting the number of users that can traverse on it (Li & Ozbay, 2012). Assessing the impact of capacity degradation comprehensively is computationally expensive as the capacity degradation of each network component should be enumerated exhaustively. Therefore, studies that use capacity degradation approach normally limit the number of network components that are being assessed (O. Cats & Jenelius, 2016).

### **3.4.3 Layer IV and V: Probability and extent of disruption**

The fourth layer talks about the number of components that are simultaneously disrupted and the last layer speaks of the likelihood that the components are disrupted. There are three possible combinations of simultaneous components disruption within this layer: deterministic disruptions of individual components, deterministic disruptions of multiple components, and probabilistic disruptions of multiple components. Probabilistic disruptions of individual components are not theoretically possible, since probability can only be applied if there are more than one components to be disrupted.

Deterministic disruptions of individual component disrupt each prespecified network component individually. The term full-scan approach is used if all components in the transport network are going to be disrupted independently (Rodríguez-Núñez & García-Palomares, 2014). Applying this approach especially in a large-scale transport network demands expensive computing cost as the metrics need to be calculated for a large number of iterations. Alternatively, there are also studies that only disrupt several prespecified network elements, which Murray et al. (2008) call scenario-specific approach. For instance, Jansuwan and Chen (2015) disrupt only road segments that have bridges on it in order to identify the most critical bridges in the study region.

The scenario-specific approach also enables disruptions of multiple elements simultaneously, both deterministically and probabilistically. This is especially relevant when decision makers want to understand the impact of certain scenarios such as sea level rise (Demirel et al., 2015), seismic disaster (Du et al., 2015), or snowfall (An, Leng, Wang, Li, & He, 2015) to the performance of the transport system. Probability disruptions require a more advanced mathematical technique in order to enumerate numerous disruption scenarios and to identify the contribution of each network element since each element may not only be disrupted once. As a consequence, this approach consumes more computation costs.

### **3.4.4 Enumeration of the five layers**

A coherent enumeration of assessment techniques layers presented in Figure 10 results in eight categories of assessment techniques as shown in Table 5. Category A7 which uses a static technique does not entail further

elaboration of components disruption, thus does not have layer III, IV and V. Multiple-stage analysis in category A8 usually involves one or more single-stage assessment based on the number of stages that the analysts want to conduct.

Table 5 Assessment techniques categories

Type	Layer I	Layer II	Layer III	Layer IV	Layer V
A1	Single-stage	Interdiction	Complete	Individual	Deterministic
A2	Single-stage	Interdiction	Complete	Multiple	Deterministic
A3	Single-stage	Interdiction	Complete	Multiple	Probabilistic
A4	Single-stage	Interdiction	Partial	Individual	Deterministic
A5	Single-stage	Interdiction	Partial	Multiple	Deterministic
A6	Single-stage	Interdiction	Partial	Multiple	Probabilistic
A7	Single-stage	Static			
A8	Multiple-stage				

The distribution of each category used in previous transport network criticality studies based on reviewing 78 papers is displayed in Figure 11. Interdiction techniques especially category A1 and A2 are the most commonly used techniques for assessing criticality. The relatively larger number of single component disruptions (A1 and A4) compared to multiple components disruptions (A2, A3, A5, and A6) shows that multiple components disruptions, although necessary for capturing components interdependency, are still a difficult task. In fact, there is no single widely-acknowledged technique to orchestrate multiple components disruptions for a transport network criticality assessment. Static technique category (A7) ranks third, showing that there are a substantial number of researchers that only use the business as usual condition for assessing criticality.

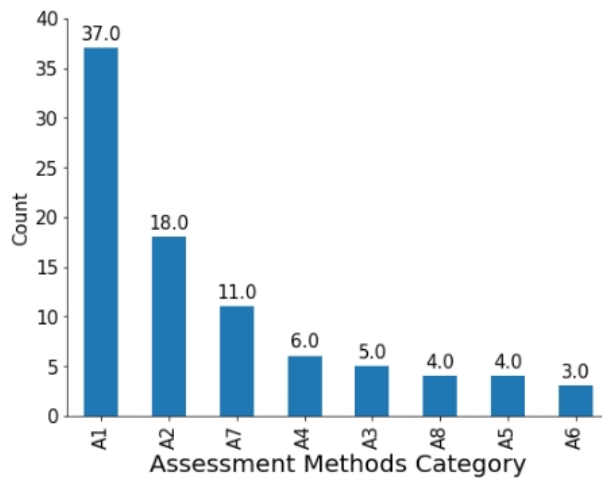


Figure 11 Sorted assessment techniques distribution from 78 reviewed papers

### 3.5 Chapter 3 Summary

In a nutshell, this chapter has discussed the following points:

- The general aspects of transport network criticality have been synthesized. There are three main aspects: network component centered (criticality should be assessed on the network's links and/or nodes), contribution to serviceability (criticality score should represent a network element's role to the whole transport system), and disruptions (most criticality metrics require interdiction technique in order to be computed).
- An operationalization framework of the criticality aspects has been proposed. The contribution to serviceability aspect translates to transport network criticality metrics while the disruption aspect translates to assessment techniques to calculate the metrics.
- The enumeration of the operationalization framework leads to ten metrics categories and eight assessment techniques categories. These metrics will be tested for Bangladesh's multimodal freight transport network as a case study. The corresponding assessment techniques, especially the interdiction technique, will determine which network assignment method is practically feasible for the criticality study. This will be further elaborated in Chapter 4.
- A critical review of the most widely used metrics and assessment techniques categories has been presented. It is found that system-based metrics have been more frequently used compared to topological metrics, while the single stage, individual interdiction technique is the most frequently used technique due to its simplicity compared to the other techniques.

*This page is intentionally left blank.*



# Chapter 4: Bangladesh Freight Transport Network Case Study

The operationalization of the criticality aspects synthesized in Chapter 3 is applied to a case study of Bangladesh's multimodal freight transport network. This chapter provides a detailed specification of the freight transport model as well as the implementation of the interdiction technique. As a start, a brief theoretical review of multimodal freight transport modeling approaches is presented in Section 4.1. Additionally, this section describes the specific modeling approach that will be used in the case study. Next, a contextual background of Bangladesh's multimodal freight transport is provided in Section 4.2 to give a basic understanding of the social, economic and geographical features of Bangladesh. Lastly, the specification of the transport model is explained in Section 4.3 based on the selected modeling approach presented in Section 4.1. The technical implementation of the interdiction technique is also provided in this section.

## 4.1 A brief review on multimodal freight transport modeling

In its earlier development, a freight transport model is a graph-based static model that represents the flow of cargo among locations in a given geographical boundary. The road, railway, and waterway paths are represented as links in the graph while the intersections, city centroids, stations, ports, and hubs are represented as nodes. Recent developments in this field have advanced the methodology to dynamic simulation models (Jong et al., 2016). As an example, Burgholzer et al. (2013) develop a micro simulation-based intermodal transport network to evaluate critical sections of the northeastern area of Austria. Nevertheless, the graph-based modeling approach is selected in this study because it is the most widely used approach for transport modeling (Mattsson & Jenelius, 2015) and because of the intensive, detailed Bangladesh multimodal network data.

In this section, general freight transport modeling approaches are explained. This is mainly based on the extensive and comprehensive discussion by Tavasszy and De Jong (2013). Further, the multimodal dimension of freight transport models is briefly discussed as the case study incorporates both road and waterway networks of Bangladesh. Based on these two reviews, a specific approach for this case study is outlined.

### 4.1.1 General approach to freight transport modeling

A generic approach in transport modeling is the four-step transport model (Ortuzar & Willumsen, 2011). As displayed in Figure 12, the four-step transport model starts by generating trips among places in the study area. Namely, the first step should answer the question of how many trips produced by each place (the production factors) and how attractive that particular place is for appealing trips to that place (the attraction factors) in a given time span. By determining the production and the attraction factors, the trip distribution can be calculated. The outcome of the trip distribution step is an Origin-Destination (O/D) matrix. An O/D matrix is an  $n \times n$  table that provides information on the number of trips from/to all places of interests.

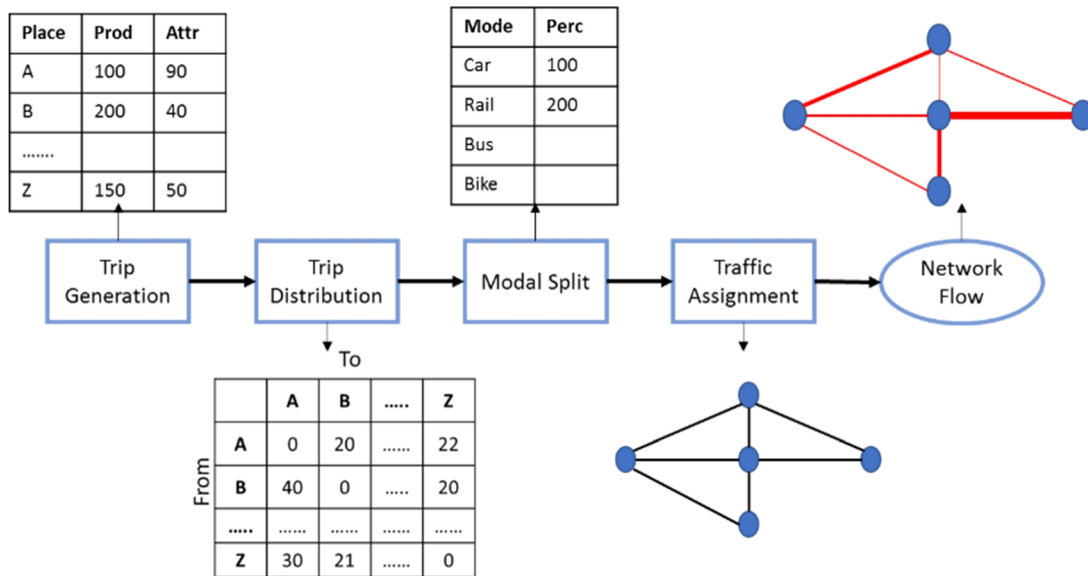


Figure 12 Four-step modeling (Ortuzar & Willumsen, 2011)

After knowing the trip distribution, the next step is calculating the modal split for each mode in the study. This step has been traditionally conducted by splitting each mode individually. For instance, traveling from place A to B can be done by either car, train, or bicycle alone, rather than by combinations of different modes. Recent modeling practices have enabled mode changes to get from one place to another. This approach is called supernetwork and will be explained in the next section. Lastly, the trip flows are assigned onto the transport network. This traffic assignment step starts by delineating the shortest path routes between all O/D pairs by using a shortest path algorithm. The flows are then assigned on top of these shortest routes based on the number of trips between the corresponding O/D pair. Three most popular techniques for traffic assignment are, in increasing complexity, All-or-Nothing (AON) assignment, probit assignment, and user equilibrium (UE) assignment. The ability to replicate real-world phenomena increases as the complexity increases. However, it is at the expense of higher computation cost. The magnitude of the flows on each path can be visualized by adjusting the thickness of the path (see Figure 12).

While originally intended for modeling passenger trips, the four-step modeling approach has been adapted for modeling freight and cargo trips as well. Tavasszy and De Jong (2013) propose four options to model freight transport depending on the modeling purpose and the data availability (see Figure 13). There is one fundamental difference between freight transport modeling and the standard transport modeling. Rather than using the number of trips, freight transport modeling starts with the amount of goods (normally in tonnage unit) transported from one place to another. These figures have to be converted to a number of trucks and/or trips. This step is termed freight conversion. One logical consequence of this is that the magnitude of tonnages transported from one place to another does not necessarily represent the traffic flow between those places. Different commodities have different density, which make any two different commodities with the same weight may take different truck volume and thus produce a different number of trips. The amount of goods transported between regions is derived from the socioeconomic statistics of the study object.

The first chart on Figure 13 shows the most comprehensive approach of freight transport modeling. The O/D matrix is differentiated into trade O/D and transport O/D. The former matrix stores information about the original number of trips from one place to another while the latter incorporates intermediate hubs between any two places where goods are sometimes stored temporarily. Therefore, a comprehensive freight transport modeling does not only need

information on the start and the end points of the economic centroids (i.e. O/D nodes), but also the inventory hubs between them. This makes the transport O/D matrix larger than the original trade O/D matrix.

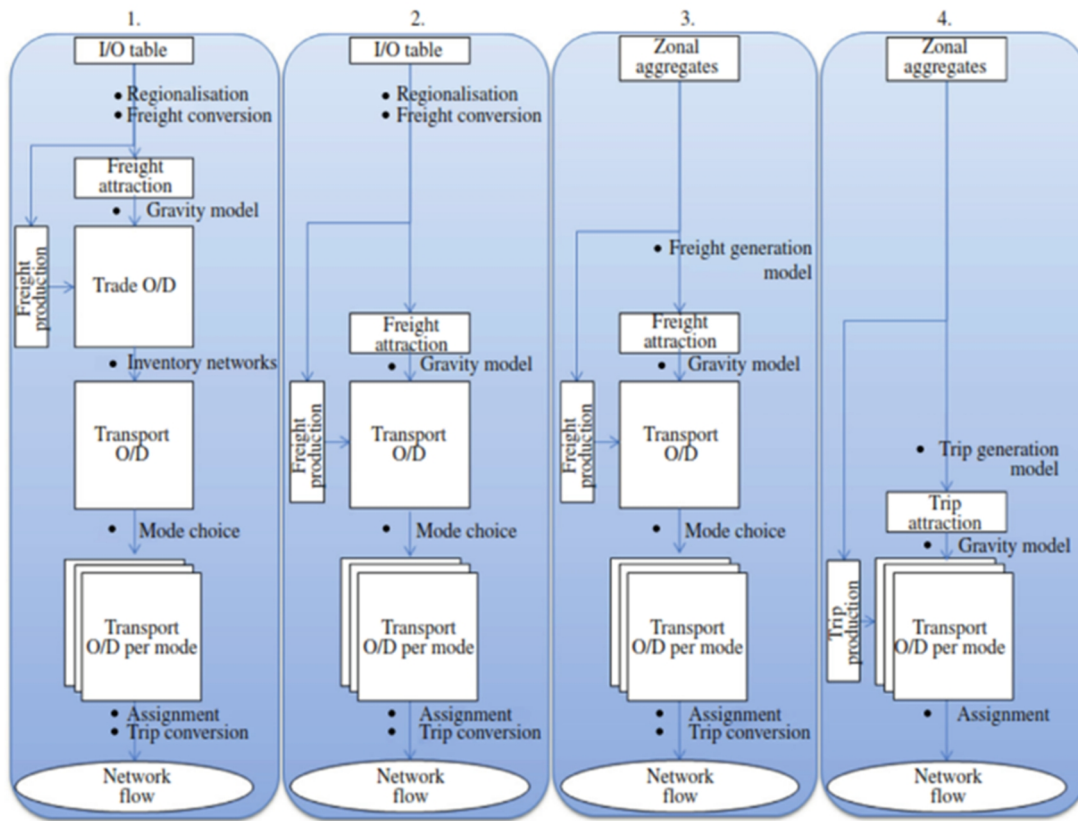


Figure 13 Options for freight modeling approach, adopted from Tavasszy and De Jong (2013)

The second option of freight transport modeling approach excludes the trade O/D matrix by eliminating the inventory networks. This option assumes that there is no intermediate stop when goods are transported from one place to another. A positive advantage of this simplification is a reduction in model complexity which reduces data requirements and computational cost. The drawback of this assumption is obvious; the clarity of the final network flow assignment may be reduced since the network structure is not captured in fine detail.

The third option differs from the second one on the freight production and attraction generation step. In the second option, an input/output (I/O) table or even a multiregional input/output (MRIO) data is needed. An I/O table is statistical data that captures the relations between different economic sectors in a country. For instance, an I/O table breaks down data on how many cars are produced from a specific combination of inputs such as metals, plastics, and ceramics. This dependency is needed to calculate the O/D matrix with a higher validity as the attraction factors of a region to a particular goods type is dependent on the production factor of the other commodities in that region. This phase is labeled as regionalization.

Data on I/O table is scarce in developing countries such as Bangladesh. As an alternative, option 3 of freight transport modeling approaches handles this situation by using the zonal aggregates of each region. Zonal aggregates are aggregated data about the amount of goods produced in a region for a broad range of commodities. Sometimes,

the zonal aggregates data is available in monetary unit instead of in tonnage unit. In that case, the value should be translated into tonnage unit so that it can be used in the modeling exercise.

The final option eliminates the mode choice module by developing O/D matrices directly for each mode under consideration. The modeler therefore does not need to understand the attractiveness of different modes for each commodity. Although this drastically reduces model complexity, the emerging pattern of adjustments of the modal split due to the proposed interventions or uncertainties cannot be adequately captured. Furthermore, the amount of goods of a commodity in its natural unit (e.g. tonnage) is assumed to be perfectly correlated to the number of trips it generates.

Rather than seeing them as categorical, the four modeling approaches can be regarded as a spectrum of simplification possibility in freight transport modeling. In practice, the chosen modeling approach may lie somewhere in between these four options. The final modeling approach should be selected based on the purpose of the modeling study, the time availability of the modeling study, and the estimated complexity needed to capture sufficient insights to satisfy the study objective.

#### **4.1.2 Multimodality of freight transport model**

Conventionally, transport models do not integrate different means of transportation modes. Instead, they retain the network of each mode separately. This is also the main purpose of the mode choice module, which is to select the mode to be used as a mean of transportation between two places. In freight transport cases, for instance, goods can either be carried by trucks or ferries to get to other places, but not by combinations of both. This independent unimodal network representation does not epitomize the real-world situation, where there is often multimodality in transporting goods between regions. A multimodality nature in transport modeling can be apprehended by creating a supernetwork.

Supernetworks are schematically shown in Figure 14. A supernetwork is developed by overlaying two or more networks of different transportation modes. Goods can move to another mode through the transshipment nodes (represented by red points in Figure 14). The transshipment nodes should contain information about the additional penalty for switching modes. The penalty represents extra costs incurred to move goods between modes in terms of time and/or monetary costs.

A practical challenge when implementing this concept is identifying where goods can shift from one mode to another. The level of difficulty is dependent on the desired level of simplification. As an example, if the goal of the modeling study is to capture aggregated tri-modal (road, railway, and sea) freight transport flows of a maritime country such as Indonesia or Philippines, considering only main ports and stations is sufficient. Thus, the transshipment nodes can be manually created by hand. Manual establishment of these connecting nodes is less favorable once a model with a higher detail is desired as the number of the actual transshipment nodes increases. Different treatment is also required for different characteristics of a country's multimodality. For example, the ubiquitous presence of inland waterway routes in Bangladesh increases the number of transshipment nodes abruptly. Manual creation of transshipment nodes becomes even more burdensome since in reality there may be thousands of transshipment nodes.

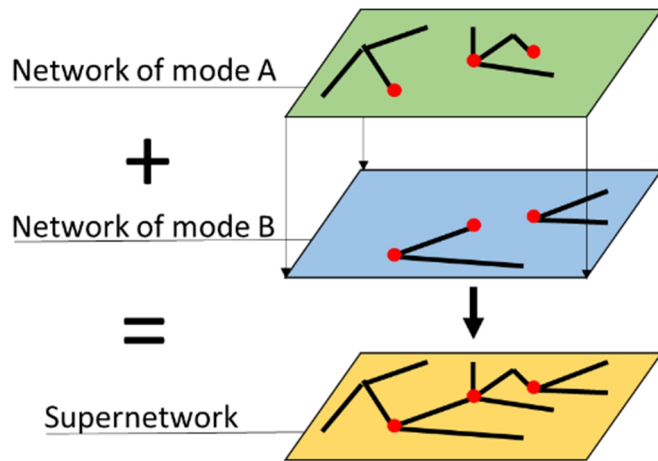


Figure 14 Multimodal supernetwork illustration

Mode choice in a supernetwork transport model is assimilated within the shortest path determination between two nodes. Therefore, the mode choice is not determined prior to the network assignment, but rather during the network assignment step itself. Consequently, an independent mode choice module is not necessarily required when multimodality feature presents.

### 4.1.3 Approach applied in this case study

Figure 15 outlines the modeling approach used in this case study. The modeling cycle begins by processing the raw socioeconomic statistics and the transport network data. The data preprocessing step is intended to manipulate the data in a way that it is usable for a transport modeling study since the raw data sometimes does not come in a usable format. The execution of these steps is explained thoroughly in Section 4.3.

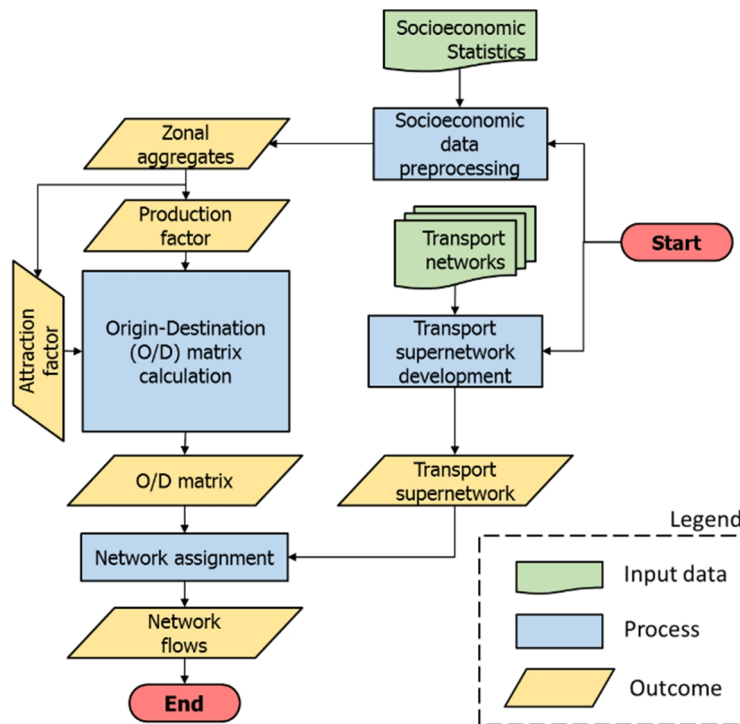


Figure 15 Overview of modeling approach for this study

Preprocessing socioeconomic data produces zonal aggregates information which is further distinguished into production and attraction factors. The units of the production and attraction factors should be consistent as these will be used in calculating the O/D matrix. At the same time, multiple transport networks are integrated into a supernetwork that will be utilized in the network assignment step. Once the O/D matrix and the supernetwork are ready, the flows are assigned to the links in the supernetwork.

*Origin – Destination (O/D) matrix calculation*

Due to unavailability of I/O (Input-Output), regional trade, and make-use table for Bangladesh, the calculation of the O/D matrix relies on the zonal aggregates data of the key products and follows a simple gravity model. The attraction factors of a region and the distance between two regions become the arguments of the gravity model. The gravity model to calculate the O/D matrix uses the following equation:

$$x_{ij}^g = x_i^g \frac{y_j^g a_{ij}}{\sum_j y_j^g a_{ij}} \dots\dots\dots (Eq 1)$$

Where  $x_{ij}^g$  is the amount of commodity  $g$  transported from region  $i$  to region  $j$ ,  $x_i^g$  is the production factor of commodity  $g$  from region  $i$  (in tonnage unit),  $y_j^g$  is region  $j$ 's attraction factor for commodity  $g$ , and  $a_{ij}$  is the distance attractiveness to transport goods from  $i$  to  $j$ . In this case study, each commodity is differentiated into local-consumption purpose and export-market purpose. Both purposes require different attraction factors. The distance attractiveness is inversely proportional to the linear euclidean distance between region  $i$  and  $j$  ( $d_{ij}^e$ ) and is defined by the following equation:

$$a_{ij} = \frac{a}{d_{ij}^e} \dots\dots\dots (Eq 2)$$

where  $a$  is an arbitrary constant that should be determined based on the minimum and the maximum linear Euclidean distance of all O/D pairs in the network to avoid extremely high and extremely low values.

*Network assignment*

The resulting O/D matrix is fed into the transport supernetwork in the network assignment step. Two uncongested assignment methods are considered for this step: all-or-nothing (AON) assignment and probit assignment. The main difference between the two is that the latter one incorporates stochasticity from drivers' perception errors on choosing the shortest path routes between any two places. Both assignment methods are algorithmically presented in the text box below and are textually explained in the following paragraphs.

AON assignment permutes all O/D pairs and iterates over all the permutations. In each iteration, the shortest path between two centroids (i.e. origin-destination) is calculated by applying Dijkstra shortest path finding algorithm (Dijkstra, 1959). The actual length (in kilometers) of the transport network is used as an argument for calculating shortest paths in a weighted graph by using Dijkstra's algorithm. The flow from/to the centroids pair is assigned to all links that belong to the shortest path of that pair. Although this assignment method is computationally cheap, it undermines the perceptions variability of drivers. In order to apprehend this weakness, probit assignment can be used instead.

**def AONAssignment:**

```
for i in ODPairsSet:
    _____ for j in ODPairsSet where j != i:
    _____ set shortestPath_ij = apply weightedDijkstraAlgorithm(node_i, node_j)
    _____ for link in shortestPath_ij:
    _____ set linkFlow += ODMatrix(i,j)
```

**def probitAssignment:**

```
for n in numberIterations:
    _____ apply randomNormal(networkLinksLength)
    _____ set allShortestPathsLinks = emptyList
    _____ for i in ODPairsSet:
    _____ for j in ODPairsSet where j != i:
    _____ set shortestPath_ij = apply weightedDijkstraAlgorithm(node_i, node_j)
    _____ for link in shortestPath_ij:
    _____ set linkFlow += ODMatrix(i,j) / numberIterations
    _____ append link to allShortestPathsLinks
    _____ for link in allShortestPathsLinks:
    _____ apply penalty(link)
```

Probit assignment differs from AON assignment by introducing an arbitrary number of iterations along with stochasticity of links' lengths. In each iteration, before finding the shortest paths between all O/D pairs, the links' lengths are sampled from a normal distribution. The stochasticity introduced by this effect enables finding more than one shortest path between two centroids. After that, the same routine as AON assignment is conducted. The links from all shortest paths of all O/D pairs are stored into a list. To further force the model to find more than one shortest path, a penalty can be given to all links in this list. This makes the links which previously have become a part of the shortest paths less attractive for the shortest path calculation in the next iterations.

Although probit assignment presents real-world situation more realistically, it is computationally more expensive. Therefore, the selection of assignment methods depends on the metrics to be calculated. Metrics that require interdiction techniques obliges iterative computations of shortest paths after removals of each link in the network. Probit assignment will not be favorable in this situation especially if the network size is too large. In this case, AON assignment is more preferred.

## 4.2 Contextual background of Bangladesh freight transport

This section provides a contextual background of Bangladesh, especially its freight transport governance and infrastructure. As a start, the main highlights of the geographical features (administrative area, important hubs for economic activities, and three big rivers) of Bangladesh are described. Road and inland waterway networks are the two modes included in this case study. Therefore, a basic understanding of their infrastructure profile and their recent development is essential. Lastly, the general institutional setting of transportation infrastructure in Bangladesh is given.

## 4.2.1 Geographical features of Bangladesh

The highest administrative level of Bangladesh, which is equivalent to the NUTS-1 classification of Europe, is called 'division'. There are eight divisions in Bangladesh, which are further divided into 64 districts (NUTS-2 equivalent) which native name is *zila*. The third layer of its administrative area is the sub-district that is named *upazila*. There are 490 sub-districts in Bangladesh that can be further broken down into 4553 union councils (lowest administrative level for rural area) and municipalities (lowest administrative level for suburbs).

From an economic perspective, the two most important divisions in Bangladesh are Dhaka and Chittagong. Bangladesh is known as the major garments exporter in the world (Mottaleb & Sonobe, 2011) and around 90% of garments in Bangladesh is produced in Dhaka (Bangladesh's capital city) and Narayanganj (a district located just to the south of Dhaka). Import and export activities are conducted through seaports and land borders. Two main seaports in Bangladesh are the Chittagong and Mongla seaports, while one of the busiest land borders is the Benapole landport that connects Bangladesh to India in the west (see Figure 16 below).

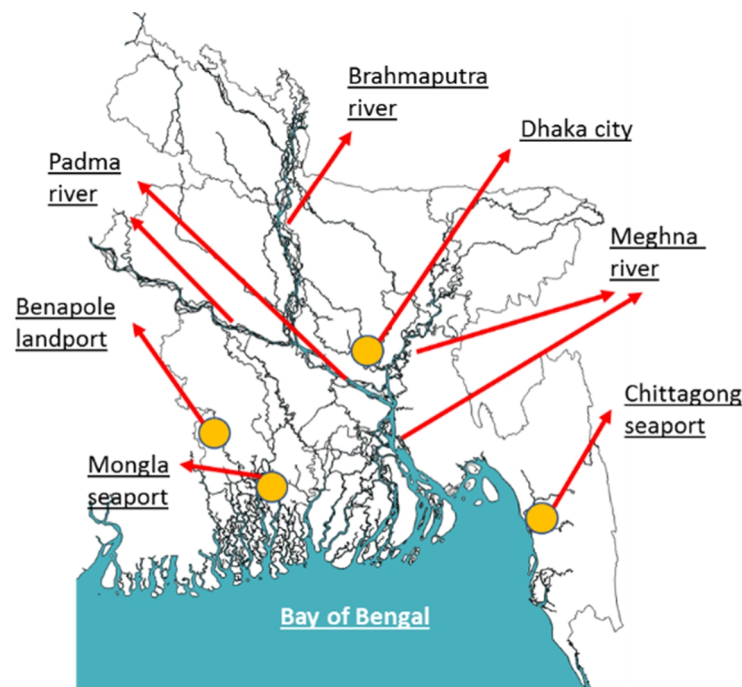


Figure 16 Geographical highlights of Bangladesh

A unique natural geographical feature of Bangladesh is that it is situated among three major rivers that subdivide Bangladesh into several land segments (see Figure 16). From the north, there is the Brahmaputra river flowing that originates from the Tibet part of China to the north of Bangladesh. From the west, the Padma river continues the stream of the Ganges river in India to the central part of Bangladesh, just to the south of Dhaka district. The Padma river is continued by the Meghna river that stretches along the way to the Bay of Bengal in the southern part of Bangladesh.

A major and prominent natural disaster that hits Bangladesh annually is the extreme flooding that may inundate approximately 20% of its land area (Monirul Qader Mirza, 2002). Consequently, the road and railway networks are disrupted and the economy goes into a temporary lockdown. Alternatively, the modal share changes as more transportation activities are done through the waterway. On the other hand, extreme drought may happen on the



other season of the year, reducing the water level of the inland waterway routes and limiting the maximum weight a ship can carry. In some occasions, river level rises and storm surges occur, damaging the inland ports and making them inoperative for some periods. In short, the uncertain natural phenomena jeopardize the serviceability of the transport network (Koetse & Rietveld, 2009).

#### **4.2.2 General overview of freight transport infrastructure**

The main transport modes for transporting goods in Bangladesh are roads, railways and inland waterways. Almost 90% of freight transport activities in Bangladesh are carried out by trucks (Volgers, Nagel, de Jong, & Kluskens, 2016), making road networks the most vital infrastructure element in the transport system. Nevertheless, the presence of hundreds of sailable waterways makes inland waterway transport a crucial element for Bangladesh's transportation network (Awal, 2006).

##### *On road transport*

Roads in Bangladesh are categorized into three classes: N (National) roads, R (Regional) roads, and Z (Zilla) roads (JICA, 2015). The N roads are the longest roads that connect the capital city (Dhaka) to big cities in other divisions, international highway, and major seaports and land borders. The R roads connect different districts with each other, especially those that are not connected by the N roads. The Z roads are small roads which primary function is to provide connections at the sub-district level. In total, there are approximately 21000 kilometers of roads in Bangladesh, composed of 3500 kilometers of 71 N roads, 4200 kilometers of 121 R roads, and 13500 kilometers of Z roads (Alam, 2012). Around 91% of these roads have been paved although the individual conditions vary; some are in poor conditions, and some are in good conditions.

While N, R and Z roads are primarily responsible for providing connections from divisions administrative level to sub-districts administrative level, road connections within the sub-district level are categorized into upazila, union, and village road. By 2009, as long as 36477 kilometers of upazila roads, 42085 kilometers of union roads, and 172319 kilometers of village roads have been built (Local Government Engineering Department of Bangladesh, 2009). This long stretch of road is especially important to reach rural areas in Bangladesh, as there are hundreds of small, remote villages spread all over the country (Njenga & Davis, 2003).

Besides the road itself, another important element in Bangladesh's road transport system is the bridges. The ubiquitous presence of inland waterway forces Bangladesh to construct a large number of culverts and bridges. There are around 20000 bridges in Bangladesh, with more than 5000 of them categorized as 'bridges' and more than 12000 of them categorized as 'culverts' (Bangladesh Roads and Highways Department, 2017). However, more than 14500 of these bridges were constructed before the year 2000, and around 5000 bridges are either in bad or poor conditions. To apprehend this issue, the Roads and Highways Department of Bangladesh has developed an integrated information system named Bridge Maintenance Management System (BMMS) to help monitor bridges conditions.

##### *On inland waterway transport (IWT)*

Bangladesh has a vast network of inland waterways with around 24000 kilometers of rivers, canals, and streams. However, only around 6000 kilometers is navigable for transport activities, and this number may go down to as low as 3970 kilometers in the dry season (Mahmud, Rahman, & E-Rabbi, 2007). Therefore, the seasonal variability throughout the year strongly influences the navigability of Bangladesh's IWT. The navigable waterways are classified into four groups according to their serviceability that is approximated by their depth (see Table 6).

Table 6 IWT classification, acquired from Mahmud et al. (2007)

IWT Class	Total Length (km)	Max Vessel Draft (m)
Class I	683	3.66 – 3.96
Class II	1000	2.14 – 2.44
Class III	1885	1.52 – 1.83
Class IV	2400	Less than 1.52

Access to inland waterways is provided by river ports (also called ferry *ghat*) and landing stations. There are approximately 21 river ports and 380 landing stations by 2009 (Bangladesh Ministry of Environment and Forests, 2009). The river ports are mainly situated along the three major rivers to provide connections between lands on different sides of the river. Due to its vital role in connecting different parts of Bangladesh, the waiting time in the river ports can be as high as sixteen hours (Tesche, 2010). The landing stations on the other hand are scattered throughout smaller waterway segments of arterial river branches. They are used to maintain connections in rural areas. Around 43% of the landing stations are located in the rural areas of Barisal division (mid-south region of Bangladesh, just to the north of the Bay of Bengal).

*On recent developments in transport infrastructure*

Surprisingly, the mode share of freight transportation via inland waterways has been decreasing in the previous decades, as shown in Figure 17. A rising trend can be observed for the road transport, which shows a doubling increase in modal share between 1975 and 2015. This is partly due to the extensive road development that was outlined in Bangladeshi Government’s 1984 rural development strategy. Nevertheless, the absolute number of cargo handled by inland waterway transport is still increasing at two to three million tons annually. Moreover, thousands of unregistered small boats are still utilized to provide access to one fourth of the rural population (Bangladesh Ministry of Environment and Forests, 2009).

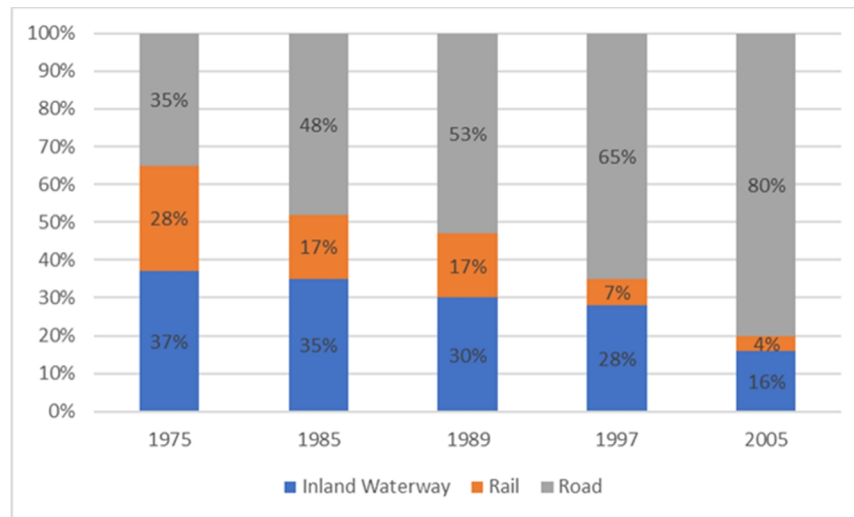


Figure 17 Evolution of cargo modal share, obtained from Smith (2009)

The significant increase in road modal share is also instigated by the construction of the Bangabandhu bridge that crosses the Brahmaputra river in 1998. Popularly called as the Jamuna multipurpose bridge, this new bridge is the only road segment that connects the northwestern districts of Bangladesh that were disconnected from the largest

mainland in the east before. The construction of Bangabandhu bridge has been claimed to shift the geographical pattern of production activities and to reduce the poverty rate in Bangladesh (Bayes, 2007).

One big ongoing infrastructure project in Bangladesh is the construction of the Padma bridge that will provide road connection across the Padma river between Mawa and Paturia. Previously, only ferry connection is available on this route. Since this corridor is also a continuation of the import-export corridor from Benapole landport, the ferry connection has become extremely congested. The waiting time can reach up to four hours in Paturia and sixteen hours in Mawa (Tesche, 2010). Therefore, a successful construction of this bridge is expected to have economic benefits as high as 1,749,510 million taka (Bangladesh’s currency), which is 39% relative to Bangladesh’s base national income (Raihan & Khondker, 2010).

### 4.2.3 Institutional setting of transport infrastructure

Maintenance and development of transport infrastructure in Bangladesh are principally the government’s responsibilities. Figure 18 shows that there are four ministries responsible for the transport system in Bangladesh. The road and shipping authorities will be highlighted in this section.

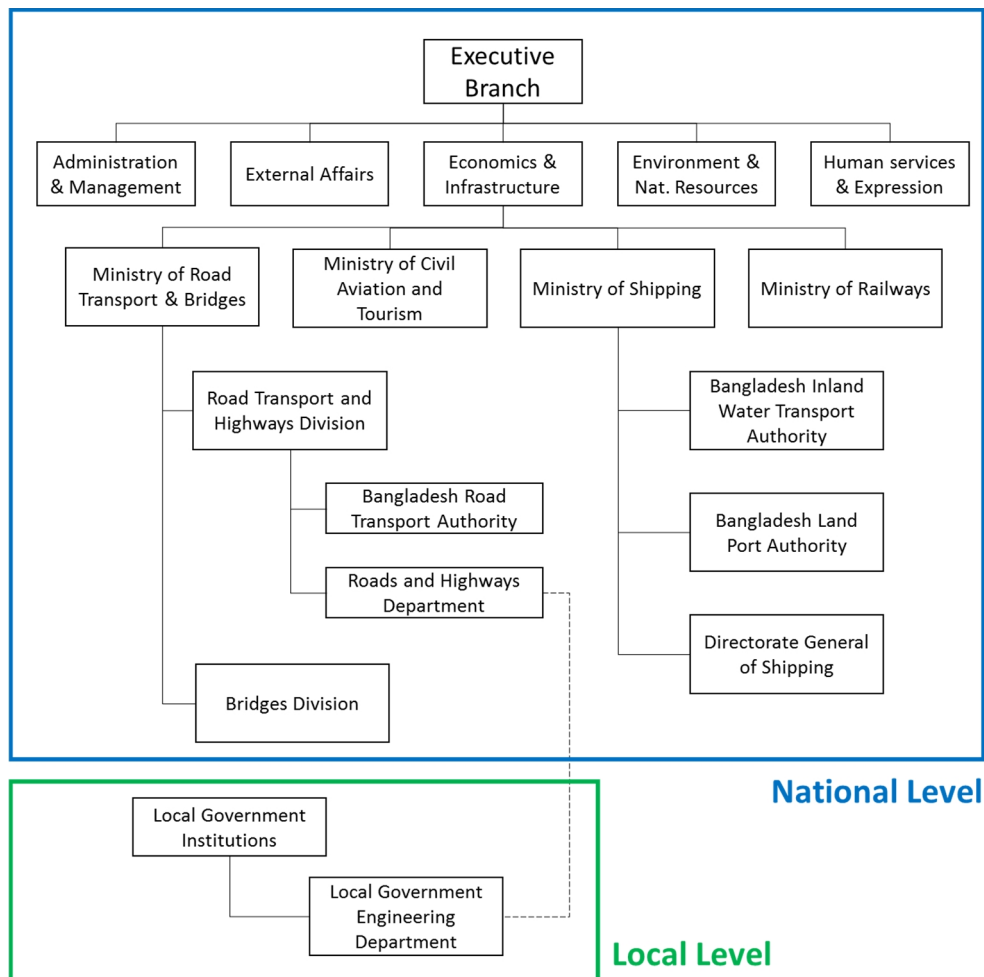


Figure 18 Relevant institutions to freight transport system

The Ministry of Road Transport and Bridges has two main divisions, namely Road Transport and Highways Division (RTHD) and Bridges Division. The former is accountable for construction and maintenance of the main road networks (N, R and Z roads) while the latter is responsible for bridges longer than 1.5 kilometers. Within RTHD, Bangladesh Road Transport Authority (BRTA) provides regulatory functions to manage the discipline of Bangladesh's road sector while infrastructure development and maintenance are the concerns of the Roads and Highway Department (RHD). Upazila, union and village roads are not governed by the central government. Rather, they are the responsibilities of the Local Government Institutions (LGI). A research body named Local Government Engineering Department (LGED) provides technical analyses to support final decision making and planning by LGI.

Three authorities within the Ministry of Shipping that are primarily relevant to the freight transport network are Bangladesh Inland Water Transport Authority (BIWTA), Bangladesh Land Port Authority (BLPA), and Directorate General of Shipping (DGS). The provision of waterway infrastructure itself is BIWTA's responsibility. Dredging projects, hydrographic services, and provision of pilots and navigational aids are examples of BIWTA's tasks. There are also responsibilities that are considered to be overlapping with DGS, as BIWTA also regulates licensing and scheduling of waterway routes and tariffs (Guillossou, 2007). BLPA, as its name suggests, manages thirteen landports in Bangladesh, including the Benapole landport.

### **4.3 Model specification**

This section describes the model specification of Bangladesh's multimodal freight transport network based on the four processes in Figure 15. As a lot of metrics require interdiction techniques to be computed, a smart technical implementation of interdiction techniques that considerably reduces the computation time is discussed as well. The software packages utilized in this study can be found in Appendix A and an online documentation of the codes can be found at <https://github.com/bramkaarga/transcrit>.

#### **4.3.1 Socioeconomic data and O/D matrix calculation**

In order to achieve a higher model resolution, the O/D matrix in this study considers district-level administrative areas of Bangladesh. Economic data on further administrative layers (e.g. sub-districts) is not available and thus hinders the modeling exercise to go into more detail. Each district is represented by a single centroid (i.e. node) in the network. Therefore, the O/D matrix provides information on goods flows among these centroids.

The O/D matrix calculation begins by determining which products should be included in the analysis. Rather than considering all types of products in Bangladesh's economy, an 80-20 Pareto rule is applied for products selection. That is, only commodities with the highest contribution to, and account for up to 80% of Bangladesh's total economic output are considered. For each commodity, not all sub-products are considered. The same Pareto logic is directed to select the specific sub-products to be included in the model.

Since the data of aggregate economic output is available in monetary unit instead of in tonnage unit, a key assumption in this approach is that the economic output of each commodity is linearly correlated with its the tonnage units. Nevertheless, the monetary unit is still transformed into tonnage unit based on other statistical reports before it is being used. Table 7 shows the final sets of products included in this study and their contribution to the overall economic output.

Production purpose of each commodity is differentiated into production to serve the local market (consumptions within Bangladesh) and production for exporting to other countries. Consequently, the attraction factors of the

local-based market and export-based market differ. Table 7 presents the attraction factors for the local-based market purpose of each commodity. As for the export-based market, the attraction factor is the total annual throughput of the ten land ports and two seaports (Chittagong and Mongla seaports).

*Table 7 Commodities selected in this study*

<b>Products</b>	<b>Percentage</b>	<b>Cumulative Percentage</b>	<b>Sub-products</b>	<b>Attraction Factors (Local market)</b>	<b>Local Share</b>	<b>Export Share</b>
Garments	34%	34%	Garment	Population	6%	94%
Basic metals	17%	51%	Steel	Population	98%	2%
			Raw jute	Jute mill	100%	0%
Textiles	13%	64%	Processed jute	Garment factory	46%	54%
			Textile	Population	46%	54%
			Rice	Population	86%	14%
Foods	11%	75%	Fruits	Population	86%	14%
			Potatoes	Population	86%	14%
			Sugar	Population	86%	14%
			Wheat	Flour mill	86%	14%
Nonmetal minerals	7%	82%	Bricks	Household	91%	9%

Socioeconomic data of Bangladesh is collected from Bangladesh Bureau of Statistics' official website (Bangladesh Bureau of Statistics, 2013). The tonnage volume of commodities produced is available on the district-level while the share of the commodities' local and export-based market is only available on the national level. Therefore, the local and export shares are assumed to be uniform across all districts. The geographical distribution of these socioeconomic data for all 64 districts can be seen in Appendix B.

After data collection and preparation, the gravity model described in Section 4.1.3 calculates the O/D flows between each district. The calculation results in a 64 x 64 matrix. For visualization convenience, OD matrix on division level is displayed instead of on district level in Figure 19.

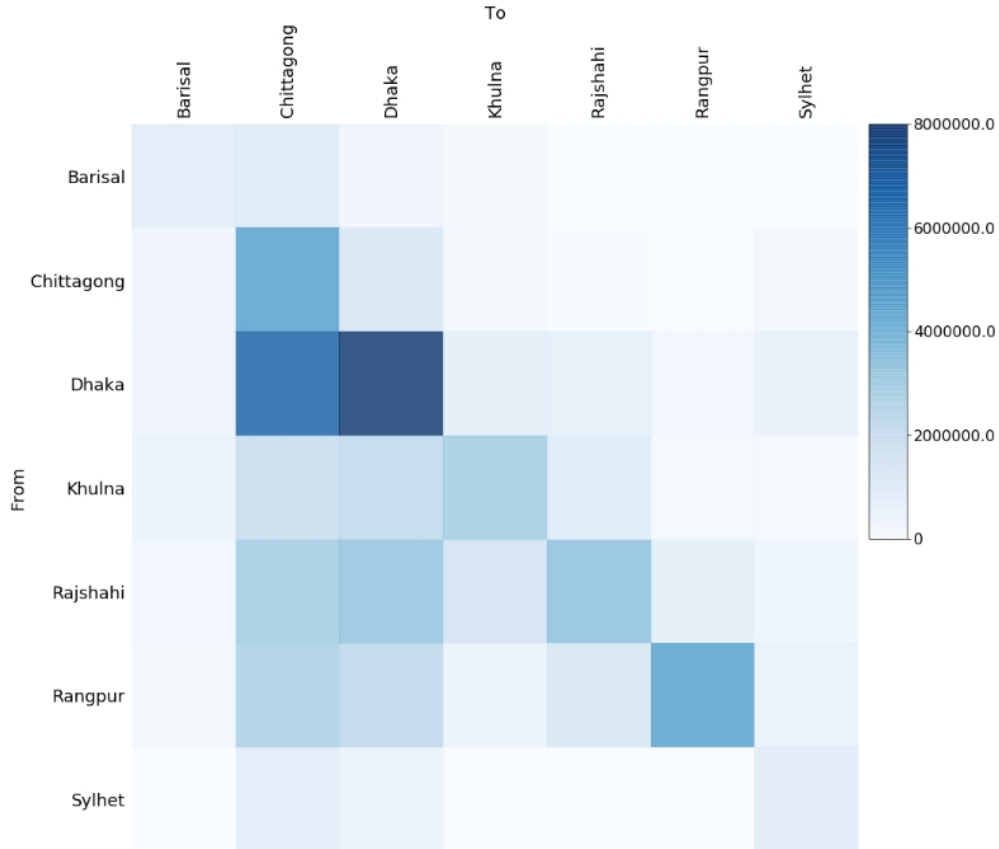


Figure 19 O/D matrix heatmap on division level (units in tonnage)

It can be observed that Dhaka and Chittagong absorb a substantially large amount of goods flow. The reason behind this is that for local consumption, most of the products' attraction factor is population while Bangladesh population is concentrated in Dhaka. As for the export-based market, the Chittagong seaport accounts for 80% of the total export throughput in Bangladesh. This makes Chittagong an extremely attractive division for export goods flow in the model. Sylhet and Barisal divisions are the least densely populated regions. This makes goods flow to those regions small.

### 4.3.2 Transport supernetwork development

The two modes considered in this study are road networks and waterway networks since both combined have accounted for more than 95% of Bangladesh's cargo modal share (Volgers et al., 2016). The road network data is extracted from Bangladesh Roads and Highway Department's RMMS (Road Management and Maintenance System) database. The RMMS database contains tables of geocoded LRPs (location reference points) data of around 850 N, R and Z roads. LRPs are road's chainage information measured by local officials as a part of their integrated road maintenance program. The LRPs store information on the existence of bridges, culvert, ferry *ghat* and intersection in each chainage of all roads.

Although the longitude and latitude information of the road chainage is present, the database does not form one large fully connected graph yet. Figure 20b shows this issue. Each single color in that figure represents one disconnected subgraph. Therefore, for transport modeling purpose, trucks cannot go from a link of one color to another. Simply parsing the longitude and latitude information from the RMMS database results in 647

disconnected subgraphs. In order to solve this issue, a correction algorithm is developed in Python (a high-level programming language) to automatically connect each road's ending nodes if there is another road within one kilometer radius of the ending nodes. The algorithm also detects if there are any intersecting roads without the occurrence of a node in that intersection and automatically creates an additional node at the intersection. The correction algorithm produces one large, fully connected and routable graph that is suitable for transport modeling (see Figure 20c).

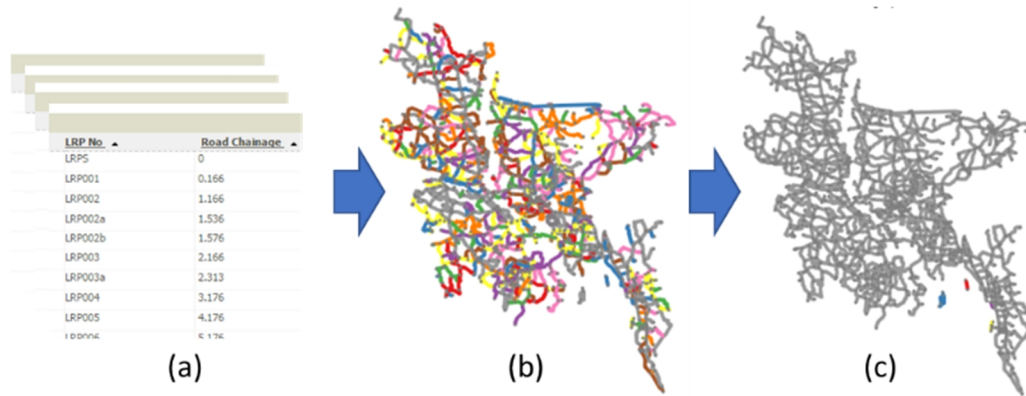


Figure 20 Road Network preprocessing scheme: (a) raw RMMS database, (b) 647 disconnected subgraphs, (c) one large connected graph

Unlike road networks, no sufficient publicly available data of waterway network is available. Therefore, the waterway network is drawn manually from the main inland waterway routes classified by Bangladesh Inland Water Transport Authority (BIWTA). There are 53 routes spanning from the southern part of Chittagong to the northern part of Rangpur.

The supernetwork is created by overlaying the road network on top of the waterway network (see Figure 21). However, the transshipment nodes for connecting the two modes cannot be arbitrarily created on every location where the road network intersects with the waterway network. The road network contains information about the location of bridges in the road segment. Therefore, if a road segment that has bridge information intersects with the waterway network, no transshipment node is created. On all other road segments where bridge information is not present, the transshipment nodes are automatically created. Lastly, all road segments that are connected with the transshipment nodes are given an extra cost to represent costs of switching from/to the waterway.

Incorporating the whole road network into the supernetwork results in around 51000 links. The huge size of the network incurs a large computation cost to calculate the criticality metrics. Therefore, in this study, the Z roads are left out of the supernetwork. This leaves only around 22000 links behind. Moreover, Z roads are primarily used for passenger transport activities within districts while the intention of this study is to model freight transport between regions.

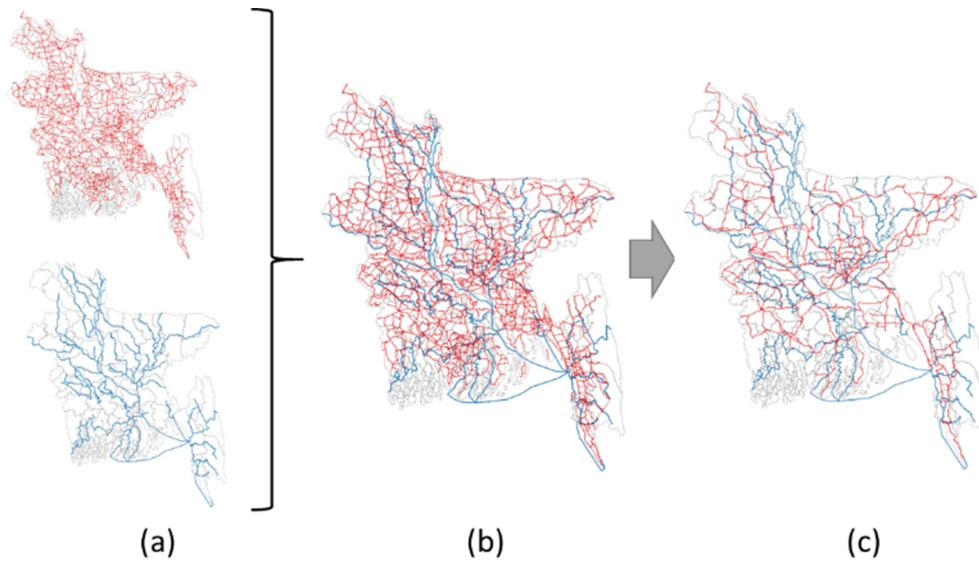


Figure 21 Supernetwork development: (a) uni-modals road and waterway network, (b) initial supernetwork, (c) supernetwork without Z roads

### 4.3.3 Network assignment

Once the OD matrix and the supernetwork are complete, the flow assignment is performed by conducting a single all-or-nothing (AON) assignment and five iterations of probit assignment with a penalty cost of 10%. The intention of doing two assignment methods is because the former one will be used for interdiction technique later due to its lower calculation time. As for the probit assignment, after each iteration, the lengths of all links that belong to the shortest paths between OD pairs are increased by 10%. This number is obtained by a manual calibration to reach lower errors between the model's mode split and the actual mode split for the cargo transport. The actual mode split information is a 2015 observation data that comes from Volgers et al. (2016).

The comparison between the actual modal split, the AON assignment's modal split, and the probit assignment's is presented in Table 8. The probit model has zero error for the road modal share and two percent difference for the waterway modal share. This is because the railway network is not included in the model. The AON assignment on the other hand has a higher error, although the magnitude is still considerably small.

Table 8 Freight modal share comparison

	Road	Waterway	Railway
Data	88%	10%	2%
Model (AON)	93%	7%	-
Model (Probit)	88%	12%	-

Figure 22 visualizes the result of the network assignments for both AON and probit methods. The blue links represent the waterway network whereas the red links represent the road network. The thicker the line and the bolder the color, the more goods flow through that network segment. The numbers on the colormap legends show



the portion of total flows going through the links. For instance, the highest number of red colormap in Figure 22a is 0.22, meaning that 22% of the total flows in the network pass through the road segment with the boldest color.

In general, it can be observed that the same road and waterway segments appear as the most critical ones in both models, although the specific number of the magnitude may differ. This indicates that although AON assignment has lower modal share accuracy, it can still provide similar insights in finding the most critical network segments as the probit assignment does.

A road corridor spanning from Rangpur division in the northern part of Bangladesh to the Chittagong port in the southern part of Bangladesh appears as the most critical road segment in Bangladesh. With Dhaka located at the center of Bangladesh and Chittagong located in the south, this corridor transports goods from the northern part of the country to Dhaka for local consumption and continues further down to Chittagong for export. A waterway route from Dhaka to Chittagong also appears as the most critical waterway segment. These facts underline the regional imbalances in Bangladesh as most economic activities are centered in Dhaka and Chittagong.

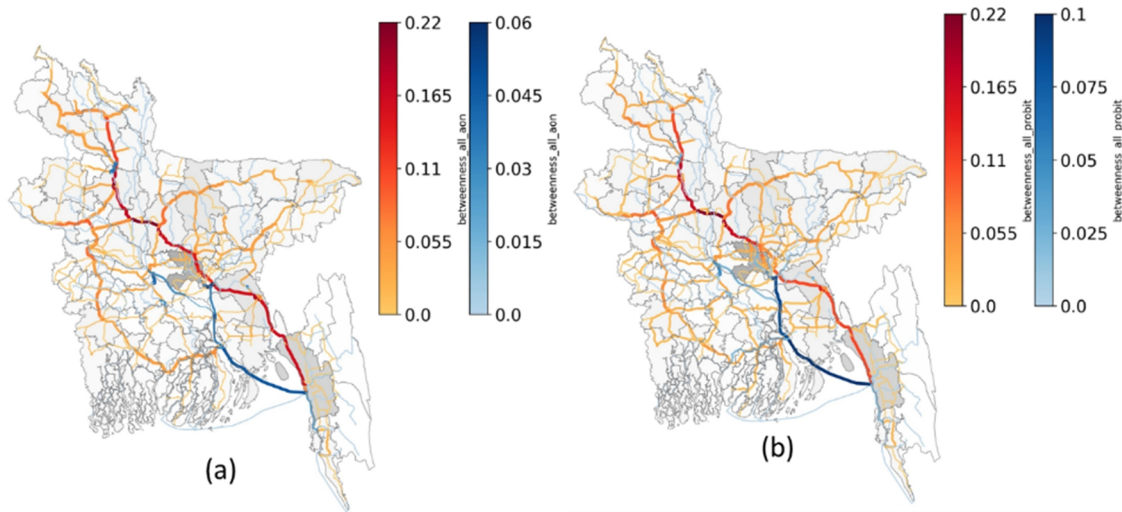


Figure 22 Network flow from (a) AON assignment, and (b) probit assignment

#### 4.3.4 Interdiction technique implementation

Interdiction techniques in essence recalculate the performance of the network after the removal of a network component. The contribution of the component to the overall system performance is measured by the change in the performance before and after that component's removal. On the other hand, due to the size of the network, calculating the shortest paths between all OD pairs takes around 1.5 minutes. Iterating this for thousands of links in the network will take days to finish. To overcome this issue, the dictionary feature in Python is utilized. The technical implementation, for instance for calculating the increase in total travel cost, is exhibited in Figure 23.

The first step is to calculate the shortest paths between all OD pairs (step 1 in Figure 23). All links within the shortest path and the total cost of that shortest path is stored in a dictionary. Dictionary is a Python object that holds a mapping relationship between 'keys' and 'values'. Each OD pair becomes the key in the dictionary while the links set and the total travel cost of the shortest path for that OD pair are stored as the corresponding values of the key (step 2

in Figure 23). Next, the total initial cost of the system is calculated by summing up the shortest path costs of all OD pairs (step 3 in Figure 23).

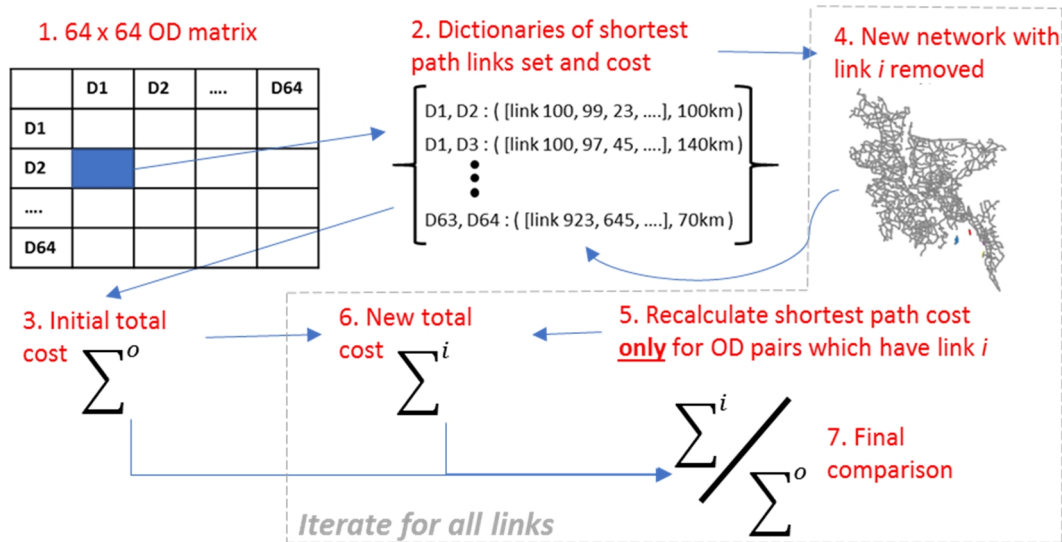


Figure 23 Illustration of technical implementation of interdiction technique

After the dictionary is complete, the interdiction phase is started. Each link in the network is removed individually and in isolation. Suppose that link  $i$  is removed from the network (step 4 in Figure 23). The shortest path cost of the OD pairs is recalculated. However, as opposed to recalculating the shortest path of all OD pairs, the dictionary is used to find out which OD pairs contain link  $i$  in its shortest path links set (step 5 in Figure 23). Next, new shortest path routes and shortest path costs are only recalculated for those particular OD pairs. This routine reduces the computation cost abruptly as only few OD pairs' shortest cost need to be recalculated (instead of recalculating more than 4000 OD pairs' shortest path in each link removal, for the case of Bangladesh). The new total cost can be recalculated by a simple summation of subtraction between the original shortest path costs and the new shortest path costs of the affected OD pairs (step 6 in Figure 23). Finally, the total shortest path cost before and after link  $i$ 's can be computed (step 7 in Figure 23).

#### 4.4 Chapter 4 Summary

The main outcome of this chapter is a ready-to-use Bangladesh multimodal freight transport model for the criticality analysis in the following chapter. In more detail, this chapter has discussed the following points:

- Four main freight transport modeling approaches and a specific approach employed in the case study have been reviewed. The selected approach consists of four main steps: socioeconomic data preprocessing, transport supernetwork development, O/D matrix calculation, and network assignment.
- Geographical, infrastructure and institutional background of Bangladesh's freight transport network has been provided. The presence of ubiquitous waterway network and the three most important rivers that subdivide the country pose a unique challenge to Bangladesh's transport sector. The road transport has been getting more popular due to the construction of paved roads in rural areas.

- An implementation of the transport model specification for Bangladesh's multimodal freight transport has been explained. The district-level O/D matrix is calculated by using a gravity model, taking into account the Euclidean distance between the districts. The transport supernetwork (road + waterway segments) is developed by incorporating the geocoded information of bridges location in Bangladesh. Probit assignment is used to calculate metrics that do not require interdiction techniques, while the All-or-Nothing assignment is used for metrics that demand interdiction techniques. The transport model is ready to be used for the criticality analysis in the next chapter.
- A smart Python-based implementation of the interdiction technique that substantially reduces computation time has been described as well.

*This page is intentionally left blank.*

# Chapter 5: Criticality Analysis Results Evaluation

The Bangladesh’s multimodal freight transport model developed in Chapter 4 is used to evaluate Bangladesh’s freight transport network criticality. In this Chapter, eighteen criticality metrics derived from the ten metrics categories discussed in Chapter 3 are deployed to the freight transport model. The results of the metrics are evaluated to understand the metrics’ (dis)similarities to each other. As a start, Section 5.1 provides an overarching framework used for evaluating the criticality metrics. The evaluation consists of three general steps: individual assessment, robustness analysis, and metrics comparison. The results of these steps are explored in Section 5.2 to 5.4. Lastly, Section 5.5 is dedicated to investigate the generalizability of the metrics comparisons to other transport networks.

## 5.1 Evaluation framework

The evaluation of the criticality metrics in this study follows an approach shown in Figure 24. There are more than 35 criticality metrics found from the literature review. Evaluating all metrics is not needed and is not possible because of three reasons. First, some metrics can only be calculated if a specific data of the transport network under study is available. For instance, the lack of information on the probable behavior of freight drivers during disruption hinders the calculation of lost user benefits from canceled trip as proposed by A. Chen, Yang, Kongsomsaksakul, and Lee (2007). Second, several metrics, especially those that rely on analytical solutions are only applicable to small scale abstract networks (He, Jia, & Li, 2014). Using too many metrics is not necessary if the metrics represent the same criticality aspects which in turn may only create more information overload to the decision makers. A set of metrics set selection criteria is developed to filter the large amount of metrics found from the literature review.

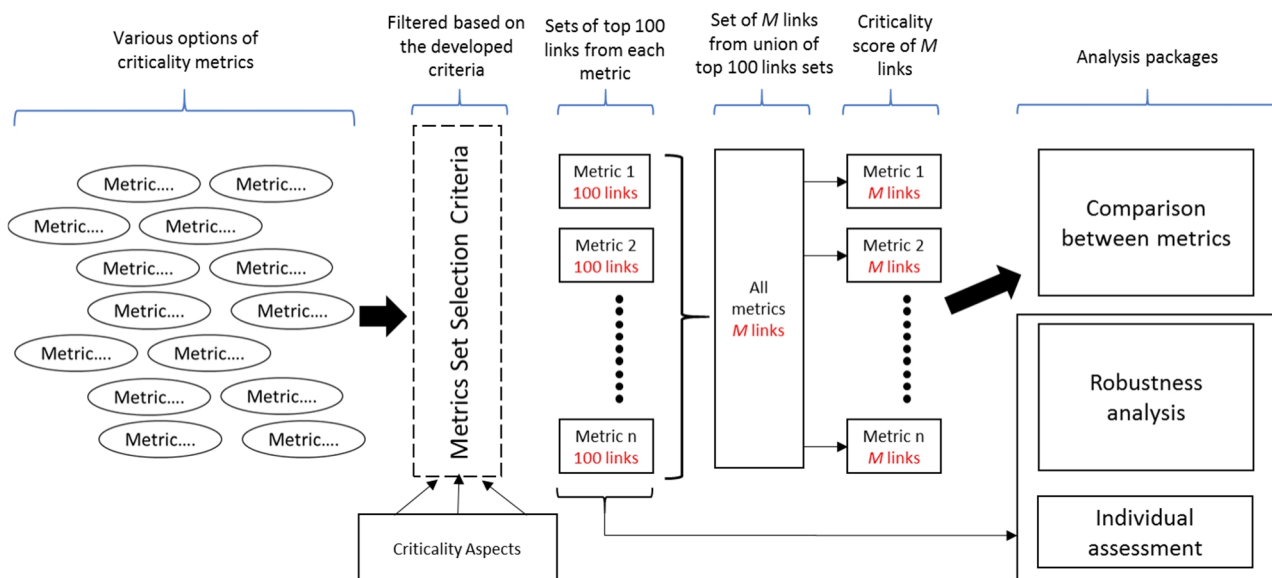


Figure 24 Metrics evaluation framework

Not all links' criticality values are considered for further analysis. Rather, only a subset of links is used. The practical reason behind this is because there are an enormous number of links in the case study (more than 1200 links) and in some metrics, the criticality scores of some of these links are zero. The occurrence of hundreds of links with zero criticality scores creates data noises that may significantly refract the results. This also helps decision makers in focusing on a smaller number of transport network segments to be prioritized.

In accordance with Figure 24, the first step of the analysis is to record the top 100 most critical links from each criticality metric into their links set. Supposing that there are  $n$  metrics used, there will be  $n$  sets of top 100 most critical links. The union of links from these  $n$  sets of top 100 critical links is taken into a new set of links. This process results in a new set of links that contains  $M$  number of links. These  $M$  links are used for comparisons between all metrics.

Two kinds of analysis are operated on the set of the top 100 links for each criticality metric. First, for each metric, the top 100 links' criticality scores are assessed individually in order to understand the statistical characteristics of that metric. Then, modifications in model and metrics parameters are applied to study the metrics' robustness to uncertainty.

### 5.1.1 Criticality metrics set selection criteria

On his paper on robustness analysis of road network, Snelder et al. (2012) describe seven questions that can be used to assess road network robustness indicators. Some of these questions are adopted as a foundation to establish requirements for selecting a set of criticality metrics. However, the questions posed by Snelder et al. (2012) are insufficient because they focus on assessing an individual indicator rather than selecting a set of indicators (i.e. multiple indicators). Therefore, the lists are expanded and categorized in Table 9.

*Table 9 Requirements for selecting set of criticality metrics*

<b>Pragmatic usefulness</b>
<ul style="list-style-type: none"> <li>#1. The metrics should represent (a subset of) transport network criticality aspects.</li> <li>#2. The metrics should be able to be easily explained to decision makers, including those who are not familiar with transport network criticality.</li> </ul>
<b>Practical feasibility</b>
<ul style="list-style-type: none"> <li>#3. The metrics should be able to be estimated by a computer model.</li> <li>#4. The computation time to calculate the metrics should be acceptable.</li> <li>#5. Data required to calculate the metrics should be available.</li> <li>#6. The metrics should be assessed on each network component.</li> </ul>
<b>Exhaustiveness</b>
<ul style="list-style-type: none"> <li>#7. The set of metrics should represent as many metric categories presented in Table 4 as possible.</li> <li>#8. The number of metrics in each category should be sufficient enough to enable within-group comparison.</li> </ul>

**Pragmatic usefulness** ensures that the metrics are relevant for a criticality analysis, which ultimate goal is to rank network components or to find the most critical network components. To achieve this, the selected metrics should

be reflected back to the criticality aspects discussed in Section 3.2. Additionally, criterion #2 guarantees that the metrics can be easily explained, both technically and functionally, to decision makers. This criterion safeguards the face validity of the metrics as decision makers are the ones who have tacit knowledge of the problem.

**Practical feasibility** ensures the computability of the selected metrics. Several metrics require detailed specific transport and/or socioeconomic related data while other metrics only require transport network information to compute. Therefore, the availability of data is an essential prerequisite in selecting a set of metrics (criterion #5). The metrics should also be able to be computed within an acceptable computation time (criterion #3 and #4). If a metric takes too long to compute, other similar metrics that belong to the same metrics category can be employed instead.

Criterion #6 is a special criterion specific to the aim of this study, which is to compare the results between different criticality metrics. As a consequence, metrics that require two-stage analysis, such as those which firstly identify the most vulnerable region and continued through the identification of the most critical network components in that vulnerable region, are excluded from the selection. This is because even though the metrics are technically applicable for real-world decision making, they do not permit comparisons of criticality ranking of all network components at once.

The third criteria set, **exhaustiveness**, is also of particular importance in this study. Exhaustiveness ensures within-group (criterion #8) and between-group (criterion #7) diversity of the selected metrics. The aim of these criteria is to explore plausible, distinct network elements ranking results that are expected to emerge from using a diverse set of metrics. There is of course a tradeoff between this criteria set and the practical feasibility criteria set, as calculating more metrics takes more time.

### 5.1.2 Individual metrics assessment

The individual metrics assessment comprises studying the distribution of criticality scores of the links in the network and visualizing them geospatially. There can be multiple possibilities of the distribution as illustrated in Figure 25. Understanding this distribution is important for two reasons: (i) making sense of the resulting criticality scores for real-world decision making and (ii) selecting a statistical test for metrics comparisons. For the former, the assessment is conducted only for the top 100 links since we want to understand the behavior of the criticality metrics for the most important segments. For the latter, the assessment is conducted for the  $M$  links described before since we are interested in selecting an appropriate statistical comparison method.

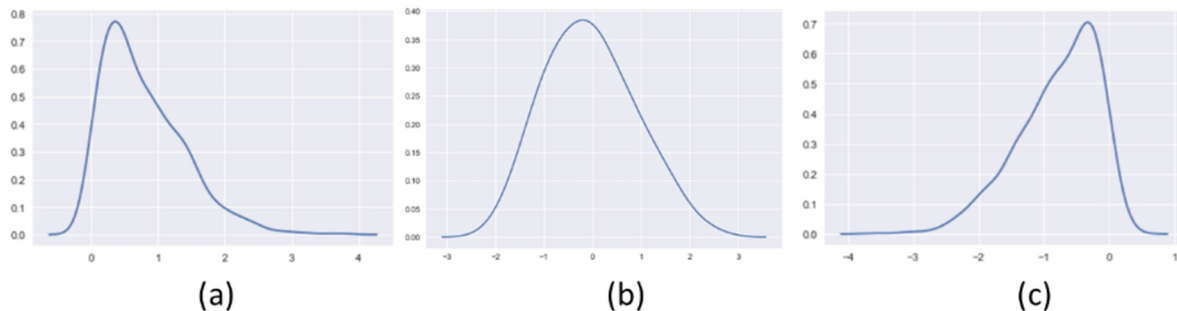


Figure 25 Possible distribution of criticality values: (a) negatively skewed, (b) normal, (c) positively skewed

If the distribution of a criticality metric score follows a negatively skewed distribution (Figure 25a), the metric exhibits a scale-free behavior of networks. A scale-free network is a network where a small number of components have a high degree (in our case high criticality score) while a larger number of components have a low degree.

Albert, Jeong, and Barabási (2000) have proven that a scale-free network is resistant to random disruptions but vulnerable to targeted attacks. In the context of a freight transport network, if a metric exhibits a scale-free behavior, decision makers can just focus on network components that reside at the 'tail' of the distribution.

Criticality metric's scores can also follow a normal distribution (Figure 25b). On the one hand, a perfectly normally distributed criticality metric does not have 'outlier'. This implies that there is no single source of failure in the system based on this metric. On the other hand, there are a lot of network components with middle-rankings which criticality scores are close to each other. This raises difficulties when decision makers want to select a larger number of transport segments.

A positively skewed distribution (Figure 25c) poses different challenges to the interpretation of the criticality results. Decision makers can ignore the left part (the tail) of the distribution, but the selection of the most critical links becomes harder. This distribution troubles decision makers if they want to select only a small number of the most critical links because a positively skewed distribution has a large number of data points with high values.

Observing the distribution is also important for determining the statistical tools to be used for metrics comparisons. Parametric statistics tools such as student t test and Pearson correlation coefficient necessitate the normal distribution of the sample set. Therefore, if the distribution is skewed, nonparametric statistics should be used instead.

The second assessment is done by geovisualizing the results of the criticality analysis. The visualization should be made interactive so that decision makers can observe what would happen if a smaller or larger number of top  $n$  critical links are selected. Geovisualization enables decision makers to quickly grasp the location of the critical segments.

### **5.1.3 Robustness analysis and uncertainties demarcation**

The extent to which the criticality results are dependent on data and assumptions can be observed by analyzing the robustness of the metrics when faced with uncertainties. Robustness analysis is done by modifying several parameters which can be deemed as uncertain, and followed by recalculating the criticality scores. The uncertainties studied in this research are categorized into transport model uncertainties and metrics parameter uncertainties. Transport model uncertainties encompass uncertainties that occur during the transport modeling phase discussed in Chapter 4. Metric parameter uncertainties are metric-specific uncertainties such as distance sensitivity to calculate accessibility index. A hundred replications are conducted in this study, where a unique combination of uncertainties typifies each replication.

Transport model uncertainties come from the stochasticity of traversing through links, calculation of OD matrix, and flow assignment on the network (see Table 10). There are two parametric uncertainties and one structural uncertainties present in the O/D matrix calculation: production factors scaling parameter, attraction factors scaling parameter, and deterrence function. A scaling factor between 0.75 to 1.5 is applied to all nine production factors (export of steel, bricks, foods, jute, textile and garments, textile production for local consumption, wheat production for local consumption, raw jute production for local consumption, foods production for local consumption, and other non-foods production for local consumption) and two attraction factors (district population and total export attractiveness) independently. The scaling factors aim at embracing the uncertain future developments of the different economic sectors.



Table 10 Transport model uncertainties

Uncertainties	Step	Description	Default value	Range
Production factor scaling	O/D matrix calculation	Scaling variable given to each type of production factors independently (9 parameters in total)	1	Uniform (0.75, 1.5)
Attraction factor scaling	O/D matrix calculation	Scaling variable given to each type of attraction factors independently (2 parameters in total)	1	Uniform (0.75, 1.5)
Deterrence function	O/D matrix calculation	Formulation of representation of deterrence function	Linear Euclidean distance	<ul style="list-style-type: none"> <li>• Linear Euclidean distance</li> <li>• Network-based shortest path</li> <li>• Logit model</li> </ul>
Links length perception error	Network assignment	Scaling variable given to each link independently before network assignment	1	Uniform (0.75, 1.5)
Penalty	Network assignment	Penalty given to each link in shortest paths set, applicable only for probit assignment	1.2	Uniform (1, 1.5)

Since there is no data available for validating the volume of commodities traded among the districts, empirically validating the O/D matrix is not possible. Thus, the deterrence function should be treated as a structural uncertainty. Three different deterrence functions are considered in this study: (i) the standard linear Euclidean distance based deterrence function, (ii) the network shortest path length and (iii) the logit model. The network shortest path length has the same formulation as the linear Euclidean distance, except that the denominator in Eq 2 is changed to  $d_{ij}^{sp}$  (the network's shortest path distance between centroid  $i$  and  $j$ ). The equation is therefore:

$$a_{ij} = \frac{a}{d_{ij}^{sp}} \dots\dots\dots(Eq 3)$$

The logit model takes the Euclidean distance between the centroids and is formulated as follow:

$$a_{ij} = \frac{\exp(-\beta d_{ij}^e)}{\sum_j \exp(-\beta d_{ij}^e)} \dots\dots\dots(Eq 4)$$

where  $\beta$  is a logit sensitivity parameter set to 0.05 and  $d_{ij}^e$  is the linear Euclidean distance between centroid  $i$  and  $j$ .

Two kinds of uncertainties are taken into consideration during network assignment. Links length perception error tries to relax the assumption of freight trucks drivers' perfect knowledge on the cost to travel on the route. The length of each link is sampled independently at the beginning of the modeling cycle. Consequently, the calculation of

the shortest path based deterrence function is also affected by this uncertainty. A scaling factor between 0.9 to 1.5 is used in this independent sampling.

The second uncertainty in network assignment step is the penalty given to links that belong in shortest path routes set of all OD pairs. This is to force the model to find a second-best shortest route for each OD pair, instead of using only a single shortest route between them. Hence, this penalty only applies for probit assignment. Metrics that require interdiction techniques are not affected by this uncertainty since they use all-or-nothing assignment.

It is important to note that the O/D matrix calculation uncertainties are only applicable to system-based metrics. Topological based metrics do not incorporate socioeconomic properties of the study object, which makes changes in the O/D matrix irrelevant. The network assignment uncertainties on the other hand are relevant to all metrics.

Figure 26 shows the three robustness analyses on the results of the experiment. Rank robustness assesses the change of links rankings between each replication. To accomplish this, Spearman-rank correlation coefficient is used. Spearman-rank correlation coefficient is a paired nonparametric statistics technique that computes the direction and strength of the relationship between rankings of values from two variables. The correlation coefficient takes a value between -1 (negative relationship) to +1 (positive relationship). The closer the correlation coefficient to any of these ends, the stronger the association between the rankings of the two variables. For a metric's rank robustness purpose, each replication acts as a single variable. Therefore, there are 100 variables for each metric. Spearman correlation coefficients between each replication are computed and plotted in a heatmap. If there are a lot of high correlation coefficient values from the heatmap, it can be inferred that the rankings of the metric are robust.

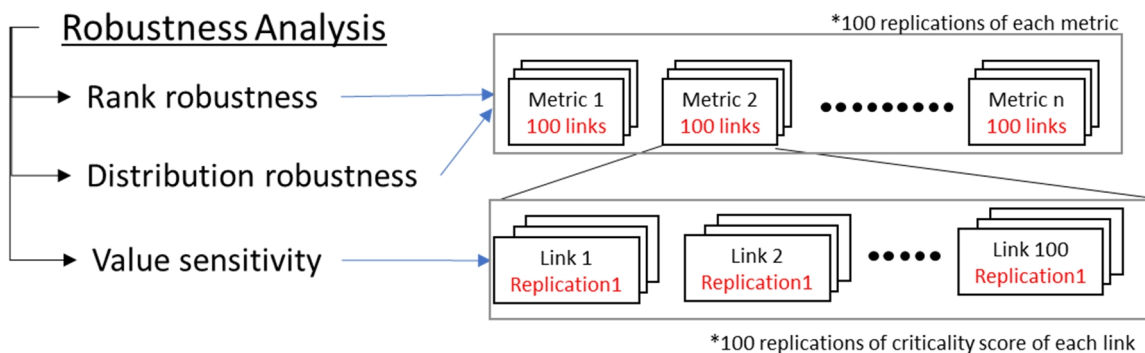


Figure 26 Robustness analysis scheme

The next step in robustness analysis is to observe if the shape of the criticality scores' distribution changes between replications. If the shape does not significantly change, it is safe to infer the qualitative interpretation of that metric's distribution pattern (see Section 5.1.2) based on its business as usual result. Otherwise, extra attention should be put when concluding the results of the analysis since the criticality result may be very dependent on the uncertainties. A two-sample Kolmogorov-Smirnov (K-S) test can be used for this objective. The test evaluates whether the data points of two variables come from the same type of distribution by measuring the distance of their distributions. If the K-S distance statistics value is closer to zero, the null hypothesis that the distributions of the two variables are the same cannot be rejected. The two-sample K-S test is applied between all replications for each metric, similar to the analysis conducted in rank robustness assessment. If there are a lot of K-S distance values which are close to zero in the heatmap, it can be concluded that the distribution of the metric scores is robust.

In the first two robustness analyses, the criticality scores from all links in each replication are bundled into a single dataset, resulting in 100 datasets for each metric. Unlike these first two, the last robustness analysis considers all 100 different criticality scores of a metric from each link as a single dataset. This is for the reason that we want to understand to what extent the values of the criticality metric change due to uncertainties. In short, the individual criticality scores of all links in the network from one replication act as a single dataset in the first two analyses, while the criticality scores of one link is a single dataset in the value sensitivity analysis (see Figure 26).

In order to analyze the variability of a link's criticality values, statistical dispersion measures are used. The criticality scores are firstly normalized by dividing the criticality score of a link from each replication to the criticality score of that link in the business as usual scenario. This normalization is applied since each metric has a different magnitude of criticality (e.g. some metrics have a magnitude between 0 to 1 while others may have a magnitude between 0 to 150). Afterward, two statistical dispersion measures are used: median absolute deviation (MAD) and standard deviation (SD). MAD is the median of the absolute differences between all data points and the median of the dataset. Therefore, it is considered as a robust measure of scale for quantifying statistical dispersion due to its insensitivity to outliers. In some cases, however, it is possible that the criticality score of a link changes abruptly due to a specific combination of uncertain parameters, creating outliers for that particular link's criticality score. SD fits for capturing this effect due to its sensitivity to outliers. The MAD and SD scores of each link are aggregated in order to get the aggregate MAD and SD for a metric as a whole.

If both the aggregated MAD and SD of a metric are low, we can infer that the criticality values of that metric are not sensitive to parameter changes. If the MAD is far lower than the SD, then although in general the metric is not sensitive, there is a particular scenario (i.e. a combination of uncertainties) that may abruptly change the criticality value. If both are high, we can infer that the criticality value of the metric is sensitive to uncertainties.

#### **5.1.4 Comparison between metrics**

The last step of the metrics evaluation sees how the metrics overlap with each other. To begin with, a graphical observation by overlapping the distribution of criticality scores of each metric with one another for the  $M$  links defined before is conducted. The graphical observation is represented by a single by K-S statistics value that quantifies the distance between the distributions in a single value. Similar to the K-S statistics in robustness analysis, a high value of K-S distance in this step means that the distribution shapes of two metrics are considerably different. The graphical observation complements the K-S statistics in understanding how they are different.

This first step serves two purposes. First, this step provides an explicit explanatory visualization about the (dis)similarities among the metrics with regard to their scores' density distribution. Second, the results of this step can be used to reflect on the result of the correlation coefficient analysis that will be explained below.

After distribution comparisons, the paired correlation coefficients between all metrics are calculated. The correlation coefficient technique selected is dependent on the shape of the distribution. If both metrics follow a normal distribution, the parametric Pearson correlation coefficient technique can be used. Otherwise, the nonparametric Spearman-rank correlation coefficient should be used as it does not oblige the normality of the datasets. The resulting correlation coefficients are plotted on a heatmap to give an overarching summary of the analysis.

If two metrics are highly correlated, the results of both metrics signify the same set of links as critical. Consequently, one of these metrics can be eliminated from the analysis because the emerging results of one metric can be represented statistically well enough by its counterpart. Therefore, the information handed to the decision makers is

reduced while no important insights from the different metrics are lost. If two metrics have a low correlation coefficient, they should be kept in the final metrics set for further analysis. Low correlation coefficients imply that different links are considered critical by the metrics.

The elimination of the overlapping metrics follows two phases. First, metrics which in general have high correlation values with other metrics are identified. Then, for each of these identified metrics, a counterpart metric is searched. A counterpart metric is another metric which correlation coefficient with the identified metric is the highest. If the counterpart metric in general has low correlation coefficients with other metrics, the originally identified metric should be eliminated. If the counterpart metric has high correlation coefficients with the rest of metrics in the metrics set, then any of these two metrics can be removed. The final set of metrics is visualized geospatially, highlighting the top 100 most critical links from each metric.

Lastly, the second step is replicated to different subnetworks, which in this case consists of seven networks that come from the seven divisions of Bangladesh. The idea behind this is to understand if the (dis)similarities among the metrics are network dependent. If the same metrics sets are identified as similar (having high correlation values), it can be safely deduced that the comparisons are not network-specific. If not, the comparison results cannot be generalized and are network-specific.

## 5.2 Selected metrics and individual assessment

From more than 30 metrics used in previous studies, Table 11 shows the eighteen metrics selected based on the requirements specification in Table 9. These metrics represent all ten metric categories presented in Section 3.3.4. The final metrics set consists of nine topological metrics and nine system-based metrics. Several metrics categories (M5, M9, and M10) are only represented by one metric due to the limitation of data availability and the limitation of off-the-shelf metrics that fulfill the metrics selection requirements. The mathematical formulations of these metrics are available in Appendix C.

Table 11 Selected metrics set

Paradigm Layer	Category	Metric	Metric ID
Topological	M1	Change in unweighted daily accessibility	M01_01
		Change in number of nodes accessible within daily reach	M01_02
	M2	Change in unweighted total travel cost	M02_01
		Change in network average efficiency	M02_02
	M3	Unweighted link betweenness centrality	M03_01
		Change in region-based unweighted total travel cost	M03_02
	M4	Minimum link cut centrality	M04_01
		OD k-connectivity	M04_02
M5	Nearby alternative links (simplified)	M05_01	
System-based	M6	Change in weighted accessibility	M06_01
	M7	Change in weighted total travel cost	M07_01
		Change in expected user exposure	M07_02
		Change in worst-case user exposure	M07_03
	M8	Traffic flow data	M08_01
		Weighted link betweenness centrality	M08_02

	Volume over capacity	M08_03
M9	Unsatisfied demand	M09_01
M10	Exposure to disaster	M10

### 5.2.1 Brief description of the selected metrics

The two metrics representing category M1 are change in unweighted daily accessibility (coded M01\_01) and change in the number of nodes accessible within daily reach (coded M01\_02). M1\_01 follows the general accessibility definition (easiness to reach economic activities in other regions), but without taking into account the economic ‘weight’ of the regions. This metric sums up the unweighted accessibility index of each centroid to all other centroids which shortest path distance is still within the daily travel threshold. For the sake of simplicity, a daily travel threshold of 50 kilometers is used in this case study. M1\_02 measures accessibility by using the same threshold to calculate the number of all nodes (not only centroids) reachable from each centroid.

The second metric category is operationalized by change in unweighted total travel cost (coded M2\_01) and change in network average efficiency (coded M2\_02). M2\_01 quantifies the change of the total cost to get from each centroid to all other centroids, without being weighted by the traffic flows among the centroids. M2\_02 adopts the concept of network efficiency from graph theory body of knowledge. In its original form network efficiency signifies the effectiveness of information exchange between all nodes in a network (Newman, 2010). In a transport system, network efficiency indicates how efficient the network is in providing connections between all places of interests in the system.

The easiest interpretation of localized measures for topological total travel cost is by calculating the change in total travel cost, but only for the region where the link resides. This metric (coded M3\_02) divides the supernetwork into seven sub-networks based on the seven divisions of Bangladesh. The criticality of a link is therefore signaled by how the total travel cost between all districts in the division where that link resides changes if that link is removed. Alternatively, link betweenness centrality (coded M3\_01) has been widely argued as a proxy to indicate local criticality. This is in principle a standard network assignment exercise. However, instead of weighing the links based on the traffic flows between the centroids, a weight of 1 is given instead.

The fourth category talks about the provision of connectivity in the overall network. Minimum link cut algorithm, adapted from graph theory, finds the minimum set of links which if removed simultaneously will cause disconnection between two different nodes (Newman, 2010). This set of links is entitled as the ‘cut set’ of two specific nodes. Metric M4\_01 adopts this algorithm by calculating how many times a link becomes a part of the cut set between centroids pairs. Another estimate of this category is centroid pairs distinct paths. Two paths between two nodes are ‘distinct’ if there is no single node (except the start and the end nodes) from one path which is also available on the other paths. Therefore, there will be more than 64 x 63 shortest paths identified because it is really likely that there will be more than one distinct paths for each O/D pair. O/D k-connectivity (coded M4\_02) is calculated as the decrease in the total number of distinct paths if a link is removed from the network.

Both the fifth and the sixth metric categories are exemplified by one metric. A simple measure of availability of alternative links nearby a link (coded M05\_01) characterizes the criticality of a link from a local connectivity perspective. If there are only a few alternative links that are close to it, the disruption of that link may cause a local disconnection. A detailed explication for this metric is presented in Appendix C. A metric to represent system-based

accessibility is the decrease of the accessibility itself (coded M6\_01). As oppose to M1\_01, this metric incorporates the socioeconomic weights of the centroid pairs into account.

The increase in weighted total travel cost (M7\_01) is the most widely used indicator in transport network criticality and vulnerability study. The calculation of this metric is similar to M2\_01, but now the magnitude of the traffic flows between two centroids is taken into account. Two other metrics in this category (worst-case and expected user exposure) are usually used in regional vulnerability studies to transport disruption. However, the concept can be adapted for a network criticality study by aggregating the user exposure of all districts in Bangladesh. User exposure of a district is the multiplication of the delay time due to disruption and the total trips coming from that district to all other districts. The expected user exposure of a district (coded M7\_02) takes the mean value of that district's total trips-delay to all other districts, while the worst-case user exposure (coded M7\_03) takes the maximum value.

The second most widely used category has the simplest indicators. By using empirical data of traffic counts, the total traffic flow (coded M8\_01) and the expected congestion (M8\_03) of a transport network segment can be calculated. The last indicator for this category is basically the result of a network assignment and is termed 'weighted link betweenness centrality' (coded M8\_02).

The last two categories are also embodied by one metric each. For system-based network-wide connectivity, a common measure in transport study is to calculate the number of trips that are canceled due to the disruption of a particular link (coded M09\_01). It is normally called 'unsatisfied demand' since network disruption reduces the supply-side factor of the transport system. As for the final category, the exposure of the transport segment to a natural disaster (coded M10) expresses the localized connectivity vulnerability of the segment. A historical flood map of Bangladesh is used as the natural disaster scenario in this study.

### **5.2.2 Individual assessment of the selected metrics**

Figure 27 exhibits the distribution of the top 100 most critical links for each metric. Most of the metrics follow an exponential distribution where there are few links which criticality scores are extremely high. Moreover, all metrics have a downward slope distribution pattern. Therefore, the decision-making challenge for the stakeholders follows the decision-making challenge of a negatively skewed distribution in Figure 25a. That is, if decision makers only want to consider a few number of transport segments, the identification of the segments is relatively easy. The difficulty in selecting the segments rises as the number of segments that want to be considered increases. This is because the marginal differences of criticality scores for links with lower rank are small.

Taking a closer look at the distribution of each metric provides more insights to the characteristics of the metrics. For instance, the shape of the distribution's tail of each metric is slightly different. There are only a few, but slightly normally distributed links in the distribution tail of M01\_01, M01\_02, M02\_01, M02\_02, M07\_02 and M07\_03. It implies that there is no single source of failure in the system since there are more than one links with a relatively higher criticality score. The case is different for metric M04\_01 and M07\_01. In both metrics, there is only one link which criticality score is far higher than the rest of the links. The outlier link can be entitled as the single source of failure in the system.

Besides the distribution pattern, the paneled graphs in Figure 27 need to be reflected back to the meaning of the metric and the criticality aspects that the metric represents. For instance, a gentle slope of M10 shows that there are a lot of links that are severely exposed by a natural disaster. It implies that the network connectivity in general is prone to natural disaster. The existence of outlier link based on M07\_01 indicates that there is one critical segment that

forces a lot of drivers to take a substantially longer detour when disrupted. If decision makers do not want to incorporate the number of drivers who have to take detours (thus adopting user-equality paradigm), metric M02\_01 can be observed instead. This metric shows that there are several network segments that incur considerable detour time if disrupted. Maintaining connectivity throughout the country can be done by observing M04\_01. From this metric, there is one link that appears in numerous district pairs' cut set. Protecting this segment may be a top priority.

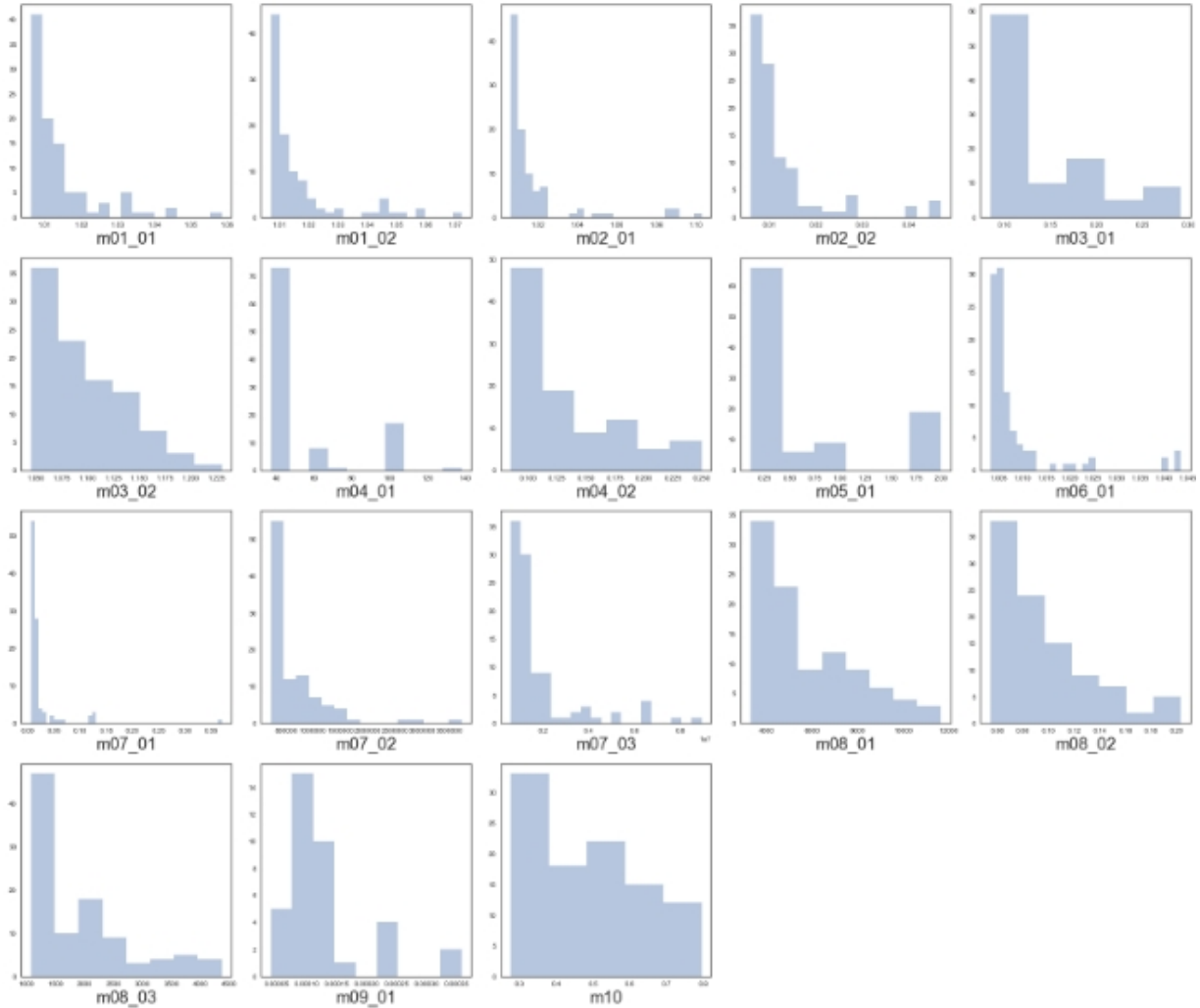


Figure 27 Distribution scores from each metric

Another tool that is useful for the individual assessment is the spatial visualization of each criticality metric as portrayed in Figure 28. The top  $n$  links selected are indicated by a bolder red color for the road segments and a bolder blue color for the waterway segments. With this tool, analysts and decision makers can select any metric that they want to observe from the drop-down list and any number  $n$  for the top  $n$  links of the chosen metric. For instance, the first two pictures in Figure 28 shows the top 50 and top 120 most critical links from M01\_01 while the other two shows the top 50 and top 110 most critical links from metric M03\_01. For metric M01\_01, if only the top 50 links are selected, it can be seen that most of the critical segments are located around Dhaka and the Bangabandhu bridge in the middle part of Bangladesh. When a larger number of links are selected, other road segments in the western and southern parts of Bangladesh emerge as critical.

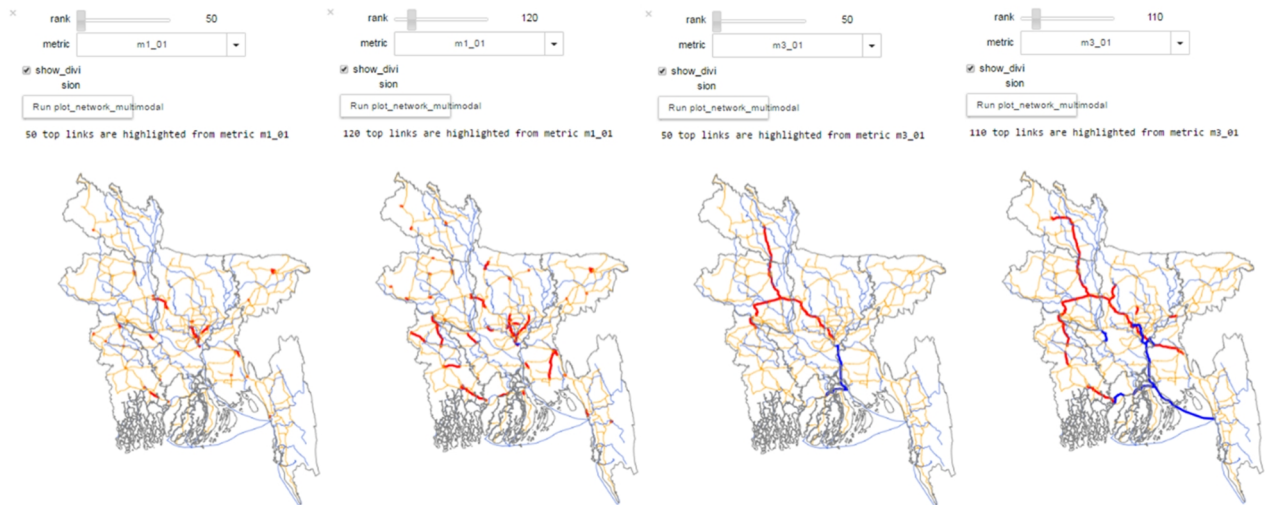


Figure 28 Multiple metric-rank combinations from individual geovisualization tool

### 5.3 Robustness results

Before discussing the robustness analyses results, the uncertainties in each metric will be revisited first. Table 12 shows the uncertainties that influence each metric. As stated earlier, O/D matrix uncertainties only affect system-based metrics (M6 - M9) as topological metrics do not require socioeconomic data. Uncertainty in network length affects both topological and system-based metrics. There are four metrics that do not have any uncertainties: M08\_01 and M08\_03 because both metrics are based on the empirical data of traffic flow, and M04\_01 and M04\_02 because both only talk about the topological structure of the transport network irrespective of the network's length. A hundred replications have been executed by randomly sampling the uncertainty space.

Table 12 Uncertainties review

Category	Metric ID	Uncertainties			
		O/D	Network Length	Parametric	Remarks
M1	M01_01	-	✓	$\beta$	Distance sensitivity indicator, set to 1
	M01_02	-	✓	$\theta$	Threshold for daily reachable travel distance, set to 30km
M2	M02_01	-	✓	-	-
	M02_02	-	✓	-	-
M3	M03_01	-	✓	-	-
	M03_02	-	✓	-	-
M4	M04_01	-	-	-	-
	M04_02	-	-	-	-
M5	M05_01	-	-	b	Buffer size of each link in order to find another shortest path, set to 6km
M6	M06_01	✓	✓	$\beta$	Distance sensitivity indicator, set to 1
M7	M07_01	✓	✓	-	-
	M07_02	✓	✓	-	-



	M07_03	✓	✓	-	-
	M08_01	-	-	-	-
M8	M08_02	✓	✓	Penalty	Penalty given to each link which becomes part of shortest paths, set to 1.2
	M08_03	-	-	-	-
M9	M09_01	✓	-	-	-
M10	M10	-	-	b(dis)	Buffer size of each link in order to calculate the mean flood exposure from floodmap raster statistics

### Rank robustness results

The Spearman-rank correlation results between each replication for topological metrics are displayed in Figure 29 while the system-based metrics' are shown in Figure 30. Each point in both the x and y axes represents one replication. Therefore, there are 100 data points in both x and y axes. The colormap represents the Spearman-rank correlation coefficient between each replication. A diverging colormap is chosen because the value of the correlation coefficient may range from -1 to 1. The bolder the blue color (lower spectrum of the colormap legend), the closer to minus one the correlation value is. *Vice versa*, the bolder the red color (upper spectrum of the colormap legend), the closer to 1 the correlation value is.

Figure 29 shows a strong, positive rank-based relationship between each replication in metric M2\_01 and M2\_02. They are followed by M1\_01 and M1\_02 where it can be observed that there are occurrences of lighter red color in the heatmaps. Metric M3\_02 and M5\_01 come afterward, while metric M3\_01 has the highest portion of lighter red color in its colormap.

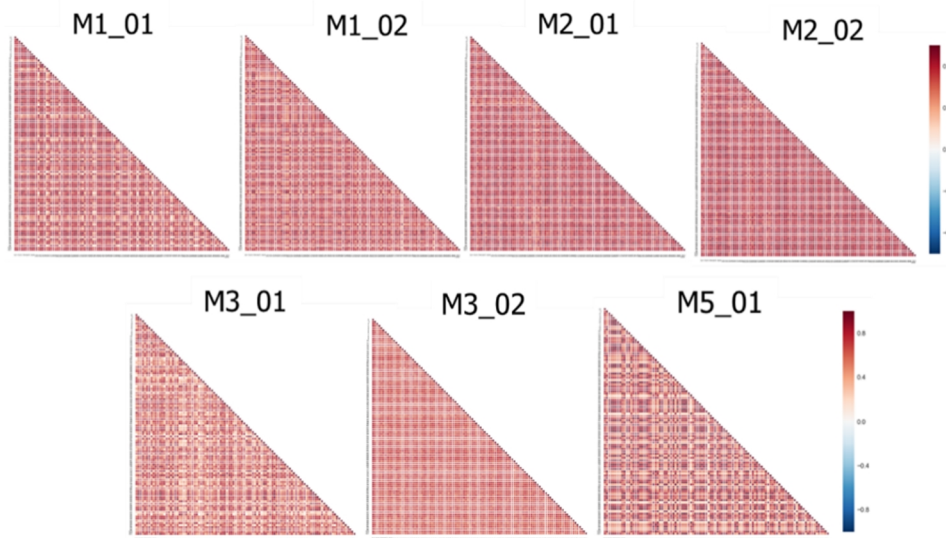


Figure 29 Heatmap of spearman correlation between each replication for topological metrics

For topological metrics, metrics that calculate criticality based on network-wide aggregation (M1 and M2) are in general more robust than metrics that determine criticality score based on localized spatial boundary (M3 and M5). This implies that the impact of uncertainties when observed on the entire network is smaller than when observed on

a local level. As a consequence, if the main goal of the criticality study is to analyze the functionality of a transport infrastructure for the whole country, uncertainties may not significantly change the ranking of the critical segments.

The same pattern can also be observed in system-based metrics, as Figure 30 shows fewer occurrences of lighter red color for network-wide metrics (M6 and M7) than for localized metric (M8\_02). However, a less distinctive pattern is observed when contrasting network-wide accessibility (M6) and network-wide total travel cost (M7) metrics from topological and system-based perspective. In topological metrics, it is quite evident that total travel cost based metrics (M2) is more robust than accessibility based metrics (M1), while the difference is not too noticeable in system-based metrics (M6 and M7).

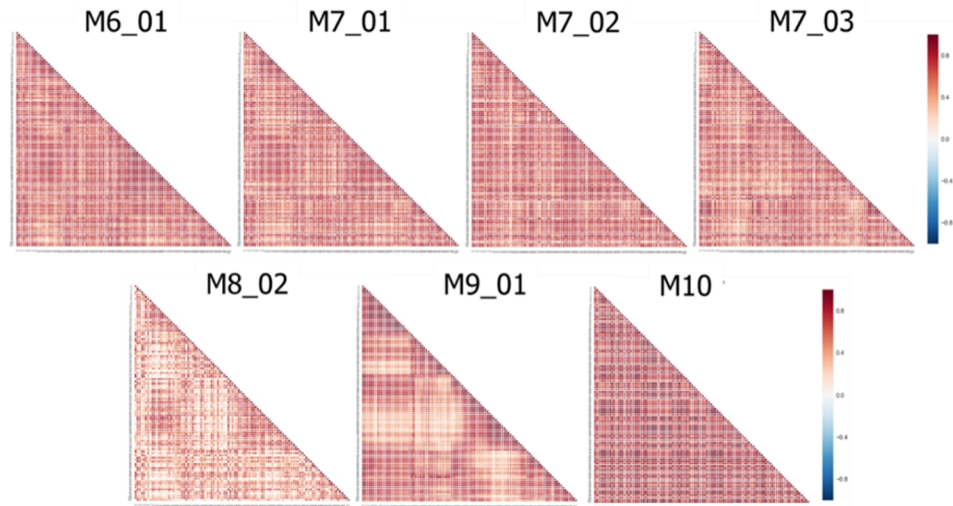


Figure 30 Heatmap of spearman correlation between each replication for system-based metrics

Comparing Figure 29 and Figure 30 shows that there is a larger portion of lighter color in system-based metrics than in topological metrics. This signifies the ample influences of the future uncertain dynamics of socioeconomic developments impose on changes of links' ranking. It is especially alarming when a large investment on the existing infrastructure is going to be made based on the criticality analysis, as different links may come as the most critical ones in the future. In this case, further decision making under deep uncertainty study can be done (Lempert, 2003).

#### Distribution robustness results

The distribution robustness for topological and system-based metrics, indicated by the Kolmogorov-Smirnov (K-S) distance among the replications, is shown in Figure 31 and Figure 32 respectively. A non-diverging colormap is chosen for the heatmap because the K-S distance only ranges from 0 to 1. A darker blue color symbolizes smaller distance (closer to 0) while a lighter green or yellow color symbolizes larger distance (closer to 1). The interpretation of the K-S distance to the robustness of the metrics is reciprocal to that of Spearman-rank correlation; a smaller K-S distance implies that the distribution shapes of the two datasets are similar. Therefore, the more dark-blue color appears in the heatmap, the more robust the metric is distribution-wise.

Based on Figure 31 and Figure 32, metrics that have a substantially high distribution robustness are M1, M2, M3\_02, and M10. In these metrics, occurrences of uncertainties do not significantly change the distribution pattern of the criticality scores. Therefore, the qualitative interpretation (see Section 5.1.2 for explanation and 5.2.1 for the result) of the metric's distribution pattern can simply be based on the business as usual's distribution pattern. For instance,

it can be expected that regardless of the uncertainties, the distribution pattern of M1\_01 (see Figure 27) remains negatively skewed. The few critical links in the distribution's tail are likely to remain exist under any circumstances.

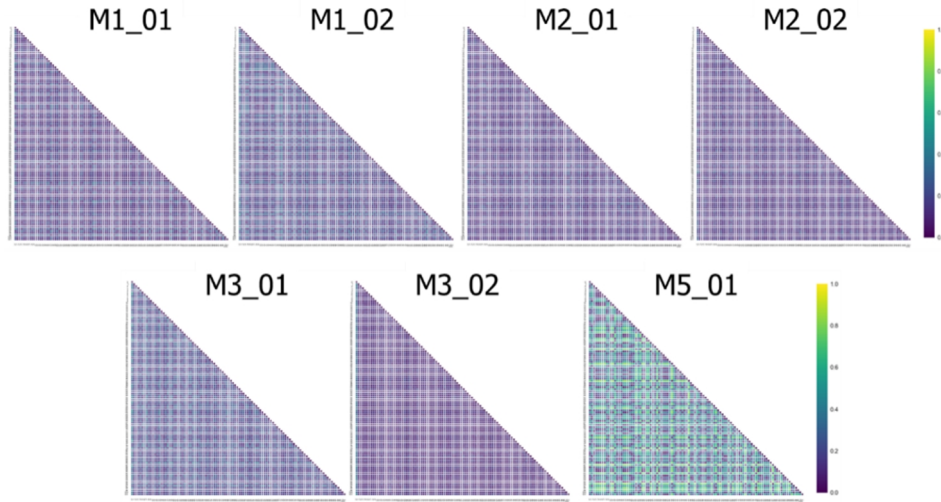


Figure 31 Kolmogorov-Smirnov distance between each replication for topological metrics

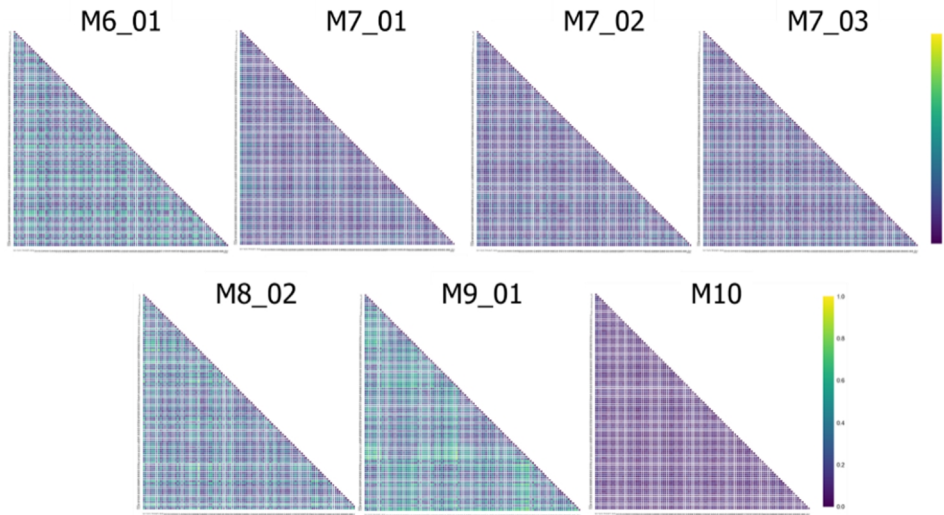


Figure 32 Kolmogorov-Smirnov distance between each replication for system-based metrics

There are a lot of greener colors in the heatmaps of M5\_01, M6\_01, M8\_02, and M9\_01, signifying a low degree of distribution robustness. This indicates the differences in distribution patterns when different model settings are applied. For instance, although there are a few numbers of extremely critical links based on M6\_01's business as usual result (see Figure 27), these extremely critical links may not exist under different scenarios.

Lastly, similar to rank robustness, it is evident that the system-based metrics are less robust compared to topological metrics as there are more greener colors appear in system-based metrics' heatmaps. This further confirms the crucial role socioeconomic uncertainties play in transport network criticality analysis.

### *Value sensitivity results*

The last robustness analysis observes the magnitude of the criticality scores' changes by calculating the Median Absolute Deviation (MAD) and Standard Deviation (SD) (see Figure 33). One noticeable pattern on the figure is that, similar to the other two analyses, topological metrics scores are more robust than system based metrics because they have smaller MAD and SD. This result is not surprising as different values of socioeconomic factors will directly affect the criticality scores of system-based metrics. However, one interesting fact is the large difference between the MAD and SD for system-based metrics. This indicates the occurrence of outlier values in some replications. Therefore, some socioeconomic scenarios may abruptly scale up (or down) the criticality score of different links in the network.

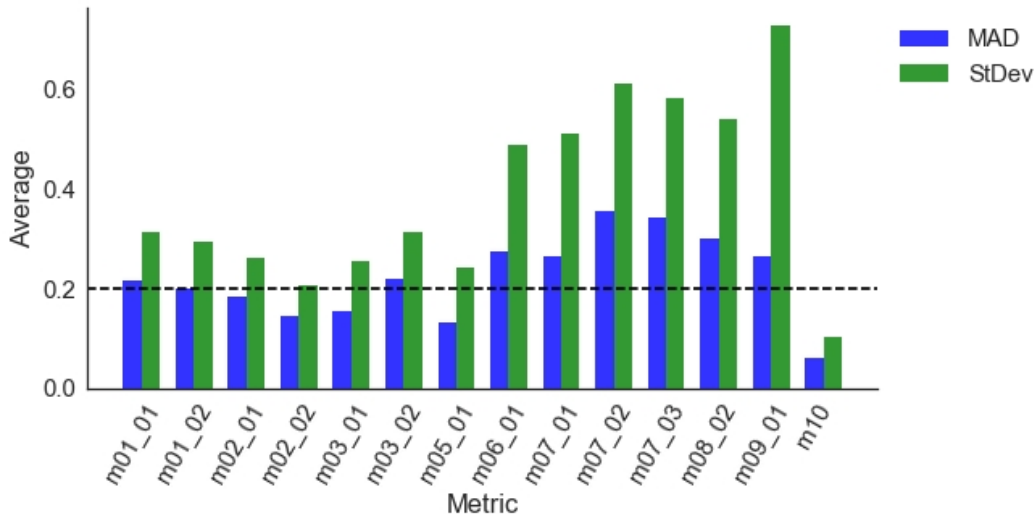


Figure 33 Value sensitivity of all metrics

This fact is in line with the result of the other two robustness analyses. The multiplier effect that socioeconomic factors give to system-based metrics may drastically change the links ranking. As an example, several transport segments are prevalently used to carry some commodities from one district to another. If the production of this commodity increases significantly relative to the other commodities', then the transport segments used by that commodity will be even more critical. As a further consequence, other links become less critical. Thus, the overall criticality ranking and distribution patterns change.

## 5.4 Metrics comparison and elimination

Unifying the top 100 links from each metrics yields a total of 563 links which criticality scores will be considered for metrics comparisons. The first step in metrics comparison is to understand the difference between the distribution patterns of each metric, which will be done in two ways: overlapping the distribution patterns of the criticality metrics with one another and calculating the Kolmogorov-Smirnov (K-S) distance between them. The full visualization of the overlaps can be seen in Figure 51 in Appendix D while the K-S distance between them is displayed as a heatmap in Figure 34.

As expected, a large fraction of the heatmap displayed in Figure 34 has lighter colors and thus low K-S distances. Therefore, the downward slope distribution patterns of the criticality metrics are not statistically different. Accordingly, it is safe to infer the qualitative interpretation of these metrics in a similar way.

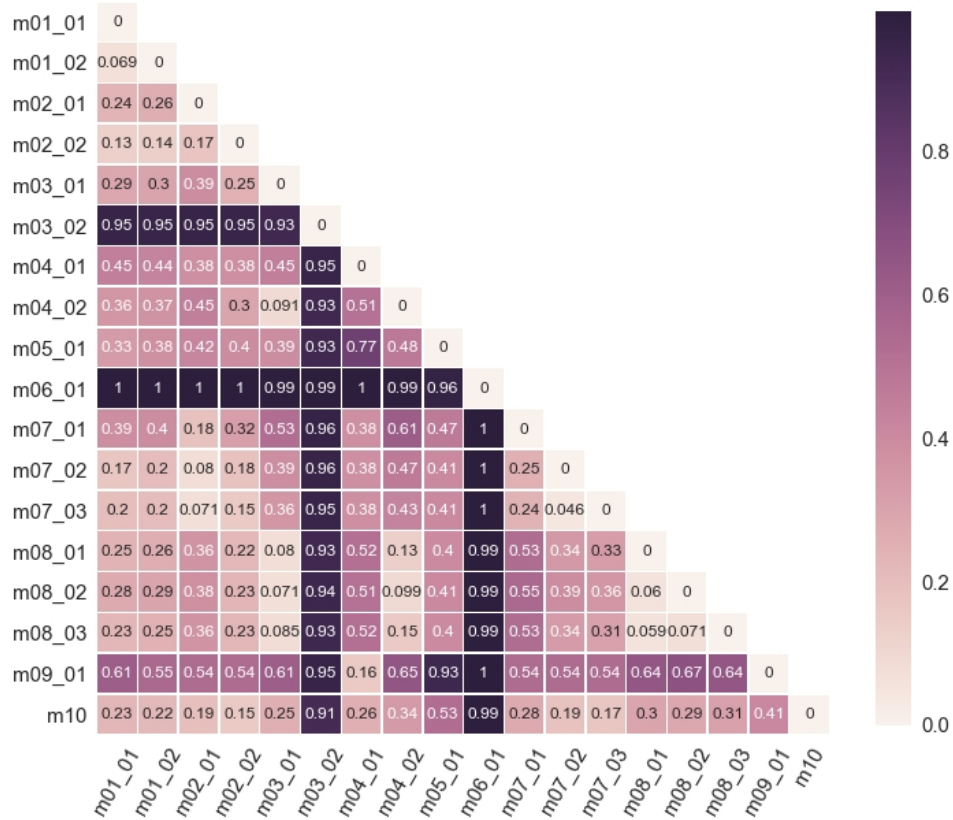


Figure 34 Kolmogorov-Smirnov distance between metrics distribution

Noticeable large distances are spotted for M03\_02 and M06\_01. According to Figure 51 in Appendix D, this is because when a larger portion of links is considered, the distribution patterns of these two metrics are positively skewed instead of negatively skewed. This result suggests that both metrics should not be eliminated in the final metrics set due to their different distributional behaviors.

Since most metrics do not follow a normal distribution, the Spearman-rank correlation coefficient is used instead of the Pearson correlation coefficient. The result of the Spearman-rank correlation is displayed in Figure 35. The result is quite diverse; several metrics pairs have a high correlation, some have low correlation, and some are even negatively correlated.

Obvious negative correlations are found in M05\_01, M08\_01, M08\_03, M09\_01 and M10. They can be interpreted as follow. Since M05\_01 illuminates links with a small number of alternative routes nearby them, a negative correlation with this metric means that links that are considered critical by other metrics also have plenty alternative links located close to it. Both M08\_01 and M08\_03 are calculated by taking the empirical trucks AADT (annual average daily traffic) data in Bangladesh. However, they do not contain information about the traffic density of the waterway. Consequently, their correlation coefficients are generally low. M10 identifies links that are severely exposed to flood as critical. Analogous to M05\_01, a negative correlation with this metric suggests that links that are exposed to flood are not critical based on the other metrics.

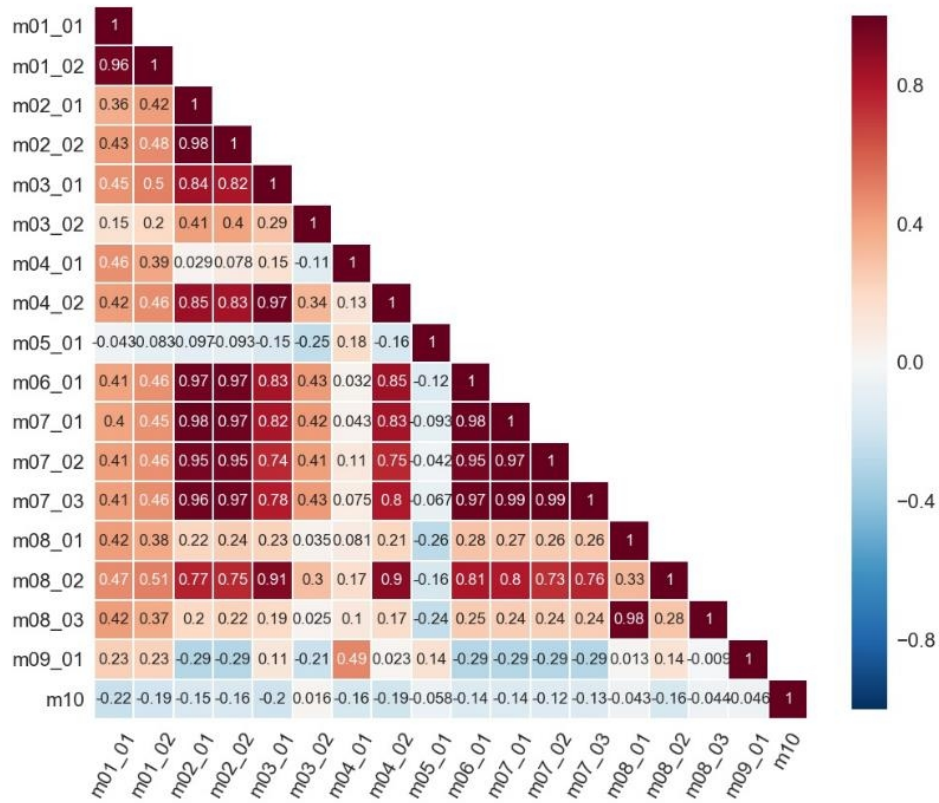


Figure 35 Spearman-rank correlation coefficient between metrics

Another important finding from the heatmap is the pattern of correlation coefficients between metrics within the same category (e.g. between M1\_01 and M1\_02). The within-group correlation coefficients for metrics in category M1, M2, and M7 are in general higher than 0.9. However, the same pattern does not emerge in metrics in category M3, M4, and M8. Therefore, high correlation coefficients for metrics within the same category only apply to network-wide accessibility and network-wide total travel cost metric categories (M1, M2, and M7). Localized measures and connectivity-based measures on the other hand are metrics specific. That is, although conceptually they represent the same criticality aspects, the transport segments that they highlight as critical are different.

As for the within-group correlation coefficients of the localized measures (M3, and M8), the occurrence of low correlation coefficients may be attributed to the two possible definitions of ‘localized’ as discussed in Section 3.2.2. On the one hand, localized can refer to a geospatially localized contribution of the transport network element, which for instance is embodied by M3\_02 (change in total travel cost in the region where the disrupted link belongs). Alternatively, localized can also refer to the static local characteristics of the network. The second definition is embodied by M3\_01 (unweighted betweenness centrality) since betweenness centrality is in principle a local attribute of links in a network.

Metrics that in general have high correlation can be identified from this heatmap, to further be eliminated so that the number of metrics in the metrics set is reduced. Their counterpart metrics are also identified based on the rule described in Section 5.1.4. These identified metrics are listed in Table 13.

Table 13 Metrics with high correlations

<b>Metrics with high correlation in general</b>	<b>Counterpart metric</b>	<b>Eliminated?</b>
M01-01	M01-02	
M01-02	M01-01	✓
M02-01	M02-02	
M02-02	M02-01	✓
M03-01	M04-02	✓
M04-02	M03-01	
M06-01	M2-01, M2-02, M7-01, and M07-03	
M07-01	M06-01 and M07-03	✓
M07-02	M06-01 and M07-03	✓
M07-03	M06-01, M07-01, and M07-02	✓
M08_02	M03_01	

There are six metrics that can be eliminated based on the correlation coefficient analysis. Metric M01\_01 and M01\_02 have an extremely high correlation coefficient. Between these two metrics, it is observed that M01\_02 has higher correlations with other metrics, compared to M01\_01's correlations with other metrics. Therefore, M01\_02 is eliminated. The same logic also applies between M02\_01 and M02\_02, and between M03\_01, M8\_02 and M04\_02.

Metric M06\_01 is a unique one. Although it has high K-S distances with other metrics, it has strong positive correlations with a lot of metrics. Therefore, it is decided that M06\_01 is kept in the final metrics set while the other three are withdrawn.

The final 12 metrics are displayed in a geovisualization panel as shown in Figure 36. The top 100 links based on each metric is highlighted, with red colors representing road segment and blue color representing waterway segment. As opposed to the individual geovisualization tool illustrated in Figure 28, the geovisualization panel provides a helicopter view of the most critical links based on all metrics. Thus, the transport network segments that appear as critical in more than one metrics can be identified.

There is no single transport segment that is identified as critical by all metrics at once. However, there are several road segments that appear as critical in many metrics. The N1 road segment from Dhaka to Feni is considered to be critical by metric M2\_01, M3\_02, M4\_02, M6\_01, M8\_01, and M8\_02. The fact that this segment is critical from both topological metrics and system-based metric shows that the massive flow of goods from Dhaka to Chittagong is not the only reason that makes this road segment important. Rather, the topological structure of Bangladesh's transport network along with the geographical spread of the districts centroids make the segment critical. Another road segment that appears in a lot of metrics is the N405 connection across the Bangabandhu bridge near Sirajganj all the way to the N5 that goes to Rangpur in the north. This road segment can be found as critical in M2\_01, M4\_02, M6\_01, and M8\_02. It is evident that this road segment becomes a part of the shortest path route from a lot of districts in the south and in the east to districts in Rangpur division in the north.

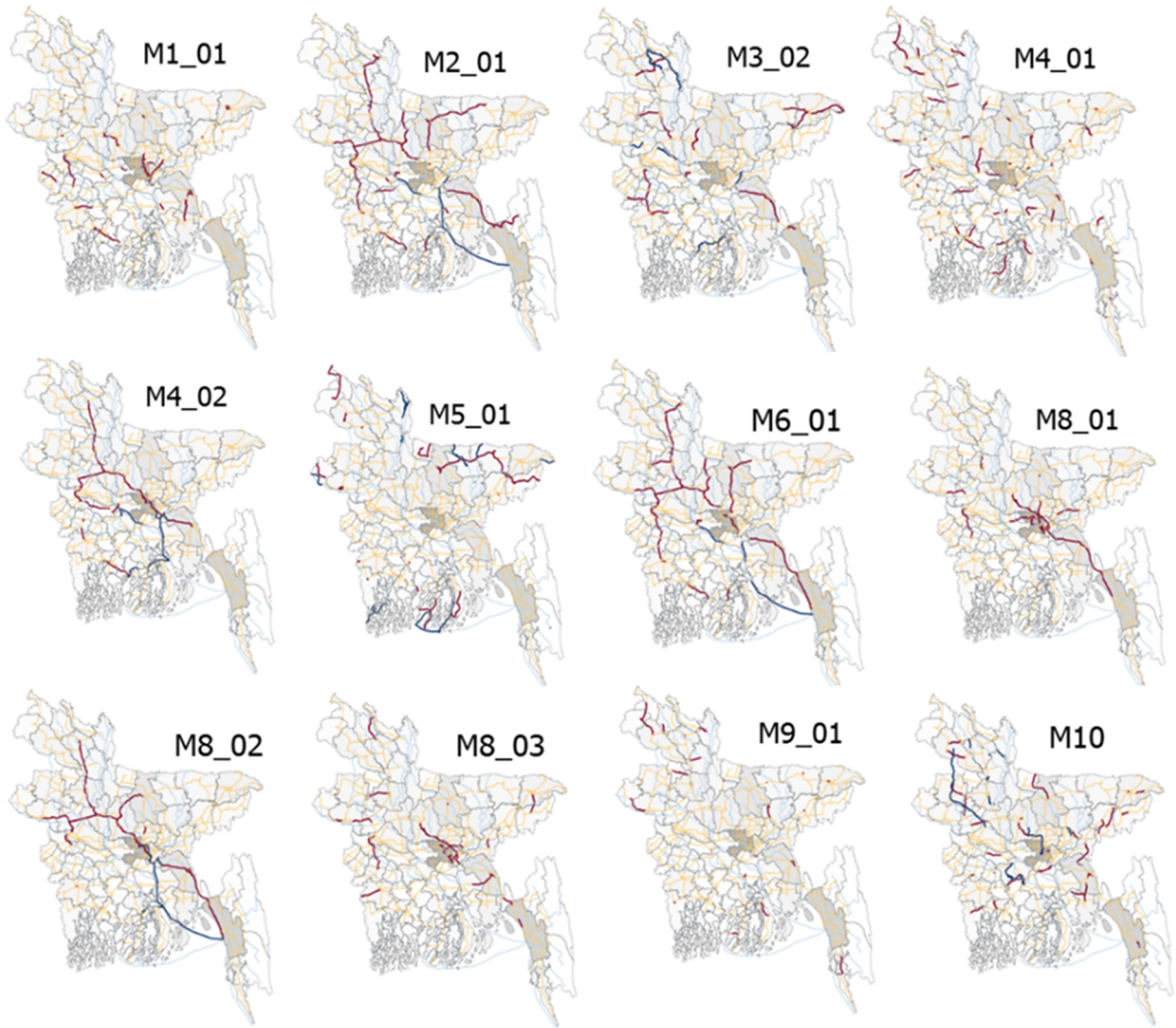


Figure 36 Geovisualization panel of the remaining metrics

Contrasting topological metrics to their system-based counterparts shows that both perspectives sometimes highlight different links as critical. For instance, M6\_01 highlights a north to south corridor from Rangpur to Chittagong as critical. Furthermore, there are also several road segments in the mid-west part of Bangladesh identified as critical by this metric. M1\_01 highlights an entirely different set of links. It highlights a lot of smaller road segments from the mid-west to the southwestern part of Bangladesh. Additionally, there are also a few short road segments in the east recognized by this metric. The only similar results are found for network-wide total travel cost based metric (M2 and M7). Since M6\_01 represents M7\_01, M7\_02, and M7\_03, it is safe to infer that the same links appear as the most critical ones in the latter metrics. As the geospatial patterns of the critical links in M2\_01 and M6\_01 are very similar, it is quite likely that M2\_01 and all M7 metrics highlight the same transport segments as critical. Except for these categories, adopting either total performance paradigm or user-equality paradigm results in highlighting different road segments as critical.

One waterway segment that appears as critical in more than one metrics is the waterway route from the estuary of the Meghna river in the Bay of Bengal to the Chittagong port in the south. This link is critical based on observation



from M2\_01, M6\_01, and M8\_02. Another small waterway segment is the Meghna river from Narayanganj (south of Dhaka, around the center part of Bangladesh) to Chandpur (north of the Meghna river estuary in the Bay of Bengal). It appears critical in not only the three metrics above, but also in M4\_02.

## 5.5 Generalization of metrics comparison

The last step in metrics comparisons is to understand if the (dis)similarities can be generalized (i.e. applicable to any network structure). Seven subnetworks comprising seven divisions in Bangladesh are created to test this proposition. They are Barisal, Chittagong, Dhaka, Khulna, Rangpur, Rajshahi, and Sylhet. The Spearman-rank correlation analysis is applied to examine the performance of each metric in all divisions. The full heatmaps of all divisions can be found in Appendix E.

In Table 14 metrics that have high correlations in general are shown for all subnetworks. For comparison purpose, two criteria are used to determine if a metric has high correlations in general. They are categorized so if the metrics have at least one correlation coefficient which is greater than 0.8, and if the other correlation coefficients have an average of 0.5 or higher.

As seen in Table 14, each subnetwork has a different set of metrics that fits these criteria. Therefore, the metrics (dis)similarities cannot be simply generalized. They are dependent on the network structure, the spatial distribution of the economic centroids, and possibly the socioeconomic profiles as well.

Table 14 Metrics with high correlations in general for all (sub)networks

Metric	Networks							
	Bangladesh	Barisal	Chittagong	Dhaka	Khulna	Rangpur	Rajshahi	Sylhet
M01_01					✓	✓	✓	✓
M01_02					✓	✓	✓	✓
M02_01	✓	✓	✓	✓	✓	✓	✓	✓
M02_02	✓	✓	✓	✓	✓	✓	✓	✓
M03_01	✓			✓	✓			
M04_02	✓			✓	✓			
M05_01			✓					
M06_01	✓	✓	✓	✓	✓	✓	✓	✓
M07_01	✓	✓	✓	✓	✓	✓	✓	✓
M07_02	✓	✓	✓	✓	✓	✓	✓	✓
M07_03	✓	✓	✓	✓	✓	✓	✓	✓
M08_02	✓		✓	✓	✓	✓		

The result also suggests that metrics that always high correlation in general are M02\_01, M02\_02, M06\_01, M07\_01, M07\_02, and M07\_03. Therefore, it can be reasoned that metrics that are based on the network-wide increase in total travel cost (M2 and M7) are always subject to elimination since they always have high correlation coefficients. Additionally, in all subnetworks, these metrics always have extremely high correlation coefficients with M06\_01. This suggests that system-based accessibility metric (M6\_01) is an effective metric to be firstly prioritized in a criticality study.

The generalization of the metric can also be observed from the ‘within-group’ perspective. To be exact, it analyzes how the correlation coefficient for metrics within the same category (e.g. between M01\_01 and M01\_02, or between M02\_01 and M02\_02) changes among different subnetworks. By observing figures in Appendix E, it is found that the within-group correlation coefficients remain high for metric category M1, M2 and M7 while they are changing in different subnetworks for metric category M3, M4, and M8. It can be concluded that within-group comparisons for metric category M1, M2, and M7 are robust for any network structure. For future studies, representing these categories with only one metric each is sufficient.

As for the other metrics, they only appear as generally critical in some subnetworks. There are also several metrics that never come as generally critical in any subnetworks: M03\_02, M04\_01, M08\_01, M08\_03, M09\_01 and M10. Representing these categories with more metrics and keeping them for the final analysis are suggested.

## 5.6 Chapter 5 Summary

In a nutshell, this chapter has discussed the following points:

- The three main steps to evaluate multiple criticality metrics of a country’s freight transport network are:
  - Individual metric assessment evaluates the business-as-usual result of each criticality metric in isolation to the other metrics. The distribution of the criticality scores and the interactive geovisualization of the criticality metrics are two useful visualization tools for this.
  - Robustness analysis of individual metrics assesses how the criticality results change under uncertain model structures and parameters. Three techniques to evaluate a metric’s robustness are rank robustness analysis (observe how the ranking changes), distribution robustness analysis (observe how the distribution of the criticality scores changes), and value sensitivity analysis.
  - Comparisons between metrics can be made by understanding the Kolmogorov-Smirnov (K-S) distance and the correlation coefficient between the metrics. If two metrics have low K-S distance and high positive correlation coefficient, they can be deemed as complementary.
- An empirical evaluation of Bangladesh’s multimodal freight transport network criticality from eighteen criticality metrics has been performed. Based on the three steps above, the key highlights are:
  - From the individual metric assessment, it is found that all metrics follow a downward slope pattern of criticality scores distribution. Furthermore, an interactive visualization to assess top  $n$  critical links based on each metric individually has been developed.
  - From the robustness analysis, it is found that topological metrics are more robust compared to system-based metrics. This emphasizes the fact that socioeconomic uncertainties play a significant role to the results of system-based metrics.
  - From the comparison between metrics, it is found that six metrics can be eliminated as their results can be well represented by the other twelve metrics.
- Not all conclusions from the metrics comparison can be generalized. When the metrics are tested on seven different subnetworks, it turns out that high between-group correlation coefficients only persist to occur between metric category M6 (system-based, accessibility) with metric category M2 (topological, total travel cost, network-wide) and M7 (system-based, total travel cost, network wide). As for within-group comparisons, high correlation coefficients always occur in metric categories M1 (topological, accessibility), M2 and M7. Correlation coefficients between the other pairs change for different subnetworks.

# **Part III : Designing Criticality Metrics Selection Method**

*“If I have seen it further, it is by standing on the shoulders of giants”*

*– Sir Isaac Newton*

*This page is intentionally left blank.*

# Chapter 6: Development of Metrics Selection Method for Criticality Analysis

The literature review and the criticality analysis case study in the previous three chapters have provided a rich overview of the various ways of conducting a transport network criticality analysis. In this chapter, this information is used to develop a criticality metrics selection method for freight transport network criticality analysis. First, the main insights from the literature review and the case study are made explicit in Section 6.1. The insights are categorized into general insights, insights related to criticality metrics, and insights related to assessment techniques. Based on these insights, a method for selecting an appropriate set of metrics given the contextual situation of the criticality study is elaborated in detail in Section 6.2. Last but not least, two criticality analyses based on two different illustrative policy problems for Bangladesh's multimodal freight transport network are performed in Section 6.3 as a proof of concept of the selection method.

## 6.1 Insights from literature review and case study

This Section presents the insights gained from the literature review and the quantitative case study reported in Chapter 3 to 5. First, the general insights that have to be taken into account in future criticality studies are outlined. Next, the insights specific to the criticality metrics and the assessment techniques employed in the previous case study are presented. These insights are mainly derived from the conceptual and technical differences between the different criticality metrics and the different assessment techniques.

### 6.1.1 General insights

*Insight #1: The multiple ways of assessing criticality can be summarized by a conceptualization of criticality analysis*

The extensive and systematic literature review has revealed dozens of metrics that have been used to assess transport network criticality. The metrics were usually developed by standing on the shoulder of giants, that is, by building on earlier works on related metrics. Furthermore, these metrics are the operationalization of the researchers' belief of what criticality is. In this study, these metrics have been encapsulated within the 'contribution to serviceability' aspect of criticality analysis. Two main factors from the contribution to serviceability aspect which reflect the conceptual level of criticality analysis are the underlying paradigm factor (i.e. total performance or user equality) and the functionality factor (i.e. accessibility, total travel cost, or connectivity).

*Insight #2: When practitioners do not have an initial preference of the functionality aspect that they want to evaluate, it is better to embrace all criticality aspects in the analysis*

Criticality analysis is sometimes done without having a specific functionality (i.e. accessibility, total travel cost, or connectivity) preference *a priori* the analysis. Rather than judging which metric captures criticality the best, it should be realized that there are in principle different aspects of criticality that the metrics capture. Therefore, when practitioners do not have an initial preference for a specific criticality aspect that they want to evaluate, it is best to embrace a broad range of criticality aspects. In this way, the preference can be elicited after the analysis (Herman, Reed, Zeff, & Characklis, 2015).

*Insight #3: Some metrics are eventually correlated to each other*

Despite the numerous metrics available to assess different aspects of criticality, some of them may highlight the same network segments as critical. For instance, the quantitative case study showed that the criticality metric based on changes in socioeconomically weighted accessibility (M06\_01) is strongly correlated to the network-wide total travel cost based metrics (metrics in metric category M2 and M7) regardless of the network structure. This implies that although it is better to consider as many metrics as possible in a comprehensive criticality analysis, reduction of the final set of metrics is possible in order to moderate information overload without risking losing the insights provided by the eliminated metrics.

*Insight #4: Given the criticality results, there are still multiple ways to reach the final conclusion of the study*

Individual metrics analysis, robustness analysis, and geovisualization panels have shown that there are numerous techniques to display and analyze criticality results. Especially when multiple metrics are employed in the criticality study, the standard ranking based on criticality scores may not be sufficient. Given a criticality operationalization (i.e. modeling approach and calculated metrics), different insights can be collected by varying how the criticality results are sliced and visualized. However, it should be realized that some of these techniques may be relevant for actual decision-making and some may not be of interest, depending on the problem statement at stake.

*Insight #5: A missing presumption in most criticality studies is the initial purpose of the criticality study itself*

As a consequence of the other insights, analysts should be aware of the goal of the criticality study itself. This step is often overlooked in previous studies, where the purpose of criticality study is simply said to be the ranking of links in the network. As a result, the richness of decision-making relevant information that criticality studies can provide is underappreciated. Therefore, criticality study should start with a clear problem statement such that the criticality results can be explored in an effective and efficient way. The problem statement can still be adjusted at a later stage of the study if new insights are found during the analysis.

*Insight #6: There are three main phases in a comprehensive transport network criticality analysis*

Reflecting back to the execution of the case study from Chapter 4 and Chapter 5, a comprehensive criticality analysis can follow three main stages: problem definition, model development, and final deliberation. In the problem definition phase, practitioners should explicitly define their policy problem. In phase 2, the policy problem is translated into the set of criticality metrics that will be used to assess the transport network. Then, the transport network model is developed, the metrics are calculated, and the overlapping metrics are eliminated in the model development stage. Lastly, the criticality results are used in deliberation by using visualization tools. The visualization tools should be made interactive in order to facilitate the deliberation phase better. It is also possible that the new insights gained from the visualizations trigger the practitioners to look over the initial problem statement, thus revisiting the first phase of the criticality analysis. Therefore, these three phases may be iterative.

### **6.1.2 Insights related to the metrics employed in the case study**

The insights from the eighteen metrics applied to the Bangladesh case study can be extracted by comparing them based on their conceptual aspect representation (i.e. which criticality aspects they represent), their technical implementation, and their robustness to uncertainty. The comparison is summarized in Table 15.

Table 15 Comparison of criticality metrics performance

Code	Metric	Aspect on conceptual level	Data requirements	Assessment technique	Computation expense	Robustness
M01_01	Change in unweighted daily accessibility	User equality - Accessibility	- Transport network - Economic centroids - Average daily travel distance (optional)	Interdiction	High	High
M01_02	Change in number of nodes accessible within daily reach	User equality - Accessibility	- Transport network - Economic centroids - Average daily travel distance (optional)	Interdiction	High	High
M02_01	Change in unweighted total travel cost	User equality - Total travel cost	- Transport network - Economic centroids	Interdiction	High	Very high
M02_02	Change in network average efficiency	User equality - Total travel cost	- Transport network - Economic centroids	Interdiction	High	Very high
M03_01	Unweighted link betweenness centrality	User equality - Total travel cost	- Transport network - Economic centroids	Static assignment	Low	Medium
M03_02	Change in region-based unweighted total travel cost	User equality - Total travel cost	- Transport network - Economic centroids - Administrative area boundaries	Interdiction	Very high	High
M04_01	Minimum link cut centrality	User equality - Connectivity	- Transport network - Economic centroids	Static assignment	Low	-
M04_02	OD k-connectivity	User equality - Connectivity	- Transport network - Economic centroids	Interdiction	High	-
M05_01	Nearby alternative links (simplified)	User equality - Connectivity	-Transport network	Utilize raw data	Medium	Medium
M06_01	Change in weighted accessibility	Total performance - Accessibility	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Interdiction	High	Medium

M07_01	Change in weighted total travel cost	Total performance - Total travel cost	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Interdiction	High	Medium
M07_02	Change in expected user exposure	Total performance - Total travel cost	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Interdiction	High	Medium
M07_03	Change in worst-case user exposure	Total performance - Total travel cost	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Interdiction	High	Medium
M08_01	Traffic flow data	Total performance - Total travel cost	- Empirical traffic flow data	Utilize raw data	Very low	-
M08_02	Weighted link betweenness centrality	Total performance - Total travel cost	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Static assignment	Medium	Very low
M08_03	Volume over capacity	Total performance - Total travel cost	- Empirical traffic flow data - Transport network segments capacity (e.g. no of lanes)	Utilize raw data	Very low	-
M09_01	Unsatisfied demand	Total performance - Connectivity	- Transport network - Economic centroids - Economic production and attraction factors of centroids	Interdiction	High	Low
M10	Exposure to disaster	Total performance - Connectivity	- Hazard map (e.g. flood map) - Transport network	Utilize raw data	Low	High



The comparison of the conceptual-level criticality aspects representation can be seen from the 'Aspect on conceptual level' column. This column is derived from the 'contribution to serviceability' aspect of criticality. It is important to reemphasize that the conceptual difference between the metrics mainly lies on only two factors (the underlying paradigm factor and the functionality factor), resulting in a combination of six criticality aspects at a conceptual level. The other factor- aggregation level (i.e. network-wide or localized) - stems from computational issues in criticality analysis. Therefore, it is not part of the conceptual-level criticality aspects.

Details regarding the technical implementation of the metrics are captured by the 'Data requirements', 'Assessment technique', and 'Computation expense' columns. Based on the data requirements column, it is evident that most metrics require data on the transport network and the location of the economic centroids (e.g. representation of a city or a district as a node in the network). Only metrics based on empirical traffic flows (metric M8\_01 and M8\_03) do not require a transport network. Localized-connectivity metrics (metric category M5 and M10) on the other hand do not require information on the location of the economic centroids.

Furthermore, when comparing data dependency among these metrics, a considerable difference is found at the underlying paradigm factor. User-equality, topological based metrics (metric category M1 to M5) only demand data on the transport network and the economic centroids location, which should normally be available in any transport modeling study. System-based metrics (M6 to M10) require socioeconomic data, the availability of which is sometimes limited (e.g. available on aggregated national level, but not available on the intended disaggregation level).

The computation cost of calculating the metrics in most cases is influenced by the metrics' assessment techniques. There are three types of assessment techniques employed in this research: interdiction, static assignment, and utilization of raw data. Utilization of raw data means applying raw data on top of the transport network directly, without requiring any considerable computation. For instance, metric M10 is calculated by overlaying the geocoded raster flood map directly on the road and the waterway networks. Static assignment refers to the application of network assignment (either All-or-Nothing, probit, or user equilibrium) once in order to calculate the criticality metrics. Interdiction involves the sequential removal of transport segments as explained in Section 4.3.4.

In general, metrics that simply utilize raw data have the lowest computation cost. They are then followed with metrics that use static assignment. Interdiction has high computation cost since it necessitates the execution of network assignment multiple times. An interesting finding from the table is that there is no noticeable difference in computation time between topological (metric category M1 to M5) and system-based (metric category M6 to M10) metrics, which is contradictory to the argument of Mattsson and Jenelius (2015). One possible explanation for this is because the complexity of the system-based metrics employed in this case study, and the complexity of the examples of system-based metrics provided by Mattsson and Jenelius (2015), are different. For instance, they mention complex metrics such as financial impacts and consumer surplus, which are not utilized in this study. Nevertheless, the system-based metrics used in this study still incur more computation time compared to their topological metrics counterpart since system-based metrics include the calculation of actual traffic flow on the network. This higher cost, however, is found to be quite small.

Practically speaking, Table 15 can be directly used by practitioners when they want to select a set of criticality metrics to be evaluated in a criticality study based on their specific problem statement and data availability. This is because the table provides information regarding the represented criticality aspects, the data requirements, the computation

cost and the robustness of the metrics. Even so, a more detailed and comprehensive selection method is presented in Section 6.2.

### 6.1.3 Insights related to the assessment techniques used in the case study

Similar to the previous section, insights related to the assessment techniques are distilled from the comparison of multiple possibilities of assessment techniques based on the case study and the literature review. In this section, the term assessment technique refers to the combination of the interdiction techniques (i.e. no interdiction, individual element interdiction, or multiple elements interdiction) and network assignment methods (i.e. all-or-nothing, probit, or user equilibrium) as most criticality metrics require the assignment of traffic flows to the network. The comparison is made from three perspectives: the computation costs, data requirements, and the ability to replicate real-world phenomena. The comparison is summarized in Figure 37.

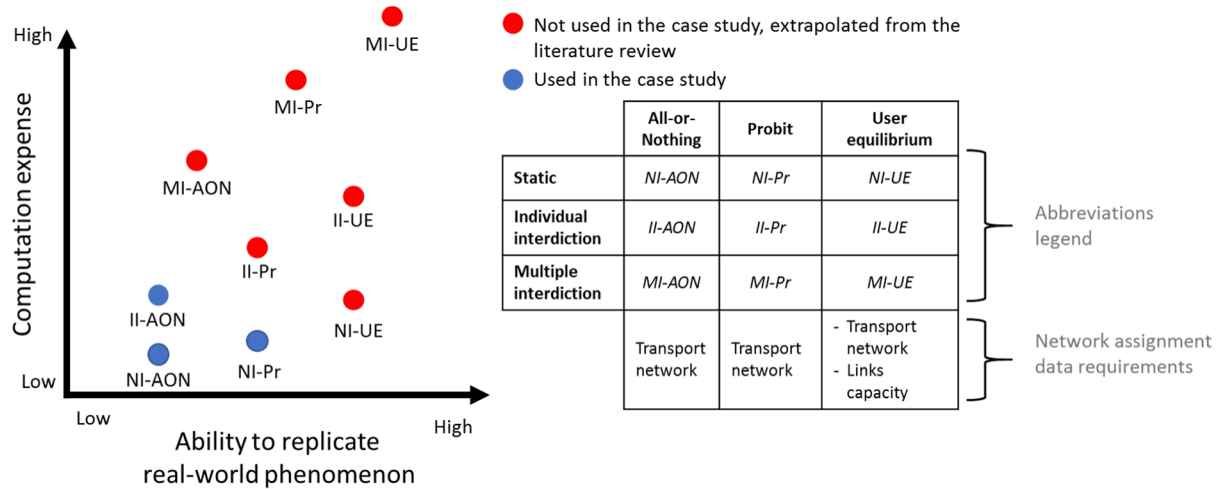


Figure 37 Comparison of assessment techniques

Out of nine assessment techniques presented in the figure above, only three were utilized in this research. This is mainly due to the insufficient information on transport network capacity, especially for the waterway network, and due to computation cost because of the extensive, detailed transport network. Still, the performance of the other six techniques can be estimated based on the three employed techniques and the literature review.

The figure clearly shows a tradeoff between the computation expense and the ability to replicate real-world phenomena (e.g. traffic density and multiple shortest routes between two centroids). Moving from All-or-nothing (AON) to User equilibrium (UE) assignment entails a significantly larger computation cost (Ortuzar & Willumsen, 2011). This is because UE assignment is composed of multiple executions of AON assignment in order to reach the equilibrium state of the transport network. However, UE assignment enables simulation of traffic density on the network, which AON assignment cannot do. In this research, for the no interdiction technique, both AON and probit assignments were used. Probit assignment was used for non-interdiction metrics while AON assignment was used for metrics that require interdiction. The computation cost is also expected to rise tremendously if multiple network elements are disrupted at once (multiple elements interdiction techniques). This is because that the enumeration of the multiple components to be disrupted increases the number of the interdiction iterations enormously.

Data availability is more influential in the selection of the network assignment method rather than to the selection of criticality metrics. The Bangladesh freight transport modeling exercise showcases this issue. For instance, the unavailability of information on transport network capacity and transshipment nodes between two modes prohibits the use of UE assignment. On the other hand, the extensive transport network that incurs large computation cost led to the use of the simplest network assignment method (the AON assignment) for doing the interdiction technique.

Relating back to the metrics comparison presented in Table 15 in the previous section, the computational cost of the metrics changes if different assessment techniques are used. For instance, metric M6\_01 in the case study was calculated by using the individual interdiction technique with AON assignment. Should probit assignment or multiple interdiction technique has been used instead, the calculation time might have risen tremendously. In short, Figure 37 complements Table 15 by providing further insights on the computation expense and the data requirements of various assessment techniques. Thus, practitioners can use Table 15 in combination with Figure 37 to select an appropriate set of criticality metrics, and assessment techniques based on data availability and computational resources.

## 6.2 An informed criticality metrics selection method

Grounded in the insights discussed above, an informed method for selecting a set of metrics to be used in a criticality study is developed. The output of this method is a set of criticality metrics (derived from the eighteen metrics applied in this study) to use, given a problem statement, conditional on data availability, and the available computational resources. Accordingly, there are three elements that practitioners should ask themselves in order to select a set of criticality metrics: (i) whether an initial preference for functionality (i.e. accessibility, total travel cost, or connectivity) exists given the problem formulation, (ii) the availability of socioeconomic data, and (iii) the preferred computational expenses to be borne.

The first element originates from the functionality factor of the contribution to serviceability criticality aspect. This element becomes the first filter since if practitioners have a specific preference of criticality functionality, the number of metrics to be considered can be drastically reduced. Metrics that do not represent the functionality of interest can be eliminated immediately from the choice set. However, if practitioners are not interested in a specific functionality, they have to conduct a comprehensive assessment by taking into account all three functionalities.

The second element is the socioeconomic data availability. Based on the metrics comparison table presented in Section 6.1.2, it is evident that system-based metrics require socioeconomic data on the production and attraction factors in all economic centroids. Nevertheless, this does not necessarily mean that only the user equality paradigm can be applied in the criticality analysis. The total performance paradigm can still be evaluated, although in a limited manner. This is because, from the generalizability analysis presented in Section 5.5, it is found that there are several topological metrics (representing the user equality paradigm) that are highly correlated with system-based metrics (representing the total performance paradigm) in any network structures. Section 6.2.1 to 6.2.4 review this argument in more detail.

The third element evaluates the computing expenses that practitioners want to spend. When the criticality study is not computationally constrained, a broader set of metrics should be considered in the criticality analysis. *Vice versa*, if there is only limited time available while the computational power is also limited, a smaller set of metrics is preferred. The computation constraint is a relative measure that should be judged by the practitioners. In general, the computation constraint is a function of the computation power as well as the associated cost needed for that

particular computation power (e.g. if cloud computing service is to be used), the time available for the criticality study, and the size of the transport network to be analyzed.

The three elements above lead to a selection method that is structured as a nested decision tree. The first two elements make the first layer of the nested decision tree and lead to four categories of metrics choice sets as displayed in Figure 38. Each category is itemized in the following subsections. Within each category, the third element (the preferred computation expense) dictates the final mix of criticality metrics to be used by the practitioners. The summary of the final choice sets of criticality metrics, including the combinations of conceptual criticality aspects that they represent, is presented in Appendix F.

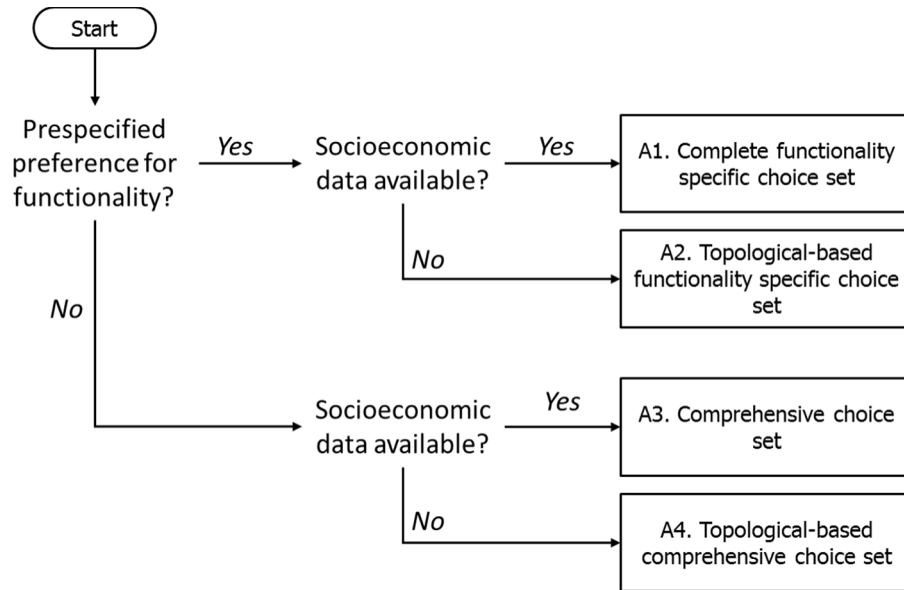


Figure 38 Criticality metrics selection decision tree - First layer

The final metrics sets, which are the outcome of the nested decision tree, are derived based on the metrics performance comparison shown in Table 15 and the generalizability of metrics (dis)similarities discussed in Section 5.5 and Appendix E (which is also concluded within the general insights in Section 6.1.1). Therefore, in order to represent a criticality aspect, metrics from other metric categories may be used instead. For instance, if metric A1 which represents criticality aspect A is highly correlated with metric B1 which represents criticality aspect B, then simply using metric A1 can already cover two criticality aspects (aspect A and B). The decision whether A1 or B1 should be selected is based on the metrics’ computational expense, data requirements, robustness, and correlations with the other metrics in the metrics set.

### 6.2.1 Complete functionality specific choice sets

The term ‘complete’ is used for naming this category because, in this category, both system-based metrics (representing the total performance paradigm) and topological metrics (representing the user-equality paradigm) are included. The term ‘functionality specific’ means that only one particular functionality (either accessibility, total travel cost, or connectivity) is of particular interest in the analysis. For each functionality, the decision tree is branched further based on the computation constraint that the practitioners face. The decision tree for this category is presented in Figure 39.

For accessibility functionality, a computation constrained analysis can simply use metric M1\_01, M1\_02, M2\_01 or M6\_01. The first two metrics exemplify user-equality accessibility aspects of criticality. They have been found to be highly correlated in any network structures. Thus, using any of these two metrics is sufficient. The total performance paradigm of this functionality is represented by metric M6\_01. However, as this metric is highly correlated with M2\_01, the latter one may be preferred as it is more robust to uncertainty. It should be noted that computation-constrained analysis can only incorporate either total performance or user-equality paradigm, but not both at once. If there is no computation constraint in the criticality study, both paradigms can be evaluated.

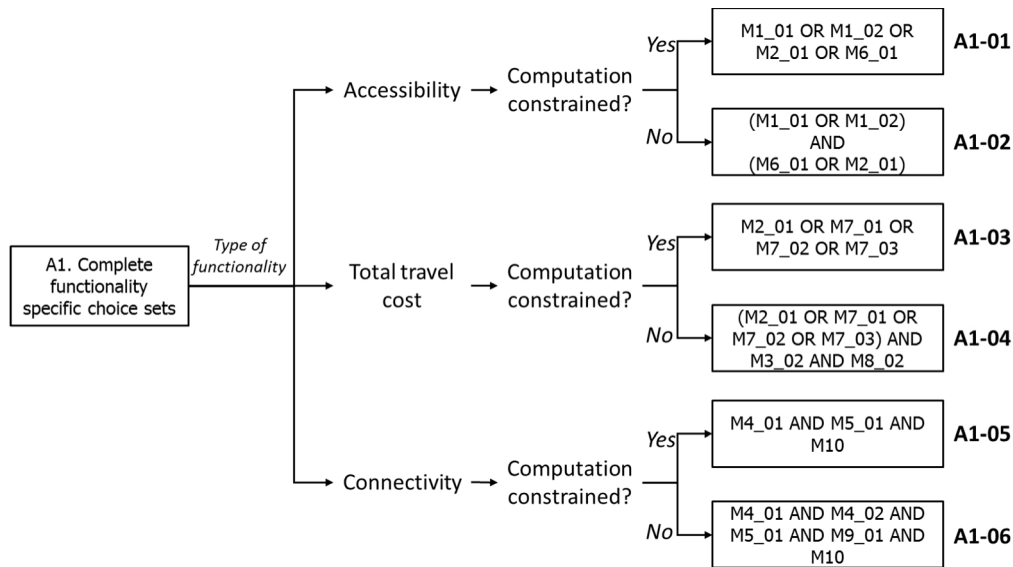


Figure 39 Criticality metrics selection decision tree - Second layer category A1

Similar rules apply to the total travel cost functionality preference. As displayed in Figure 39, there are four options for a computation constrained analysis. They are substitutable because they are highly correlated to each other. By using any of these four metrics, conceptually speaking, both user-equality and total performance paradigms have been covered. However, the empirical analysis between network-wide and localized aggregation (the aggregation level factor) of total travel cost metrics has shown that there may be distinctive results between the two. Therefore, if the criticality study is not constrained by computation time and resources, it is suggested to also calculate metric M3\_02 and M8\_02.

Connectivity functionality is a unique one, as metrics from the localized (metric category M4 and M9) and the network-wide (metric category M5 and M10) aggregation of this functionality produce very different outcomes. Luckily enough, some metrics do not entail high computation cost. A computation constrained analysis should calculate three metrics that do not require interdiction technique, making their computation cost low. If there is no computation constraint, all the five metrics should be calculated.

## 6.2.2 Topological-based functionality specific choice sets

This category differs from the previous category with regard to the initial set of metrics that can be selected as system-based metrics are straightly discarded from the choice set. Consequently, the final metrics sets in this metrics choice set category are the reduced form of the previous category. The decision tree is displayed in Figure 40.

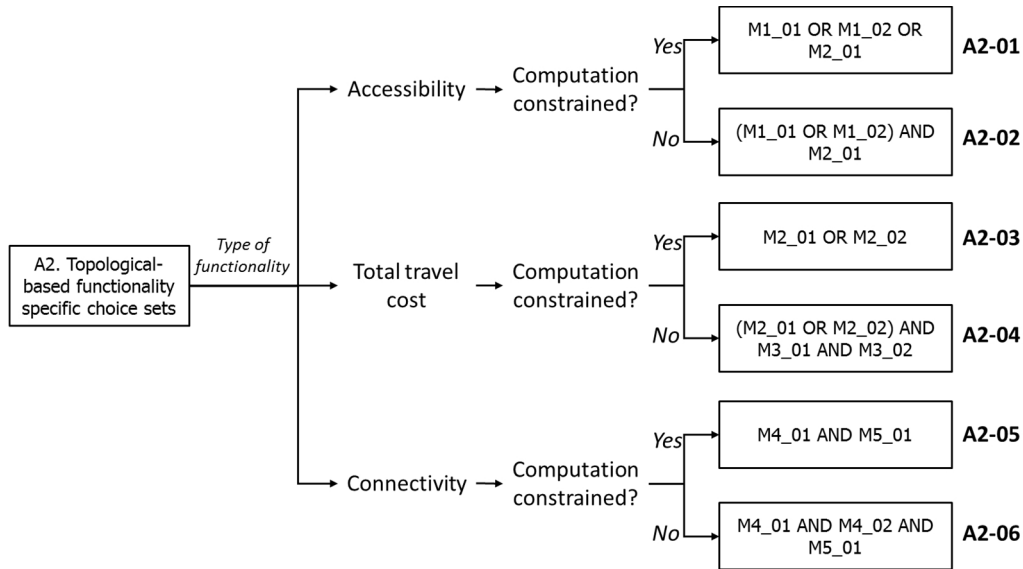


Figure 40 Criticality metrics selection decision tree - Second layer category A2

The metrics choice sets for the accessibility functionality are basically a reduced set of the metrics choice sets for the same functionality from the previous category. In this category, M6\_01 is excluded since it is a system-based metric. Still, the total performance paradigm of this functionality can be represented by calculating metric M2\_01. This makes both user-equality and total performance paradigms still evaluable in this category.

For the total travel cost functionality, any metric from metric category M2 is useful if the criticality study is computationally constrained. Due to their high correlation coefficients with metrics in category M7, metric M2\_01 and M2\_02 can be regarded as representative for both the user-equality and the total performance paradigms of the total travel cost functionality. If more computational resources are available, both M3\_01 and M3\_02 need to be evaluated as well since they have been empirically proven to be complementary to the M2 metrics.

The same reduction also applies if the connectivity functionality is preferred. A computation constrained analysis should only use M4\_01 and M5\_01. Because M4\_02 requires interdiction techniques, it entails a high computation cost, and thus it is only suitable for a non-computation constrained situation.

### 6.2.3 Comprehensive choice sets

The term ‘comprehensive’ is used in this choice sets category because instead of focusing on one specific functionality, all functionalities are included. Furthermore, this category incorporates both topological and system-based metrics. The decision tree of this category is shown in Figure 41.

Performing a comprehensive criticality analysis involves more metrics to be evaluated. Therefore, the computation constraints for this category are divided into three in order to give more flexibility to practitioners to select between different metrics sets. As mentioned in the introductory paragraphs of Section 6.2, the computation constraint is relative to the computational resources at hand. The high, medium and low distinctions in this category are therefore to be viewed as relative as well (no absolute definition of what high, medium, and low mean).

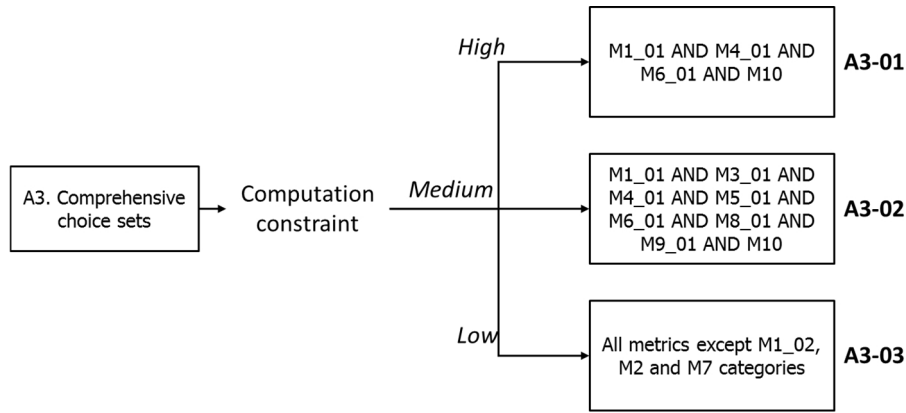


Figure 41 Criticality metrics selection decision tree - Second layer category A3

When the computation is highly constrained (e.g. the computational power and the study time are limited while the transport network is enormous and extensive), only four metrics need to be calculated in order to cover all six combinations of criticality aspects on a conceptual level (the underlying paradigm factor and the functionality factor, as explained in Section 6.1.2). This is because metric M6\_01 is highly correlated with the metrics in metric category M2 and M7. Hence, metric M6\_01 represents three combinations of criticality aspects at the conceptual level: (i) user-equality total travel cost, (ii) total performance accessibility, and (iii) total performance total travel cost. The other three combinations of conceptual-level criticality aspects are represented by M1\_01, M4\_01, and M10.

When the computation constraint is a bit more relaxed, the set of metrics to be calculated may be extended from not only fulfilling the criticality aspects at the conceptual level but also fulfilling the aggregation factor of criticality metrics. Therefore, the resulting set of metrics should cover all ten metrics categories (metric category M1 to M10). There are in total eight metrics that have to be calculated as shown in Figure 41.

If the computation constraint is minimal, all metrics should be calculated by the practitioners. The intention of doing this is to find as much complementary metrics as possible for deriving the final conclusion of the criticality analysis, as from the generalizability analysis it is found that most metrics (dis)similarities are network dependent. However, it is safe to exclude metric M2 and M7 from the metrics set since their high correlation coefficient with metric M6\_01 is robust. Metric M1\_02 can be ruled out as well since it can be well represented by M1\_01.

## 6.2.4 Topological-based comprehensive choice sets

The final category is a comprehensive analysis (i.e. trying to embrace as much criticality aspects as possible) that is limited to only topological metrics. The decision tree for this category is displayed in Figure 42.

In a situation of high computation constraint, practitioners only need to evaluate three criticality metrics. First, M2\_01 or M2\_02 replace M6\_01 from the previous category. Accordingly, these two metrics already represent three combinations of criticality aspects. The other two metrics (M1\_01 and M4\_01) complement M2\_01 and M2\_02, and represent two other combinations of criticality aspects. There is, however, one combination of conceptual-level criticality aspects that cannot be captured in this situation. No topological metric has a high correlation coefficient with metrics that represent the total performance connectivity aspect (metric M9\_01 and M10). This prevents the evaluation of the total performance connectivity aspect.

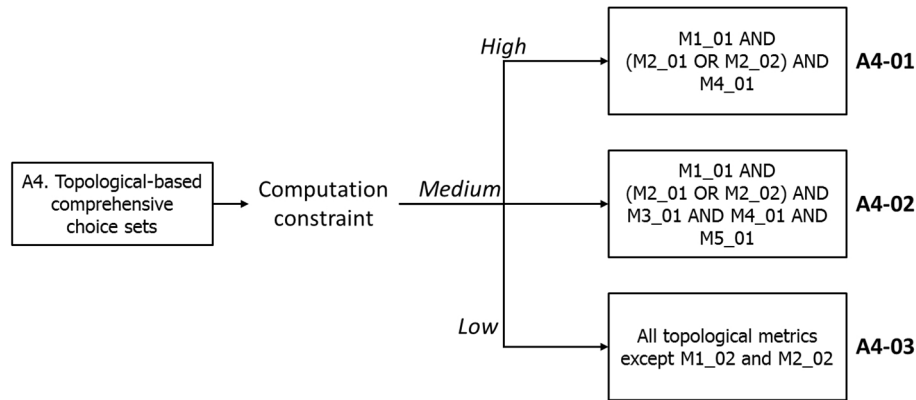


Figure 42 Criticality metrics selection decision tree - Second layer category A4

The medium computation constraint leads to five metrics to be calculated, while the low computation constraint leads to seven metrics to be used. The difference between the two is that in the latter one, metric M3\_02 and M4\_02 are also considered, while those metrics are not present in the medium constraint situation. This is because M3\_02 and M4\_02 charge a high computation expense while the conceptual-level criticality aspects that they represent have been covered by M3\_01 and M4\_01. Although, based on the empirical evidence from the case study, they highlight different sets of links as critical.

### 6.2.5 Dealing with multiple criticality outcomes

Traditionally, criticality analysis focuses on one single metric. There is no decision-making challenge in that situation since the criticality scores from the single indicator can be used directly to find out the most critical links. The case is different in this study. Several metrics sets contain more than one metrics to be evaluated. Hence, there is a possibility that the practitioners will have to deal with different outcomes from various criticality metrics.

In this section, a procedure to draw the final conclusion of a criticality analysis if multiple metrics are employed is proposed. The procedure is deduced from the Bangladesh's multimodal freight transport network case study as presented in the previous chapter, especially the metrics comparison and elimination part in Section 5.4. The complete procedure is illustrated in Figure 43. For the sake of clarity, the metrics comparison step is briefly reviewed in the following paragraphs. Afterward, two proposed techniques to derive conclusions from multiple criticality outcomes are explained.

The first step that practitioners have to do after calculating the criticality metrics is choosing the top  $n$  most critical links that they want to observe. The number  $n$  is dependent on the size of the network and is to be decided by the practitioners. For instance, the number 100 was chosen in the previous case study since Bangladesh's multimodal transport network consisted of around 1200 links. Afterward, the union of the top  $n$  most critical links from all metrics in the metrics set is extracted. This results in a set of the top  $M$  most critical links from all metrics. The criticality scores from all metrics of these links set are subject to the comparison between metrics phase.



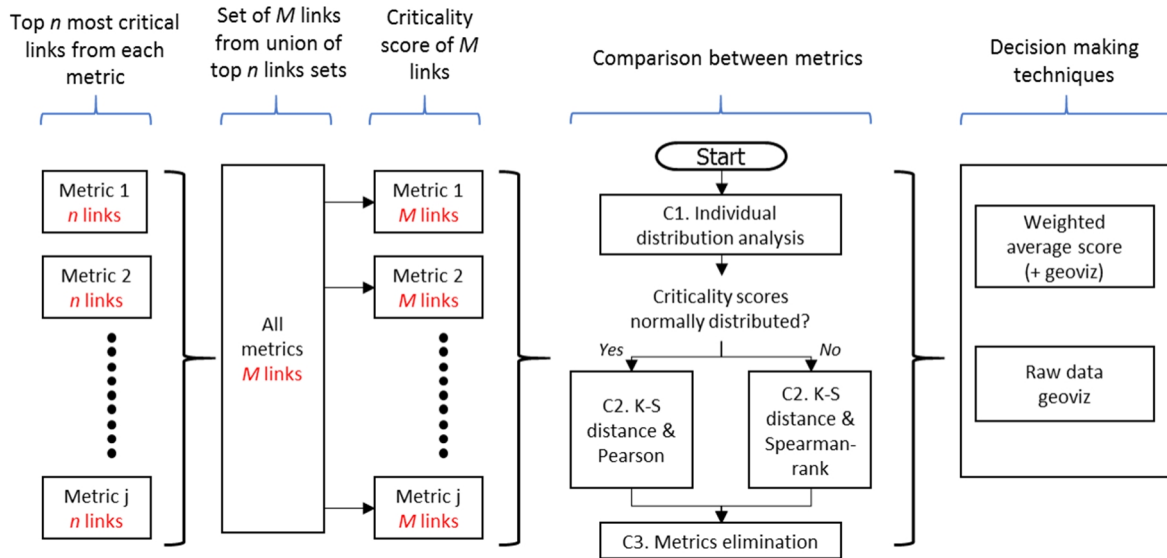


Figure 43 Proposed procedure for dealing with multiple metrics

The comparison between metrics starts by observing the individual distribution of each metric’s criticality scores (step C1 in Figure 43). The shape of the distribution determines the correlation coefficient technique to be used to compare each metric in the metrics set with one another. If the metrics’ criticality scores are normally distributed, then Pearson correlation coefficient can be applied. Otherwise, Spearman-rank correlation coefficient should be used instead. The calculation of correlation coefficients is meant to observe which metrics pairs are overlapping (i.e. having similar outcomes, step C2 in Figure 43). One of the metrics in each overlapping metrics pair is then subject to be discarded from the analysis. The Kolmogorov-Smirnov (K-S) distances between each metric complement the correlation coefficients. If the K-S distance between a metrics pair is high, then none of them should be eliminated since they have different criticality scores distributions. The K-S distance and correlation coefficient analyses result in a final (reduced) set of metrics to be evaluated by the decision-making techniques.

The fourth insight from the general insights section (see Section 6.1.1) has indicated that if the final set of metrics contain more than one metric, the standard value-based ranking may not be sufficient. Therefore, two ways to get the conclusion from the criticality analysis are proposed: weighted average score and interactive geovisualization. Each technique has its own benefits and shortcomings. Practitioners have to be aware of the techniques’ properties and choose the one that is most relevant for answering the policy problem. The techniques are detailed below.

*Weighted average criticality score (+ geovisualization)*

The central idea of this technique is to condense the criticality scores from multiple metrics into a single criticality value for each link. In this way, the standard value-based ranking method may be used to draw the conclusion while also taking all metrics into consideration. There are two issues in implementing this idea. First, the magnitude of the criticality scores from each metric is different. For instance, the values of the change in unweighted daily accessibility metric (metric M1\_01) range from 1 to 1.1 while the values of the min cut centrality metric (metric M4\_01) range from 0 to 140. Second, there is a need for the practitioners to put a relative preference in each criticality metric so that the scores from each metric can be weighted accordingly.

Consequently, there are two steps in this technique: normalization of criticality scores and assignment of preferential weights. In the first step, for each criticality metric, the score of each link should be scaled into a value within a range of zero and one. The normalization can be done by the following equation:

$$c_i^{nm} = \frac{c_i^m - \min(c_i^m) \text{ for } i \in I}{\max(c_i^m) \text{ for } i \in I} \dots\dots\dots (Eq 5)$$

where  $c_i^{nm}$  is the normalized criticality score of link  $i$  from metric  $m$ ,  $c_i^m$  is the original criticality score of link  $i$  from metric  $m$ ,  $\min(c_i^m)$  is the minimum value of metric  $m$  from all links in the network, and  $\max(c_i^m)$  is the maximum value of metric  $m$  from all links. Following the first step, the weighted average criticality score ( $c_i^w$ ) of a link can be calculated by multiplying the normalized criticality score by its preferential weight, as shown in the following formula:

$$c_i^w = \sum_{m \in mset} w^m * c_i^{nm} \dots\dots\dots (Eq 6)$$

where  $w^m$  is the preferential weight from metric  $m$ . It should be noted that the sum of the preferential weight should be equal to one ( $\sum_{m \in mset} w^m = 1$ ). In this way, the final weighted average criticality score for each links in the network is obtained and the links can be ordered by this value to get the final links ranking.

The main advantage of this technique lies in the format of this technique’s outcomes. This technique assigns a single, unique criticality value to each link in the network. Therefore, this technique offers not only the exact ranking of all links based on their criticality value, but also a clear-cut insight on the magnitude of the difference of the criticality scores amongst all links in the network. The final weighted criticality score can be displayed geospatially. This enables practitioners who have tacit contextual knowledge of the transport network to derive insights from the visualization interactively.

A disadvantage of this technique is that this reductionist approach mixes the various unique criticality aspects represented by each metric. In addition to that, the final outcome is dependent on the subjective preference that the practitioners hold. There is a risk that the result is sensitive to the preferential weights. Thus, it is subject to be debated if other stakeholders disagree with the preferential weights applied in the calculation.

Based on the pluses and minuses above, this technique is more suitable to be used for a criticality analysis in which the time frame of the study is short. The outcome from this technique can be immediately drawn since the format of the outcome is the same as the format of a single-metric criticality analysis. This makes the time to interpret the result and to make a policy recommendation from the result short.

*Raw results analysis*

The second technique leaves the distinctive criticality scores from all criticality metrics as is. In order to derive conclusions from the criticality metrics scores, all results from all metrics are geospatially visualized at the same time. This in principle is the same concept like the geovisualization panels in Figure 36. In this way, the critical links can be observed by visually inspecting the links that appear as critical in various criticality metrics. As an addition, individual distribution analysis (checking the distribution pattern of each criticality metric individually) can also complement the geovisualization in understanding the occurrence of extremely critical links on the network.

The advantages of this technique overcome the shortcoming of the previous technique. That is, it does not reduce the richness of the information from multiple criticality metrics. This technique provides a bird’s eye view of the

results from all metrics. When the final set of the most critical links has been identified, practitioners can straightforwardly see which criticality metrics (and thus, criticality aspects) are represented by the selected links, and which criticality metrics are not. Ultimately, it allows practitioners to observe the tradeoff of choosing a set of links over others.

The drawback of this technique comes from the format of the technique’s output. The technique does not permit a unique ranking of all links in the network since there is no single criticality value to be compared. Moreover, the magnitude of the difference of criticality scores between any two links cannot be examined in detail since the geovisualization panels do not offer this feature.

This technique is suitable to be used if the goal of the criticality study is to identify a short list of the most critical links along with the specific criticality aspects that they represent. This technique is also suitable if the setting of the criticality study is interactive. That is, if the final conclusion from the criticality results is to be derived from a thorough deliberation between the practitioners and the other relevant stakeholders. Such studies normally take a longer time frame.

### 6.3 Demonstration of the selection method

As a proof of concept of the selection method, two illustrative case studies are presented in this section. The case studies consist of two different hypothetical data availability and study purposes of Bangladesh’s freight transport network criticality analyses. There are two parts in each case study: (i) the problem background and selection of metrics set, and (ii) results analysis and conclusion. The model building and metrics calculation steps of the criticality analysis are not explained since they have been presented in detail in Chapter 4 and 5.

#### 6.3.1 Illustrative case study 1

##### *Problem background and selection of metrics set*

The Bangladeshi government is developing an operational restoration plan to deal with natural disasters such as annual flooding. A part of the plan talks about prioritization of precautionary budget for restoring damaged transport segments in the country. Therefore, a transport network criticality analysis is needed as a mean to prioritize the budget. However, the data available to develop the transport model is limited. There is no district-level socioeconomic data available at the moment.

Based on the problem background above, the contextual situations of the first case study are summarized in Table 16. Accordingly, metrics set A4-03 is chosen. This metrics set covers all combinations of conceptual aspects of criticality, except the total performance – connectivity aspects combination. All topological-based metrics except M1\_02 and M2\_02 are calculated.

*Table 16 Case study 1 contextual situations*

Situations	Remarks
Prespecified preference of functionality?	No
Socioeconomic data available?	No

*Results analysis and conclusion*

After developing the transport model and calculating the criticality metrics, Spearman-rank correlation coefficients and K-S distances between the metrics are evaluated. They are shown in Figure 44. There are three metrics that have high correlation coefficients and thus subject to be eliminated. They are M2\_01, M3\_01, and M4\_02. Out of these three metrics, M4\_02 has the highest average correlation coefficients. Consequently, it is removed from the metrics set.

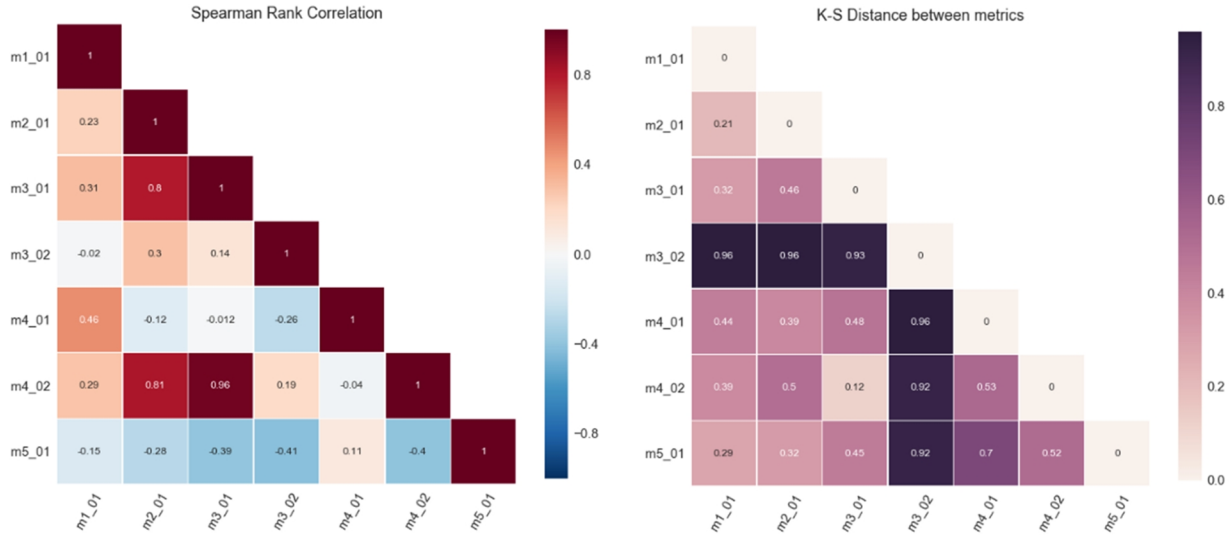


Figure 44 Spearman-rank correlation coefficients and K-S distances between metrics in case study 1

As there is no time constraint in the criticality study, it is best to visually inspect the results of all metrics in the final metrics set rather than combining them into a single metric. Therefore, raw data geovisualizations are developed to deal with multiple criticality metrics (see Figure 45). In real practice, the geovisualization can be used in an interactive manner by the stakeholders so that a better-informed decision can be made. However, in this illustrative case study, only the top 100 most critical links from each metric are presented.

Although there is no single transport segment which is found to be critical in all metrics, there are several road segments that are critical in multiple metrics. First, the Bangabandhu bridge over the N405 is critical in metrics M1\_01, M2\_01, M3\_01, and M4\_01. This segment continues further to the N5 from Hatikumrul to Sherpur in the western part of Bangladesh. Another critical road segment is the N1 from Dhaka to Feni is critical based on metrics M2\_01, M3\_01, and M3\_02. In the southwest part of Bangladesh, four critical road segments are the R750 from Jessore to Narail (critical based on metrics M1\_01 and M3\_02), the N7 from Jessore to Jhenaidah (critical based on metrics M2\_01 and M3\_02), the N704 from Jhenaidah to Kushtia (critical based on metrics M1\_01, M2\_01, M3\_01 and M3\_02), and the N7 from Jhenaidah to Faridpur (critical based on M2\_01 and M4\_01).

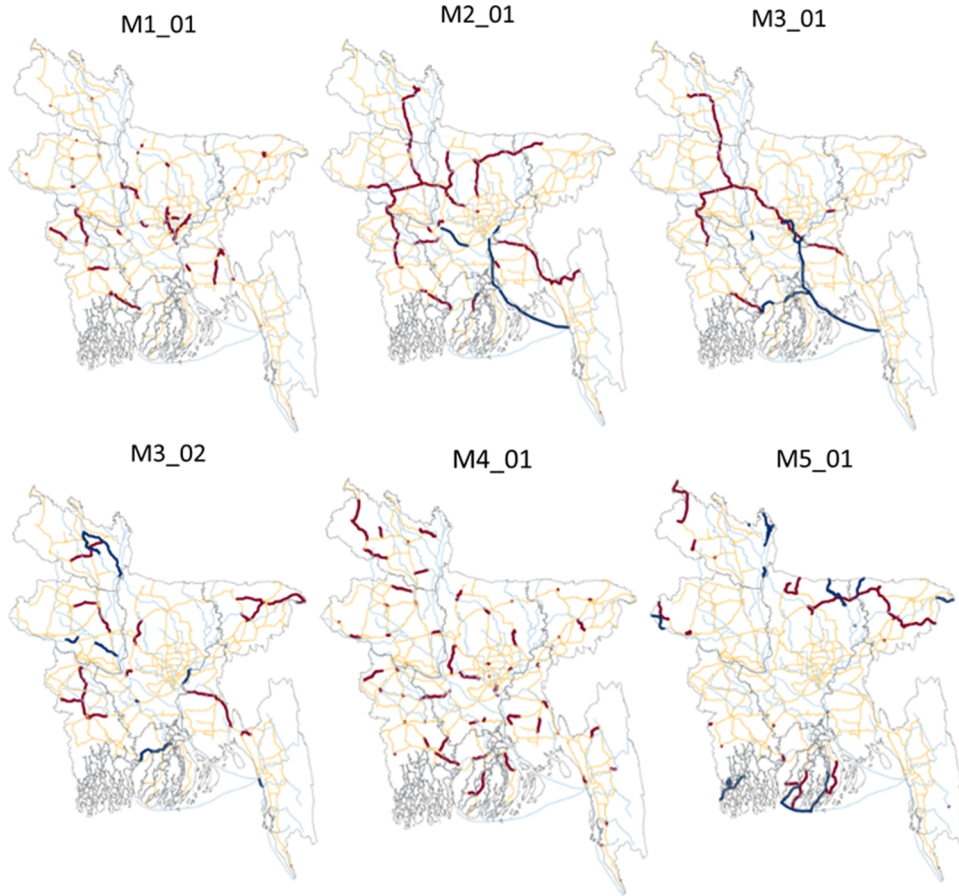


Figure 45 Geovisualization of top 100 most critical links for case study 1

### 6.3.2 Illustrative case study 2

#### *Problem background and selection of metrics set*

The president of Bangladesh asks for a brief overview of the relative importance of the transport segments in the country for the cabinet's meeting that will take place in ten days. He requests the director of Road Transport and Highways Department (RHD) of Bangladesh and the director of Bangladesh's Inland Waterway Transport Authority (BIWTA) to present a quick overview of the country's multimodal (road + waterway) transport network criticality. The director then calls the expert team to conduct the criticality analysis. There is sufficient data available for developing the transport model, including the socioeconomics statistics on the district level.

Based on the problem demarcation above, the contextual situations of the first case study are summarized in Table 16. Accordingly, metrics set A3-02 is chosen. This metrics set covers all combinations of conceptual aspects of criticality. In total, there are eight metrics that have to be calculated.

Table 17 Case study 2 contextual situations

Situations	Remarks
Prespecified preference of functionality?	No

Socioeconomic data available?	Yes
Computationally constrained?	Medium

*Results analysis and conclusion*

Similar to the previous case study, the Spearman correlation coefficients and the K-S distances between the metrics are computed (see Figure 46). The correlation coefficients heatmap clearly points metric M3\_01 as the only metric that has high correlation coefficient. Therefore, this metric is discarded from the metrics set.

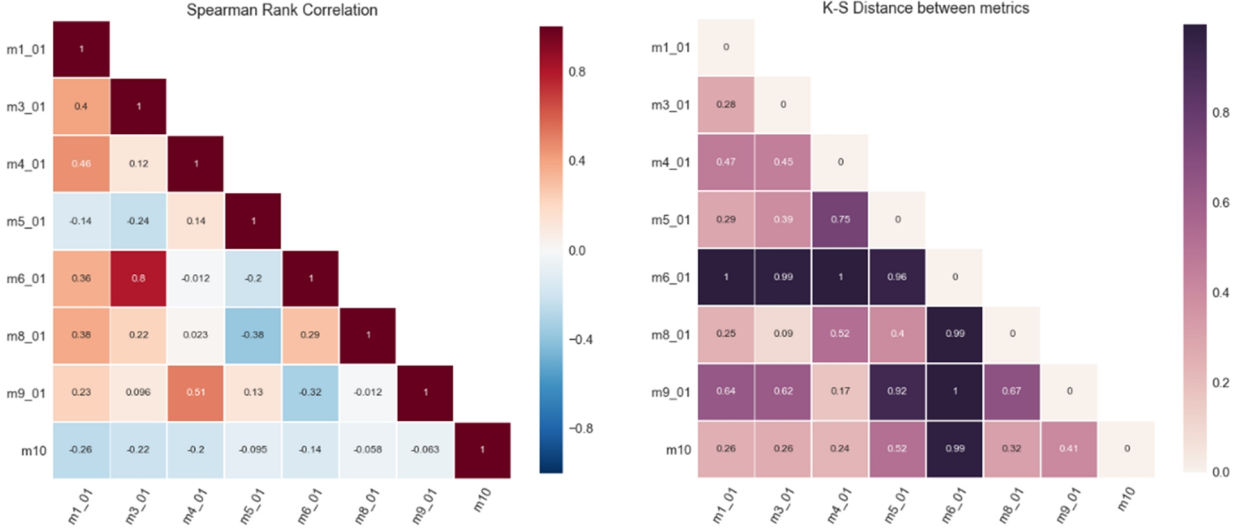


Figure 46 Spearman-rank correlation coefficients and K-S distances between metrics in case study 2

The purpose of the criticality study is an overview of the transport segments’ importance to be presented to the president and the other ministries during a cabinet meeting. The format of the final deliverable is therefore should be tailored in such a way so that it is easy to be understood by people with little or no knowledge of transport network criticality. Furthermore, the time needed to make a comprehensive analysis and write an extensive report is limited. Accordingly, a raw result analysis style as performed in the previous case study is not suitable in this context. A weighted average criticality score is used instead, with all metrics weighted equally.

The result of the weighted average criticality calculation is presented in Figure 47. Several highlights can be observed from the graph. The north-most section of N5 from Thukargaon to Panchagarh is the most critical transport segment. This is because this segment is the only road that connects the Panchagarh and Thakurgaon districts in the north, and at the same time is very prone to natural disaster. If this road is disrupted, the two districts will be disconnected from the rest of Bangladesh. Another noticeable critical segment is the N4 from Kaliakair to Elenga, which ultimately connects Dhaka to the Bangabandhu bridge on the N405. This road segment is a part of the shortest route to transport food commodities that are mainly produced in western and northwestern districts of Bangladesh to the capital city of Dhaka and to the main export hub in Chittagong. Lastly, the R812 from Narayanganj to Mawa is also critical as it connects the capital city of Dhaka and the Chittagong port to the western and the southwestern districts through the Mawa ferry crossing.

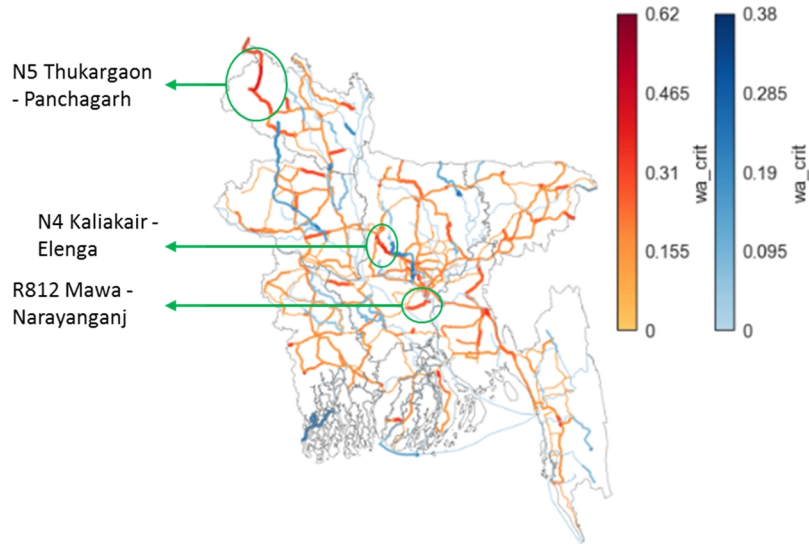


Figure 47 Geovisualization of weighted average criticality score for case study 2

## 6.4 Chapter 6 Summary

In a nutshell, this chapter has discussed the following points:

- An extensive explanation of insights from the case study and the literature review has been provided. The insights are grouped into three categories:
  - General insights for a comprehensive criticality study. These insights are gained by reflecting on the case study and the literature review.
  - A table that summarizes insights related to the criticality metrics. The conceptual and technical comparisons between the metrics are made explicit in this table.
  - Insights that are related to the criticality assessment techniques. The insights compare multiple assessment techniques based on their data requirements, their computational expense, and their relative ability to replicate real-world phenomena.
- An informed criticality metrics selection method has been developed. The selection method can guide practitioners to select the most suitable set of criticality metrics that covers as many criticality aspects as possible given the practitioners' initial preference of the transport system's functionality, the data availability, and the preferred computation expense.
- Two illustrative case studies as a proof of concept of the informed selection method have been performed. The case studies show how the different contextual situations of the criticality study lead to different metrics selection.

*This page is intentionally left blank.*



# Chapter 7: Conclusion and Reflection

This chapter is devoted to answering the research questions and reflecting back on the execution of the research. By revisiting the sub-research questions, a conclusion of the study can be derived. For the sake of societal benefit of this research, policy recommendations specific to the illustrative case studies are drafted. Afterward, limitations and prospective future research based on this study are provided. Following this, a retrospective critique on the subject of the study itself is also elaborated. Last of all, a reflection on the journey of the research is written.

## 7.1 Revisiting research questions

This research began due to two scientific concerns with regard to transport network criticality. In the first place, researchers are competing with each other in developing better means of transport network criticality operationalization. As a consequence, dozens of specific metrics and techniques have been put forward. In the second place, the practical usability of these metrics and techniques is sometimes limited due to data unavailability and in other times due to computational difficulties. Drawing upon these concerns, a research question focused on developing a criticality metrics selection method emerged. The main research question was disassembled further into five sub research questions. Therefore, answering these questions means answering the main research question.

*Sub-RQ #1 : What general aspects of transport network criticality can be synthesized from the diverse criticality definitions?*

The first step to this research was to identify the general aspects of transport network criticality that underpinned the conceptual foundation of the transport network criticality. An extensive and systematic literature review was done to address this question, resulting in three aspects of transport network criticality analysis:

1. **Network component centered;** This aspect especially distinguishes criticality analysis from other related concepts such as vulnerability, resilience, and robustness. Criticality analysis should put values on network component level (i.e. nodes or links).
2. **Contribution to serviceability;** Transport network criticality values attached to network components should in some ways represent the contribution of those components to the functioning of the transport system in general.
3. **Disruptions;** The last aspect deals with means of calculating the criticality, which generally utilize disruption techniques.

*Sub-RQ #2 : How can the criticality aspects be operationalized in practice?*

After developing the concept map of criticality aspects, the operationalization of these aspects was discussed. The contribution to serviceability aspect created a three-layered approach to defining criticality metrics (paradigm, functionality, and aggregation layers). Further, eighteen criticality metrics for the Bangladesh freight transport network case study has been defined based on this layered approach. The disruption aspect of criticality provided the foundation of the five-layered approach to criticality assessment techniques (number of stages, disruption, severity, extent, and probability layers). These techniques are often interlinked with specific metrics. In other words, some metrics may require specific assessment techniques in order to be calculated. Though not explicitly dealt within the

case study, the five-layered approach provides a systematic categorization of assessment techniques that can be useful for future criticality studies.

Of utmost importance during the operationalization phase is the role of data in criticality studies. It turns out that from a criticality metrics perspective, the role of data is important only when selecting the underlying paradigm of the contribution to serviceability aspect (i.e. total-performance or user-equality). The user-equality paradigm does not require socioeconomic data since all user groups are treated equally. In contrast, the total performance paradigm requires socioeconomic data. Interestingly, data availability is more relevant to be evaluated during the selection of the freight transport modeling approach. Congested network assignment techniques require more transport network data in terms of links capacity. Additionally, four freight transport modeling approaches and their associated data requirements have been discussed.

*Sub-RQ #3 : When applied to a real world network, how do different metrics overlap and complement one another?*

Based on the case study, differences and similarities among the metrics were analyzed. There are three important scientific insights from this. First, for a transport network criticality study, two relevant statistical techniques to characterize the (dis)similarities among the metrics are Kolmogorov-Smirnov (K-S) distance and correlation coefficient. K-S distance assesses the extent to which the distribution density of any two metrics differs. This is important for a criticality study as different distribution patterns require different ways of drawing inferences from the result of the criticality analysis. Pearson correlation coefficient and Spearman-rank correlation coefficient can be used interchangeably depending on the distribution pattern of the criticality values. If two metrics highlight the same set of links as critical, they will have a high correlation coefficient and they can be considered to be overlapping with each other. Thus, removing one of them in the further analysis will not jeopardize the validity of the final results.

Second, out of all metric categories, only category M1 (topological – accessibility – network wide), M2 (topological – total travel cost – network wide), and M7 (system-based – total travel cost – network wide) have high correlation coefficients in their own within-group metrics comparison. Representing these categories by only a single metric is sufficient. On the other hand, the different operationalization of metric category M3 (topological – total travel cost – network wide), M4 (topological – connectivity – network wide) and M8 (system-based – total travel cost - localized) results in a different set of links illuminated as critical. Using multiple metrics for these categories in future studies is accordingly suggested.

Third, metric M6\_01 (system-based accessibility metric) has been empirically proven to have results coinciding with M2 and M7 metrics. Therefore, employing this metric can already represent M2 and M7.

*Sub-RQ #4 : How robust are the metrics and their complementarity and overlap when faced with uncertainty in parameters and network structure?*

Two distinctive analyses are branching from this question: one is the robustness of the metrics individually and another one is the generalization of the comparison among them. The latter has been implicitly discussed in answering the previous research question. That is, for within-group comparison, high correlation coefficients always occur for M1, M2, and M7. For between-group comparison, M6 is always strongly correlated with M2 and M7, regardless of the network structure. The results can be generalized for other freight transport networks because they hold true for all tested subnetworks of divisions in Bangladesh. Other metric categories only appear as generally critical in several subnetworks. Therefore, metrics comparisons especially for these categories are a step that should not be overlooked in the final criticality assessment method.

The robustness of individual metrics has been assessed on three fronts: rank robustness, distribution robustness, and value sensitivity. Generally speaking, it was found that topological metrics were more robust than system-based metrics in any of these fronts. Moreover, the large discrepancy between Median Absolute Deviation and Standard Deviation in system-based metrics suggests the occurrence of outliers in their value sensitivity analysis. This shows that socioeconomic uncertainties contribute to the final criticality results of system-based metrics significantly. M1 and M2 metric categories come as the most robust ones among all metrics tested in the case study.

*Sub-RQ #5 : How can an informed selection of an appropriate set of transport network criticality metrics be made?*

An informed selection of an appropriate set of criticality metrics has been developed by understanding the comparisons of the criticality metrics on conceptual (the criticality aspects that they represent) and technical levels (the data requirements, assessment technique, computation expense, and complementarity to each other). This results in a decision tree that ultimately provides practitioners with the most appropriate set of criticality metrics to be used based on the policy problem and the technical limitations of their study. In order to select the final set of criticality metrics, practitioners should reflect on three elements: (i) whether an initial preference for transport network functionality (i.e. accessibility, total travel cost, or connectivity) exists in the problem formulation, (ii) the availability of socioeconomic data, and (iii) the preferred computational expenses. In order to demonstrate the applicability of the method, two hypothetical case studies with distinctive contextual situations were performed.

## **7.2 Policy recommendations from the illustrative case studies**

An advantage of a case study research is that it does not only contribute to the scientific world, but it also has societal benefits for the object of the case study. However, there is no exact concrete policy problem in this research. Nevertheless, the two illustrative case studies presented in Section 6.3 as well as the robustness analysis in Section 5.3 can provide valuable insights to the Bangladeshi government, especially the Ministry of Road Transport and Bridges and Ministry of Shipping. Given the policy questions presented in Section 6.3, the following policy recommendations are outlined:

1. Road segments that appear in top 100 links of many criticality metrics are the N5 from Hatikumrul to Sherpur, the Bangabandhu bridge over the N405, and the N1 from Dhaka to Feni. These roads are parts of an elongated corridor from the northern part of the country to the southern part of the country. In the southwestern part of Bangladesh, the R750 from Jessore to Narail, the N7 from Jessore to Jhenaidah, the N704 from Jhenaidah to Kushtia, and the N7 from Jhenaidah to Faridpur are found to be critical.
2. If all metrics are weighted equally, three most critical road segments are the N5 from Thukargaon to Panchagarh, the N4 from Kaliakair to Elenga, and the R812 from Mawa to Narayanganj.
3. On the one hand, the value sensitivity of system-based metrics is quite high. On the contrary, in transport network criticality study, the importance of socioeconomic uncertainties comes from their relative values among the districts rather than from their absolute values. Therefore, a change of pattern of socioeconomic activities may alter the results of the criticality analysis. This calls for an integrative planning between the Ministry of Road Transport and Bridges, the Ministry of Shipping, and other ministries under Economics and Infrastructure theme.

4. Furthermore, if in the future the socioeconomic pattern substantially changes across the country, the freight transport network criticality analysis should be redone as it is likely that different set of links will become critical.
5. In order to improve the level of detail of the freight transport model for other studies, data that should be made available by the Bangladeshi Government are the transport infrastructure capacity (especially for the waterway), the I/O table of the key products (especially a multi regional I/O table if possible), the multi-regional trade balance between districts or subdistricts, and the socioeconomic figures on a sub-district level.

### **7.3 Limitations and future research**

Despite the rigorous discussion in this research, there are several limitations and assumptions that have to be made explicit. From this elucidation, directions for future research are derived. The limitations can be grouped into three categories: limitation in the transport modeling exercise, limitation in criticality results analyses, and limitation in designing the selection method. Some limitations have been assimilated within the corresponding chapters and they are once again outlined here for clarity.

#### *Limitations in transport modeling*

1. A strict assumption used was that the economic value of a commodity was linearly correlated to the goods' tonnage. This was an eventual simplification as some commodities might in reality weigh heavily but only had small economic values, while other commodities might have lower weight but higher economic values.
2. When developing the supernetwork, if there was no information regarding the existence of any bridge on the intersecting road segments, transshipment nodes were automatically created. This might not hold true in the real world as some small ferry crossings were only usable for passenger transport rather than freight transport.
3. Both probit and AON assignments assumed an incapacitated network. Therefore, traffic congestion was not taken into account.
4. The cost of traversing a link should be defined differently for each type of modes (e.g. road and waterway). Even within the same modes, different infrastructure condition (e.g. paved and unpaved, urban and rural roads, etc) should have yielded distinctive costs. In this study, however, cost distinctions were only made for between-modes links, but not for within-modes links. If the information to operationalize this issue is insufficient, it may be possible to assume it as an uncertain factor.

#### *Limitations in criticality results analyses*

1. Some steps in the criticality results evaluation framework could have been dug in more detail. For instance, the robustness analysis only stopped at assessing the value sensitivity of the criticality scores.
2. The purpose of the comparison between metrics was to contrast each metric with all other metrics rather than contrasting two metrics side-by-side in fine detail. For the latter one, other tools such as spatially displaying the rank difference of each link based on two or more different metrics may have been useful.

3. The Spearman-rank correlation coefficients change when evaluated on different networks. They may have been some network characteristics or spatial-economic patterns that typify this change and they have not been observed in this research.
4. Since metric category M5 (topological – connectivity – localized), M6 (system-based – accessibility – network wide), M9 (system-based – connectivity – network wide) and M10 (system-based – connectivity – localized) were not frequently used in previous studies, each of them was only represented by one metric in this research.

#### *Limitations in designing the selection method*

1. The usability of the method has only been demonstrated for different problem formulations but still within the same object (Bangladesh multimodal freight transport).
2. Methodologically, the concept map of criticality aspects (Figure 7) and the metrics set requirements (Table 9) were developed solely from the literature review and the writer’s own argumentation. Thus, it is to some extent subject to the writer’s world view toward the subject.
3. The selection method focuses more on guiding practitioners to get the most appropriate set of criticality metrics rather than on drawing inferences from multiple criticality metrics. Therefore, the decision-making techniques to deal with distinctive criticality outcomes proposed in this research are still preliminary.

#### *Recommendations for future research*

1. Finding a technical workaround for doing interdiction techniques while applying probit and/or congested network assignments with low computation cost is a challenge remains to be tackled.
2. The robustness analysis can be extended further into a deep uncertainty analysis. For instance, it may be interesting to study how scenario discovery can be performed in a multiperspective criticality analysis where there are multiple metrics with different spatial outcomes.
3. Understanding the relations between the topological characteristics of a network, its criticality scores, and the metrics complementarity of that network is worth exploring for advancing the transport network and graph theory body of knowledge.
4. As the selection method was developed solely from a literature review and quantitative analysis, its form and its usability could be improved by conducting expert interviews and workshops.

## **7.4 Beyond the research: Some retrospective critiques**

Looking further beyond answering the research questions, there have been many additional thoughts that come out throughout the journey of the research. The critique here does not refer to criticism, rather, it shows my personal reflections on various insights that may not be directly related to answering the main research question itself. Critiques are to be made on three themes: the additional findings related to transport network criticality study and the methodological choices as well as the execution of the research.

### *Critique to the transport network criticality study*

Transportation is a key factor to the economic development of a country. In Bangladesh itself, the enormous development of union and village roads conducted in the past has been claimed as a vital point in lifting poverty in rural areas. It has also shifted the production pattern of agricultural products because goods can now be transported from these areas to big cities. This is what transport network criticality is supposed to be aimed at. However, after conducting a systematic literature review, I found that most studies used system-based metrics. It has been argued in this thesis that the paradigm underlying system-based metrics is utilitarianism where higher weights are put on nodes with higher economic activities. Only a small number of researchers adopted the egalitarianism two or even egalitarianism one paradigm. To my view, this signifies that transport network criticality researchers have put only little effort into addressing regional inequality issues, while inequality is a grand societal challenge.

### *Critique to the methodological approach of transport modeling*

This research has been my first experience in developing a model that in my opinion tends to be more ‘engineering’ rather than ‘sociotechnical’. My previous modeling experience has been filled with System Dynamics and Agent Based Modeling exercises, where much emphasis was put on establishing a good and valid model structure. In transport modeling, however, most possible model structures have been well developed; should it be O/D matrix calculation, I/O modeling, AON assignment, probit assignment, etc. The emphasis is thus on gathering as much relevant data as possible, making the data perfect to be inputted to the model, and calibrating some parameters in the model and/or the data to have a more valid result.

This data driven modeling exercise is new to me and I was quite shocked on how the result may change abruptly if different data is inputted, or if a slightly different model structure is applied, or if different model parameters are used. As the famous statistician George E.P. Box stated, “all models are wrong, but some are useful”, I had at some point questioned the usefulness of a kind of model that is really sensitive to its inputs. Consequently, I personally was afraid of deriving conclusions from such models.

Luckily enough, I had two ideas that suppressed my doubts. First, the highly data-dependent nature of the model does not necessarily reduce the usability of the model. Rather, discussion with stakeholders with regard to the modeling results yields important learning points for both sides (i.e. the stakeholders themselves and the analysts). Especially when the model’s result contradicts the stakeholders’ tacit knowledge, the discussion can become even more fruitful for this learning process. Additionally, throughout my own intellectual journey, I got in touch with Bankes’ idea on exploratory modeling (Bankes, 1993) which in my opinion can improve the usefulness of a model tremendously. Apparently, to the best of my knowledge, the number of transport modeling studies that uses the concept of exploratory modeling is still limited. Integrating these two methodological approaches is a promising idea not only for the sake of scientific advancement but also for providing better insights for real world decision-making.

### *Critique to the execution of the research*

A considerable amount of time in this study was devoted to acquiring good data, correcting the road network, and developing the supernetwork. They are indeed part of the major challenges in this research, and they have given me immeasurable experience and skills for conducting similar studies in the future. However, should more time have been available or should time can be reset to the early stage of this research, I would have spent more effort on calculating more criticality metrics, developing a better integrated visualization, and applying advanced deep uncertainty techniques to the criticality results.

*This page is intentionally left blank.*

*This page is intentionally left blank.*



## References

- Al Khaled, A., Jin, M., & Li, L. (2011). *Evaluating criticality of railway links based on freight flow network optimization*. Paper presented at the 61st Annual IIE Conference, Nevada.
- Alam, J. (2012). *Maintenance and rehabilitation needs report of 2012 - 2013 for RHD paved roads*. Retrieved from [http://www.rhd.gov.bd/RHDNews/Docs/Needs\\_Report\\_12-13.pdf](http://www.rhd.gov.bd/RHDNews/Docs/Needs_Report_12-13.pdf)
- Albert, R., Jeong, H., & Barabási, A.-L. (2000). Error and attack tolerance of complex networks. *Letters to Nature*, 406(6794), 378-382.
- An, S., Leng, J. Q., Wang, J., Li, W., & He, Y. (2015). Vulnerability of road network based on generalised travel time. *Proceedings of the Institution of Civil Engineers: Transport*, 168(5), 425-433. doi:10.1680/tran.12.00086
- Anam, S., Sohel-Uz-Zaman, A. S. M., & Anam, I. (2005). *Impact of Jamuna Multipurpose Bridge on the local economy*. Paper presented at the IABSE Conference, New Delhi.
- Awal, Z. I. (2006). *A study on inland water transport accidents in Bangladesh: experience of a decade (1995–2005)*. Paper presented at the International Conference on Coastal Ships and Inland Waterways, London.
- Bagloee, S. A., Sarvi, M., Wolshon, B., & Dixit, V. (2017). Identifying critical disruption scenarios and a global robustness index tailored to real life road networks. *Transportation Research Part E: Logistics and Transportation Review*, 98, 60-81. doi:10.1016/j.tre.2016.12.003
- Balijepalli, C., & Oppong, O. (2014). Measuring vulnerability of road network considering the extent of serviceability of critical road links in urban areas. *Journal of Transport Geography*, 39, 145-155. doi:10.1016/j.jtrangeo.2014.06.025
- Bangladesh Bureau of Statistics. (2013). District Statistics. Retrieved from <http://www.bbs.gov.bd/site/page/2888a55d-d686-4736-bad0-54b70462afda/District-Statistics>
- Bangladesh Ministry of Environment and Forests. (2009). *Climate change and inland navigation in Bangladesh: Information brief*. Retrieved from <http://cmsdata.iucn.org/downloads/navigation.pdf>
- Bangladesh Roads and Highways Department. (2017). Bridge Maintenance Management System. Retrieved from <http://www.rhd.gov.bd/BridgeDatabase/Default.asp>
- Banister, D., & Berechman, J. (2003). *Transport investment and economic development*. London: Routledge.
- Bankes, S. (1993). Exploratory modeling for policy analysis. *Operations research*, 41(3), 435-449.
- Bayes, A. (2007). *Impact assessment of Jamuna Multipurpose Bridge Project (JMBP) on poverty reduction*. Retrieved from [https://www.researchgate.net/publication/239919482\\_IMPACT\\_ASSESSMENT\\_OF\\_JAMUNA\\_MULTIPURPOSE\\_BRIDGE\\_PROJECT\\_JMBP\\_ON\\_POVERTY\\_REDUCTION](https://www.researchgate.net/publication/239919482_IMPACT_ASSESSMENT_OF_JAMUNA_MULTIPURPOSE_BRIDGE_PROJECT_JMBP_ON_POVERTY_REDUCTION)
- Berdica, K. (2002). An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy*, 9(2), 117-127. doi:10.1016/S0967-070X(02)00011-2
- Burgholzer, W., Bauer, G., Posset, M., & Jammerneegg, W. (2013). Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model. *Decision Support Systems*, 54(4), 1580-1586. doi:10.1016/j.dss.2012.05.060
- Cats, O., & Jenelius, E. (2015). Planning for the unexpected: The value of reserve capacity for public transport network robustness. *Transportation Research Part A: Policy and Practice*, 81, 47-61. doi:10.1016/j.tra.2015.02.013
- Cats, O., & Jenelius, E. (2016). Beyond a complete failure: the impact of partial capacity degradation on public transport network vulnerability. *Transportmetrica B*, 1-20. doi:10.1080/21680566.2016.1267596
- Chen, A., Yang, C., Kongsomsaksakul, S., & Lee, M. (2007). Network-based accessibility measures for vulnerability analysis of degradable transportation networks. *Networks and Spatial Economics*, 7(3), 241-256.
- Chen, B. Y., Lam, W. H. K., Sumalee, A., Li, Q., & Li, Z. C. (2012). Vulnerability analysis for large-scale and congested road networks with demand uncertainty. *Transportation Research Part A: Policy and Practice*, 46(3), 501-516. doi:10.1016/j.tra.2011.11.018
- Cox, A., Prager, F., & Rose, A. (2011). Transportation security and the role of resilience: A foundation for operational metrics. *Transport Policy*, 18(2), 307-317. doi:10.1016/j.tranpol.2010.09.004

- de Oliveira, E. L., Portugal, L. D. S., & Porto Junior, W. (2016). Indicators of reliability and vulnerability: Similarities and differences in ranking links of a complex road system. *Transportation Research Part A: Policy and Practice*, 88, 195-208. doi:10.1016/j.tra.2016.04.004
- Dehghani, M. S., Flintsch, G., & McNeil, S. (2014). Impact of road conditions and disruption uncertainties on network vulnerability. *Journal of Infrastructure Systems*, 20(3). doi:10.1061/(ASCE)IS.1943-555X.0000205
- Demirel, H., Kompil, M., & Nemry, F. (2015). A framework to analyze the vulnerability of European road networks due to Sea-Level Rise (SLR) and sea storm surges. *Transportation Research Part A: Policy and Practice*, 81, 62-76. doi:10.1016/j.tra.2015.05.002
- Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische mathematik*, 1(1), 269-271.
- Du, Q., Kishi, K., & Nakatsuji, T. (2015) Vulnerability evaluation of logistics transportation networks under seismic disasters. Vol. 2532. *Transportation Research Record* (pp. 45-55).
- El-Rashidy, R. A., & Grant-Muller, S. M. (2014). An assessment method for highway network vulnerability. *Journal of Transport Geography*, 34, 34-43. doi:10.1016/j.jtrangeo.2013.10.017
- Erath, A., Birdsall, J., Axhausen, K. W., & Hajdin, R. (2009) Vulnerability assessment methodology for Swiss road network. *Transportation Research Record* (pp. 118-126).
- Fang, Z., Shaw, S. L., Tu, W., Li, Q., & Li, Y. (2012). Spatiotemporal analysis of critical transportation links based on time geographic concepts: A case study of critical bridges in Wuhan, China. *Journal of Transport Geography*, 23, 44-59. doi:10.1016/j.jtrangeo.2012.03.018
- Guillossou, J.-N. (2007). *People's Republic of Bangladesh revival of inland water transport : options and strategies*. Retrieved from <http://documents.worldbank.org/curated/en/329261468003908999/Peoples-Republic-of-Bangladesh-revival-of-inland-water-transport-options-and-strategies>
- Guo, X. Y., & Xiong, W. T. (2014) Classification of the road network vulnerability based on fuzzy clustering method. Vol. 1030-1032. *Advanced Materials Research* (pp. 1974-1983).
- Ham, H., Kim, T. J., & Boyce, D. (2005). Assessment of economic impacts from unexpected events with an interregional commodity flow and multimodal transportation network model. *Transportation Research Part A: Policy and Practice*, 39(10), 849-860. doi:10.1016/j.tra.2005.02.006
- Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of planners*, 25(2), 73-76.
- Hayashi, Y., & Moriguchi, H. (2000). International comparison of background concept and methodology of transportation project appraisal. *Transport Policy*, 7(1), 73-88. doi:10.1016/S0967-070X(00)00015-9
- He, M. G., Jia, Y. H., & Li, H. N. (2014) Evaluation model of road network vulnerability and its genetic algorithm solution. Vol. 587-589. *Applied Mechanics and Materials* (pp. 1749-1752).
- Herman, J., Reed, P., Zeff, H., & Characklis, G. (2015). How should robustness be defined for water systems planning under change? *Journal of Water Resources Planning and Management*, 141(10), 04015012. doi:10.1061/(ASCE)WR.1943-5452.0000509
- Hernández, L. G., & Gómez, O. G. (2011). Identification of critical segments by vulnerability for freight transport on the paved road network of Mexico. *Investigaciones Geograficas*, 74, 48-57.
- Hsieh, C. H., & Feng, C. M. (2014). Road network vulnerability assessment based on fragile factor interdependencies in spatial-functional perspectives. *Environment and Planning A*, 46(3), 700-714. doi:10.1068/a4664
- Ibrahim, S., Ammar, R., Rajasekaran, S., Lownes, N., Wang, Q., & Sharma, D. (2011). *An efficient heuristic for estimating transportation network vulnerability*. Paper presented at the IEEE Symposium on Computers and Communications, Corfu.
- Jabareen, Y. (2009). Building a conceptual framework: philosophy, definitions, and procedure. *International Journal of Qualitative Methods*, 8(4), 49-62.
- Jansuwan, S., & Chen, A. (2015). Considering perception errors in network efficiency measure: an application to bridge importance ranking in degradable transportation networks. *Transportmetrica A: Transport Science*, 11(9), 793-818. doi:10.1080/23249935.2015.1087694
- Jenelius, E. (2009). Network structure and travel patterns: explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography*, 17(3), 234-244. doi:10.1016/j.jtrangeo.2008.06.002
- Jenelius, E., & Mattsson, L. G. (2015). Road network vulnerability analysis: Conceptualization, implementation and application. *Computers, Environment and Urban Systems*, 49, 136-147. doi:10.1016/j.compenvurbsys.2014.02.003

- Jenelius, E., Petersen, T., & Mattsson, L.-G. (2006). Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, 40(7), 537-560. doi:10.1016/j.tra.2005.11.003
- JICA. (2015). *Preparatory survey on western Bangladesh bridges improvement project*. Retrieved from [http://open\\_jicareport.jica.go.jp/pdf/12231759.pdf](http://open_jicareport.jica.go.jp/pdf/12231759.pdf)
- Jong, G. d., Tavasszy, L., Bates, J., Grønland, S. E., Huber, S., Kleven, O., . . . Schmorak, N. (2016). The issues in modelling freight transport at the national level. *Case Studies on Transport Policy*, 4(1), 13-21. doi:10.1016/j.cstp.2015.08.002
- Keeble, D., Owens, P. L., & Thompson, C. (1982). Regional accessibility and economic potential in the European Community. *Regional Studies*, 16(6), 419-432.
- Kermanshah, A., & Derrible, S. (2016). A geographical and multi-criteria vulnerability assessment of transportation networks against extreme earthquakes. *Reliability Engineering and System Safety*, 153, 39-49. doi:10.1016/j.ress.2016.04.007
- Kim, S., & Yeo, H. (2016). A flow-based vulnerability measure for the resilience of urban road network. *Procedia - Social and Behavioral Sciences*, 218, 13-23. doi:10.1016/j.sbspro.2016.04.006
- Kim, S., & Yeo, H. (2017). Evaluating link criticality of road network based on the concept of macroscopic fundamental diagram. *Transportmetrica A: Transport Science*, 13(2), 162-193. doi:10.1080/23249935.2016.1231231
- Knoop, V. L., Snelder, M., van Zuylen, H. J., & Hoogendoorn, S. P. (2012). Link-level vulnerability indicators for real-world networks. *Transportation Research Part A: Policy and Practice*, 46(5), 843-854. doi:10.1016/j.tra.2012.02.004
- Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, 14(3), 205-221. doi:10.1016/j.trd.2008.12.004
- Kurauchi, F., Uno, N., Sumalee, A., & Seto, Y. (2009). Network evaluation based on connectivity vulnerability *Transportation and Traffic Theory 2009* (pp. 637-649). Boston: Springer.
- Lempert, R. J. (2003). *Shaping the next one hundred years: new methods for quantitative, long-term policy analysis*. Santa Monica: Rand Corporation.
- Li, J., & Ozbay, K. (2012) Evaluation of link criticality for day-to-day degradable transportation networks. *Transportation Research Record* (pp. 117-124).
- Lin, J., & Ban, Y. (2013). Complex network topology of transportation systems. *Transport Reviews*, 33(6), 658-685. doi:10.1080/01441647.2013.848955
- Liu, M., Agarwal, J., & Blockley, D. (2016). Vulnerability of road networks. *Civil Engineering and Environmental Systems*, 33(2), 147-175. doi:10.1080/10286608.2016.1148142
- Local Government Engineering Department of Bangladesh. (2009). *Rural infrastructure improvement project RDP-25*. Retrieved from [http://www.lged.gov.bd/UploadedDocument/DigitalLibraryFileGallery/7/18/RUC%20Final%20Report\\_2009%20Zafar%20Final\\_25.05.2010.pdf](http://www.lged.gov.bd/UploadedDocument/DigitalLibraryFileGallery/7/18/RUC%20Final%20Report_2009%20Zafar%20Final_25.05.2010.pdf)
- Luathep, P., Sumalee, A., Ho, H. W., & Kurauchi, F. (2011). Large-scale road network vulnerability analysis: A sensitivity analysis based approach. *Transportation*, 38(5), 799-817. doi:10.1007/s11116-011-9350-0
- Lucas, K., van Wee, B., & Maat, K. (2016). A method to evaluate equitable accessibility: combining ethical theories and accessibility-based approaches. *Transportation*, 43(3), 473-490. doi:10.1007/s11116-015-9585-2
- Mahmud, S. M. S., Rahman, M. W., & E-Rabbi, S. H. (2007). *Transport system in Bangladesh: Issues and options for sustainable development*. Paper presented at the 1st Annual Conference on Regional Science, Dhaka.
- Maltinti, F., Melis, D., & Annunziata, F. (2012). *Methodology for vulnerability assessment of a road network*. Paper presented at the International Conference on Sustainable Design and Construction, Texas.
- Mattsson, L.-G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A: Policy and Practice*, 81, 16-34. doi:10.1016/j.tra.2015.06.002
- Monirul Qader Mirza, M. (2002). Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environmental Change*, 12(2), 127-138. doi:10.1016/S0959-3780(02)00002-X
- Moruzza, A. K., Matteo, A. D., Mallard, J. C., Milton, J. L., Nallapaneni, P. L., & Pearce, R. L. (2017). Method for ranking relative importance of structures to Virginia's roadway network. *Journal of the Transportation Research Board*, 2612, 20-28. doi:10.3141/2612-03

- Mottaleb, K. A., & Sonobe, T. (2011). An inquiry into the rapid growth of the garment industry in Bangladesh. *Economic Development and Cultural Change*, 60(1), 67-89.
- Muriel-Villegas, J. E., Alvarez-Uribe, K. C., Patiño-Rodríguez, C. E., & Villegas, J. G. (2016). Analysis of transportation networks subject to natural hazards – Insights from a Colombian case. *Reliability Engineering & System Safety*, 152, 151-165. doi:10.1016/j.res.2016.03.006
- Murray, A. T., Matisziw, T. C., & Grubestic, T. H. (2008). A methodological overview of network vulnerability analysis. *Growth and Change*, 39(4), 573-592.
- Newman, M. (2010). *Networks: an introduction*. New York: Oxford University Press Inc.
- Njenga, P., & Davis, A. (2003). Drawing the road map to rural poverty reduction. *Transport Reviews*, 23(2), 217-241.
- Nourzad, S. H. H., & Pradhan, A. (2016). Vulnerability of infrastructure systems: Macroscopic analysis of critical disruptions on road networks. *Journal of Infrastructure Systems*, 22(1). doi:10.1061/(ASCE)IS.1943-555X.0000266
- Ortuzar, J. d. D., & Willumsen, L. G. (2011). *Modelling transport*. Chichester: John Wiley & Sons.
- Östh, J., Reggiani, A., & Galiazzi, G. (2015). Spatial economic resilience and accessibility: A joint perspective. *Computers, Environment and Urban Systems*, 49, 148-159. doi:10.1016/j.compenurbsys.2014.07.007
- Ouyang, M., Pan, Z., Hong, L., & He, Y. (2015). Vulnerability analysis of complementary transportation systems with applications to railway and airline systems in China. *Reliability Engineering and System Safety*, 142, 248-257. doi:10.1016/j.res.2015.05.013
- Pant, R., Hall, J. W., Blainey, S. P., & Preston, J. M. (2015). *Assessing single point criticality of multi-modal transport networks at the national-scale*. Paper presented at the The 25th European Safety and Reliability Conference, Zurich.
- Posner, R. A. (1979). Utilitarianism, economics, and legal theory. *The Journal of Legal Studies*, 8(1), 103-140.
- Qi, W., Zhang, Z., Zheng, G., & Lin, X. (2015). Vertex importance analysis of Xiamen road transportation networks. *Journal of Information and Computational Science*, 12(10), 3927-3936. doi:10.12733/jics20105979
- Raihan, S., & Khondker, B. H. (2010). *Estimating the economic impacts of the Padma bridge in Bangladesh*. Retrieved from [https://mpra.ub.uni-muenchen.de/37904/1/MPRA\\_paper\\_37904.pdf](https://mpra.ub.uni-muenchen.de/37904/1/MPRA_paper_37904.pdf)
- Rawls, J. (2009). *A theory of justice*. Massachusetts: Harvard University Press.
- Reggiani, A., Nijkamp, P., & Lanzi, D. (2015). Transport resilience and vulnerability: The role of connectivity. *Transportation Research Part A: Policy and Practice*, 81, 4-15. doi:10.1016/j.tr.2014.12.012
- Rietveld, P. (1994). Spatial economic impacts of transport infrastructure supply. *Transportation Research Part A: Policy and Practice*, 28(4), 329-341. doi:10.1016/0965-8564(94)90007-8
- Rodríguez-Núñez, E., & García-Palomares, J. C. (2014). Measuring the vulnerability of public transport networks. *Journal of Transport Geography*, 35, 50-63. doi:10.1016/j.jtrangeo.2014.01.008
- Rozenberg, J., Garmendia, C. M. B., Lu, X., Bonzanigo, L., & Moroz, H. E. (2017). *Improving the resilience of Peru's road network to climate events*. Retrieved from <http://documents.worldbank.org/curated/en/691821490628878185/pdf/WPS8013.pdf>
- Schuchmann, G. (2010). Road network vulnerability-evaluation of measures in ranking damages and developments. *Periodica Polytechnica: Civil Engineering*, 54(1), 61-65. doi:10.3311/pp.ci.2010-1.07
- Scott, D. M., Novak, D. C., Aultman-Hall, L., & Guo, F. (2006). Network Robustness Index: A new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography*, 14(3), 215-227. doi:10.1016/j.jtrangeo.2005.10.003
- Smith, G. (2009). *Bangladesh transport policy note*. Retrieved from [http://siteresources.worldbank.org/INTSARREGTOPTRANSPORT/Resources/BD-Transport-PolicyNote\\_9June2009.pdf](http://siteresources.worldbank.org/INTSARREGTOPTRANSPORT/Resources/BD-Transport-PolicyNote_9June2009.pdf)
- Snelder, M., van Zuylen, H. J., & Immers, L. H. (2012). A framework for robustness analysis of road networks for short term variations in supply. *Transportation Research Part A: Policy and Practice*, 46(5), 828-842. doi:10.1016/j.tr.2012.02.007
- Soltani-Sobh, A., Heaslip, K., & El Houry, J. (2015). Estimation of road network reliability on resiliency: An uncertain based model. *International Journal of Disaster Risk Reduction*, 14, Part 4, 536-544. doi:10.1016/j.ijdr.2015.10.005
- Su, B., Hua, C., Lan, X., & Yang, Q. (2012). Computing the critical road section for the repair of a transportation network. *Systems Engineering Procedia*, 5, 173-178. doi:10.1016/j.sepro.2012.04.028

- Sullivan, J., Aultman-Hall, L., & Novak, D. (2009). A review of current practice in network disruption analysis and an assessment of the ability to account for isolating links in transportation networks. *Transportation Letters*, 1(4), 271-280. doi:10.3328/TL.2009.01.04.271-280
- Sullivan, J. L., Novak, D. C., Aultman-Hall, L., & Scott, D. M. (2010). Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice*, 44(5), 323-336. doi:10.1016/j.tra.2010.02.003
- Tavasszy, L., & De Jong, G. (2013). *Modelling freight transport*. Amsterdam: Elsevier.
- Taylor, M. A. P. (2004). *Critical infrastructure and transport network vulnerability: developing a method for diagnosis and assessment*. Paper presented at the Second International Symposium on Transportation Network Reliability, Queenstown.
- Taylor, M. A. P., & D'Este, G. M. (2007). Transport network vulnerability: a method for diagnosis of critical locations in transport infrastructure systems. In A. T. Murray & T. H. Grubescic (Eds.), *Critical Infrastructure: Reliability and Vulnerability* (pp. 9-30). Berlin, Heidelberg: Springer.
- Taylor, M. A. P., & Susilawati. (2012). Remoteness and accessibility in the vulnerability analysis of regional road networks. *Transportation Research Part A: Policy and Practice*, 46(5), 761-771. doi:10.1016/j.tra.2012.02.008
- Tesche, S. (2010). *Padma Multipurpose Bridge design traffic and economic study*. Retrieved from [http://www.transportationgroup.nz/Subgroups/NZMUGS/2010-Conference/Padma%20Study\\_Sylvia%20Tesche.pdf](http://www.transportationgroup.nz/Subgroups/NZMUGS/2010-Conference/Padma%20Study_Sylvia%20Tesche.pdf)
- Tu, Y., Yang, C., & Chen, X. (2013). Road network topology vulnerability analysis and application. *Proceedings of the Institution of Civil Engineers: Transport*, 166(2), 95-104. doi:10.1680/tran.10.00007
- Ukkusuri, S. V., & Yushimito, W. F. (2009). A methodology to assess the criticality of highway transportation networks. *Journal of Transportation Security*, 2(1-2), 29-46. doi:10.1007/s12198-009-0025-4
- Van Wee, B., & Roeser, S. (2013). Ethical theories and the cost-benefit analysis-based ex ante evaluation of transport policies and plans. *Transport Reviews*, 33(6), 743-760.
- Volgers, M., Nagel, G., de Jong, W., & Kluskens, R. (2016). *Inland waterway navigability improvement feasibility study: Early assessment & initial prioritization report*. Amersfoort: Royal Haskoning DHV.
- Wang, D. Z. W., Liu, H., Szeto, W. Y., & Chow, A. H. F. (2016). Identification of critical combination of vulnerable links in transportation networks – a global optimisation approach. *Transportmetrica A: Transport Science*, 12(4), 346-365. doi:10.1080/23249935.2015.1137373
- Wang, Z., Chan, A. P. C., & Li, Q. (2014). *A critical review of vulnerability of transport networks: From the perspective of complex network*. Paper presented at the 17th International Symposium on Advancement of Construction Management and Real Estate, Shenzhen.
- Wang, Z., Chan, A. P. C., Yuan, J., Xia, B., Skitmore, M., & Li, Q. (2014). Recent advances in modeling the vulnerability of transportation networks. *Journal of Infrastructure Systems*, 21(2), 06014002.
- Wardrop, J. G. (1952). *Some theoretical aspects of road traffic research*. Paper presented at the Institution of Civil Engineers Meeting Part II.
- Xi, S. E. (2013) Evaluation of nodes importance in of highway transportation hubs planning based on fuzzy-AHP. Vol. 253-255. *Applied Mechanics and Materials* (pp. 1181-1187).
- Yang, C., Tu, Y., & Chen, X. (2009). *Analysis method for topology vulnerability of transportation network*. Paper presented at the 2nd International Conference on Transportation Engineering, Chengdu.
- Yin, H. Y., & Xu, L. Q. (2010). Measuring the structural vulnerability of road network: A network efficiency perspective. *Journal of Shanghai Jiaotong University (Science)*, 15(6), 736-742. doi:10.1007/s12204-010-1078-z
- Zhang, X., Adamatzky, A., Yang, H., Mahadaven, S., Yang, X.-S., Wang, Q., & Deng, Y. (2014). A bio-inspired algorithm for identification of critical components in the transportation networks. *Applied Mathematics and Computation*, 248, 18-27. doi:10.1016/j.amc.2014.09.055
- Zhou, Y., Fang, Z., Thill, J. C., Li, Q., & Li, Y. (2015). Functionally critical locations in an urban transportation network: Identification and space-time analysis using taxi trajectories. *Computers, Environment and Urban Systems*, 52, 34-47. doi:10.1016/j.compenvurbsys.2015.03.001

*This page is intentionally left blank.*

## Appendix A : Software Packages Used

The codes of the transport model, metrics calculation, analyses, and visualization were completely developed in 32-bit Python version 2.7.12. Python is an open source, high-level programming language that has a user-friendly interface for general purpose programming. Various main open source libraries within Python used in this study are enlisted in the table below. On top of these general packages, a specially tailored transport network criticality library has been developed as well. This library can be found at <https://github.com/bramkaarga/transcrit>.

*Table 18 Python libraries utilized in this study*

<b>Library/Package</b>	<b>Description</b>	<b>Version</b>
Pandas	General data structure and data analysis tools	0.19.2
Numpy	General scientific computing package	1.11.1
Geopandas	Geospatial data operations and visualizations	0.2.1
Matplotlib	General data visualization and plotting library	2.0.0
Shapely	Manipulation, operation, and analysis of geometric objects	1.5.17
Networkx	Manipulation, operation, and analysis of complex graph/network	2.0.dev2017213220538
OSMNX	Retrieval, analysis, and visualization of transport network especially from OpenStreetMap	0.3
EMA Workbench	Execution of exploratory modeling approach	0.9.2
Scipy	Specific scientific computing package for STEM domains	0.18.1
Seaborn	High-level interface visualization purpose built on top of Matplotlib	0.7.1
Scikit-learn	General machine learning package	0.17.1
Rasterstats	Operations of geospatial raster datasets	0.12.0

## Appendix B : Socioeconomic Figures Geovisualization

The figures of the socioeconomic data used in the O/D matrix calculation are geospatially visualized in the following maps. The bolder the blue color, the higher the number for that particular district is. As can be seen, several commodities such as garment, steel, textile, and sugar are highly concentrated in a small number of districts. Furthermore, an interesting pattern from observing this figure is that foods related commodities (except rice) are mainly produced in the northern and the western districts while high population density can be seen in the eastern districts. Therefore, crossing the Brahmaputra, Padma and Meghna river is inevitable to distribute these foods properly.

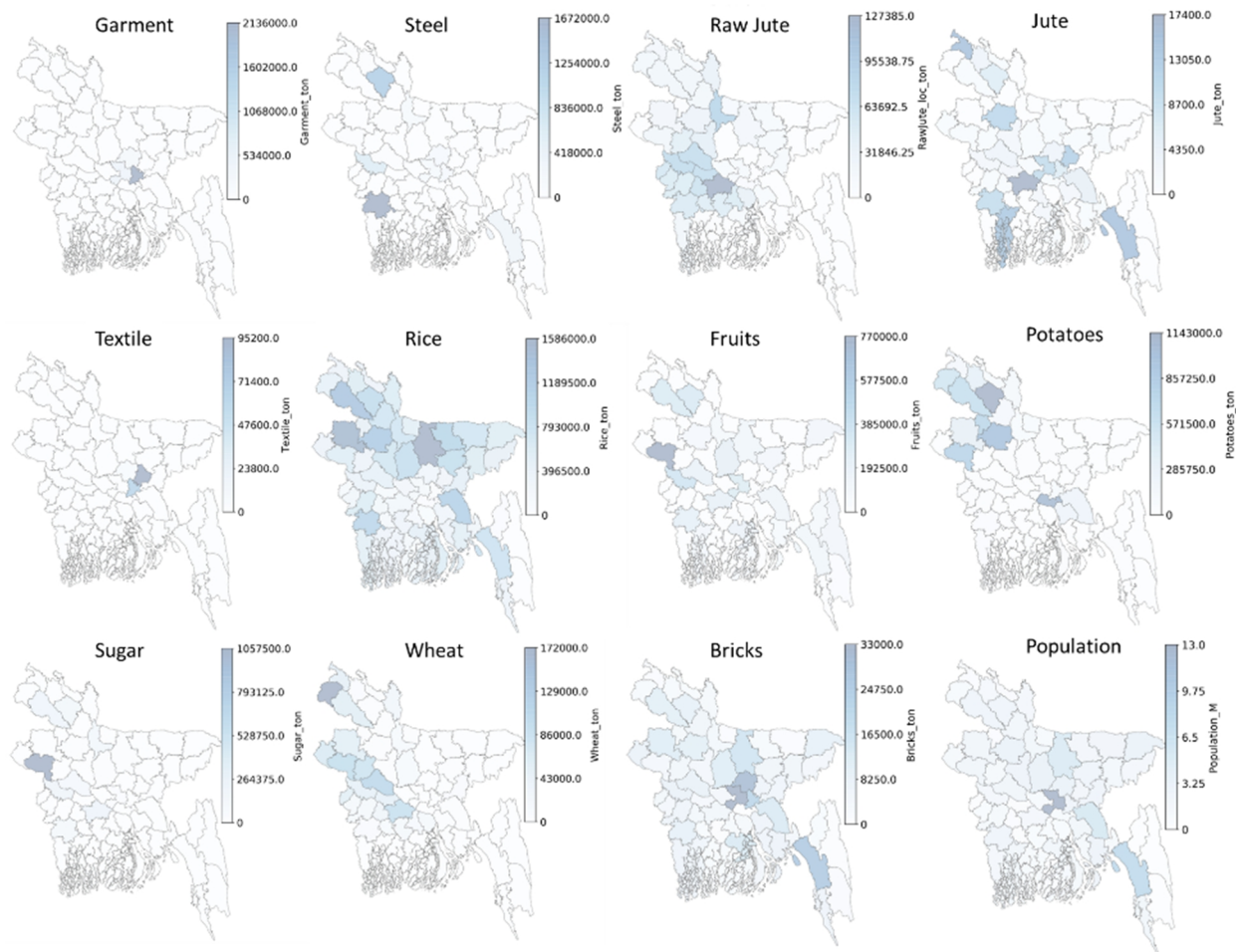


Figure 48 Socioeconomic figures distribution of key factors



# Appendix C : Mathematical Formulation of Criticality Metrics

Mathematical formulations of criticality metrics used in this study are presented in this appendix. First, all mathematical notations involved are described. Afterward, metrics formulation for each category (M1 to M10) is presented.

## Mathematical notations

Below are the mathematical notations used in this study:

$A_i^{ud}$	: Unweighted daily accessibility of node i
$A_i$	: Weighted accessibility of node i.
$AL_e$	: Number of alternative links if link e is disrupted that are still within specified distance from link e. Buffer threshold of 20km is used in this study.
$C_e$	: Capacity of link e.
$C_{ij}$	: Cost between node i and j
$E(G)$	: Efficiency of network G.
$L$	: Total length of the transport network
$l_e$	: Length of link e
$N_c$	: Number of centroids in the study.
$N_E$	: Number of links in the network.
$N_N$	: Number of nodes in the network.
$N_{OD}$	: Number of OD (origin-destination) pairs
$N_i^d$	: Number of nodes accessible from node i on daily basis
$N_i^{(e)}$	: Number of shortest paths from node i that are disrupted due to removal of link e
$ODC_{ij}$	: Number of distinct paths between node i and j within acceptable travel distance. Travel distance threshold of 50km is used in this study.
$T_{ij}$	: Volume of traffic flow from node i to node j.
$T_i$	: Volume of traffic flow going into and out of node i.
$T_e$	: Volume of traffic flow on link e.
$UE(exp)_i$	: Expected user exposure of node i.
$UE(worst)_i$	: Worst user exposure of node i.
$\theta_{ij}$	: Daily accessibility indicator. 1 if node i and j can be traversed within daily travel distance threshold, 0 otherwise. Due to computation cost limitation, daily accessibility threshold of 30km is used in this study.
$\sigma_{ije}$	: Shortest path indicator. 1 if shortest path between nodes i and j passes link e, 0 otherwise.
$\tau_{ije}$	: Cut set indicator. 1 if link e appears in cut set between OD (origin-destination) pair i and j, 0 otherwise.

Lastly, superscript '(e)' is used to indicate the value of the associated mathematical notation when link e is disrupted

### Category M1

1. Change in unweighted daily accessibility.

$$M1^{01} = \frac{\sum_{i \in OD} A_i^{ud}}{\sum_{i \in OD} A_i^{ud(e)}} \quad (Eq 7)$$

where

$$A_i^{ud} = \sum_j \frac{1}{(C_{ij})^\beta} * \theta_{ij} \quad (Eq 8)$$

2. Change in the number of nodes accessible within daily reach.

$$M1^{02} = \frac{\sum_{i \in OD} N_i^d}{\sum_{i \in OD} N_i^{d(e)}} \quad (Eq 9)$$

where

$$N_i^d = \sum_j \theta_{ij} \quad (Eq 10)$$

### Category M2

1. Change in unweighted total travel cost.

$$M2^{01} = \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} C_{ij}^{(e)}}{\sum_{i \in OD} \sum_{j \in OD, j \neq i} C_{ij}} \quad (Eq 11)$$

2. Change in network average efficiency

$$M2^{02} = \frac{E(G) - E(G)^{(e)}}{E(G)} \quad (Eq 12)$$

where

$$E(G) = \frac{2}{N_N(N_N - 1)} \sum_{i \in OD} \sum_{j \in OD, j \neq i} \frac{1}{C_{ij}} \quad (Eq 13)$$

### Category M3

1. Unweighted link betweenness centrality

$$M3^{01} = \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} \sigma_{ije}}{N_{OD}} \quad (Eq 14)$$

2. Change in unweighted total travel cost for region  $R_i$  where link  $i$  belongs.

$$M3^{02} = \frac{\sum_{i \in OD} \sum_{j \in R, j \neq i} C_{ij}^{(e)}}{\sum_{i \in OD} \sum_{j \in R, j \neq i} C_{ij}} \quad (Eq 15)$$

#### **Category M4**

1. Minimum link cut centrality

$$M4^{01} = \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} \tau_{ije}}{N_{OD}} \quad (Eq 16)$$

2. OD k-connectivity

$$M4^{02} = 1 - \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} C_{ij}^{(e)}}{\sum_{i \in OD} \sum_{j \in OD, j \neq i} C_{ij}} \quad (Eq 17)$$

#### **Category M5**

1. Number of alternative links

$$M5^{01} = 1/AL_e \quad (Eq 18)$$

Figure 49 illustrates the calculation of local alternative links. Suppose that the red link in the middle is the link of interest and the brown links are other links located nearby the link of interests. First, a buffer zone of 30km is created (the blue tube). M05\_01 considers all links which one of ending points located within the blue tube. From the illustration, link (i), (ii) and (iv) are considered as alternative links because at least one of their ending points are located within the buffer area. Link (iii), although intersecting with the buffer area, is not considered as an alternative link because none of its ending points is located within the buffer area.

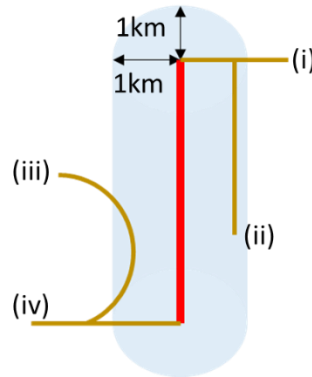


Figure 49 Illustration of number of alternative links

If a segment has no alternative links, the criticality value for that segment is considered as 2.

#### **Category M6**

1. Change in weighted accessibility

$$M6^{01} = \frac{\sum_{i \in OD} A_i}{\sum_{i \in OD} A_i^{(e)}} \quad (Eq 19)$$

where

$$A_i = \sum_{j \in OD, j \neq i} \frac{T_i * T_j}{(C_{ij})^\beta} \quad (Eq 20)$$

### **Category M7**

1. Change in weighted total travel cost

$$M7^{01} = \frac{\sum_{i \in OD} \sum_{j \in R, j \neq i} T_{ij} * C_{ij}^{(e)}}{\sum_{i \in OD} \sum_{j \in R, j \neq i} T_{ij} * C_{ij}} \quad (Eq 21)$$

2. Change in average expected user exposure

$$M7^{02} = \frac{\sum_{i \in OD} UE(exp)_i^{(e)}}{N_c} \quad (Eq 22)$$

where

$$UE(exp)_i^{(e)} = \frac{\sum_{j \in OD, j \neq i} T_{ij} * (C_{ij}^{(e)} - C_{ij})}{N_i^{(e)}} \quad (Eq 23)$$

3. Change in worst-case user exposure.

$$M7^{03} = \frac{\sum_{i \in OD} UE(worst)_i^{(e)}}{N_c} \quad (Eq 24)$$

where

$$UE(worst)_i^{(e)} = \max(T_{ij} * (C_{ij}^{(e)} - C_{ij})) \text{ for } j \in OD, j \neq i \quad (Eq 25)$$

### **Category M8**

1. Empirical traffic flow

The traffic flow is indicated by the empirical trucks average annual daily traffic (AADT) data on each link obtained from RMMS database.

2. Weighted link betweenness centrality

$$M8^{02} = \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} T_{ij} * \sigma_{ije}}{\sum_{i \in OD} \sum_{j \in OD, j \neq i} T_{ij}} \quad (Eq 26)$$

3. Volume over capacity

$$M8^{03} = \frac{T_e}{C_e} \quad (\text{Eq 27})$$

**Category M9**

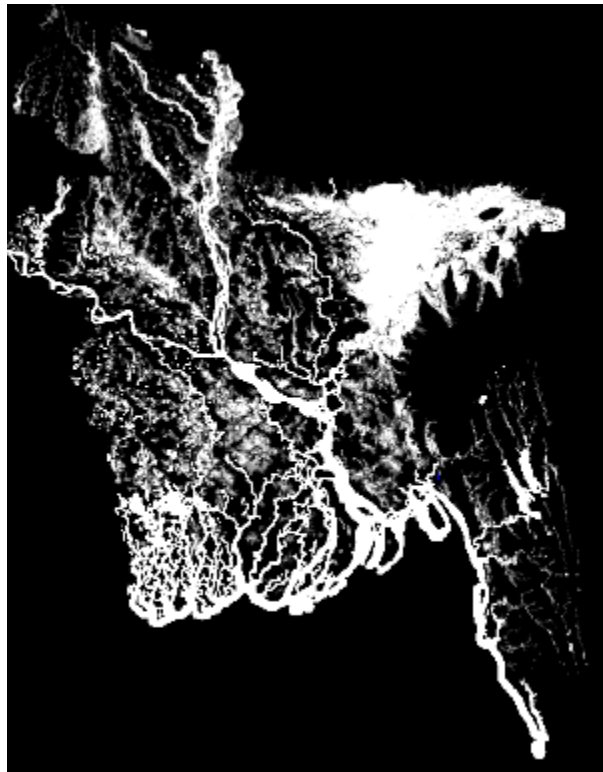
1. Unsatisfied demand

$$M9^{01} = \frac{\sum_{i \in OD} \sum_{j \in OD, j \neq i} T_{ij} - T_{ij}^{(e)}}{\sum_{i \in OD} \sum_{j \in OD, j \neq i} T_{ij}} \quad (\text{Eq 28})$$

**Category M10**

1. Exposure to natural disaster

The natural disaster considered here is the probability of flooding in each road segment. A fluvial (riverine) defended 1 in 75 (1.3%) flood map is used as the input data to calculate flooding probability (see Figure 50). The flood map comes in TIFF format (Tagged Image File Format), a filetype which is commonly used to store raster graphics. Raster statistics are then applied by overlapping the flood map with the supernetwork. However, as the supernetwork comes in LineString datatype, a buffer of 500m is applied to transform the supernetwork into Polygon datatype. This allows application of raster statistics from the flood map to the supernetwork.



*Figure 50 1 in 75 Fluvial defended flood map of Bangladesh*

# Appendix D : Metrics Density Overlaps

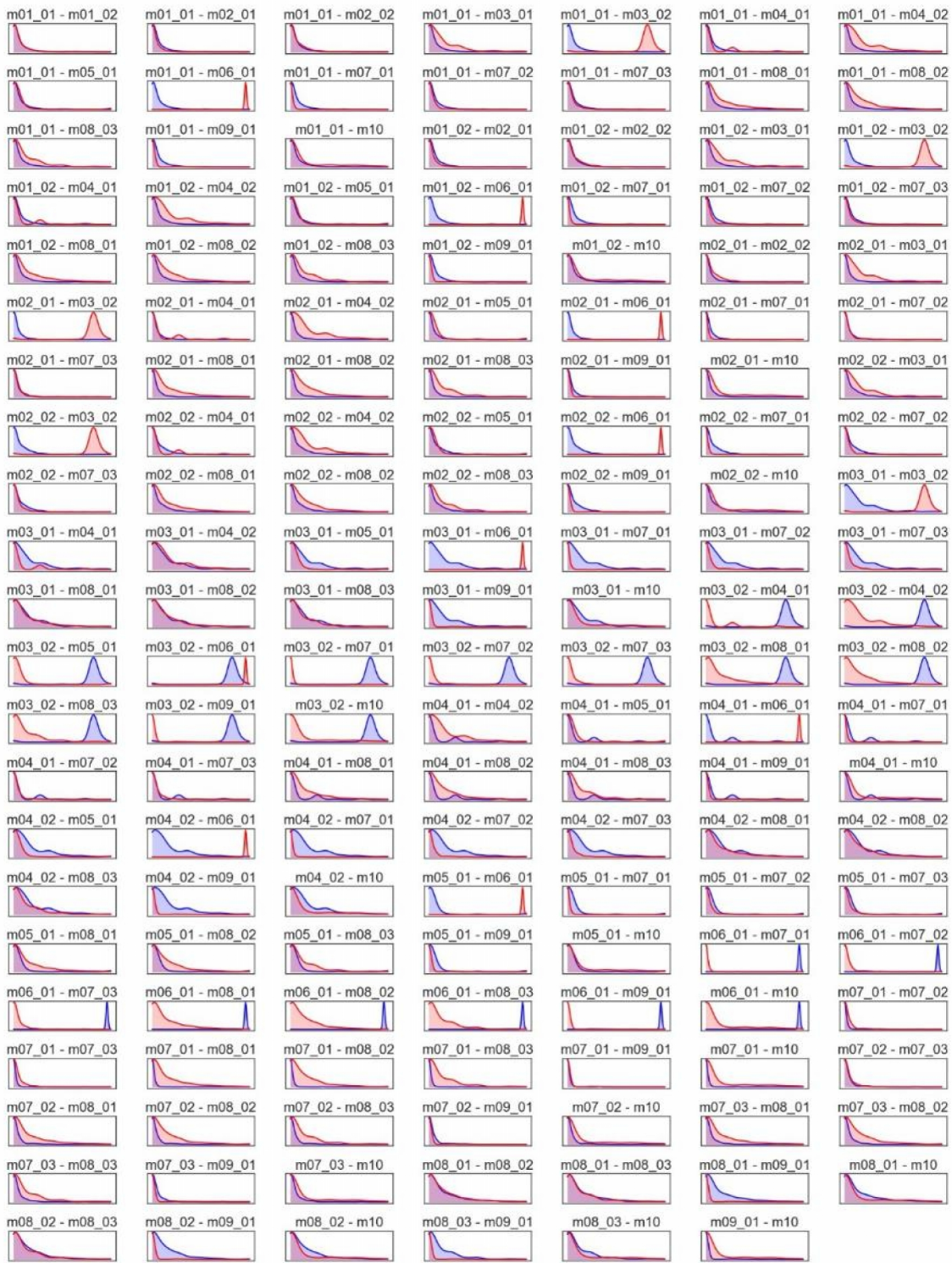


Figure 51 Density overlap for all metrics



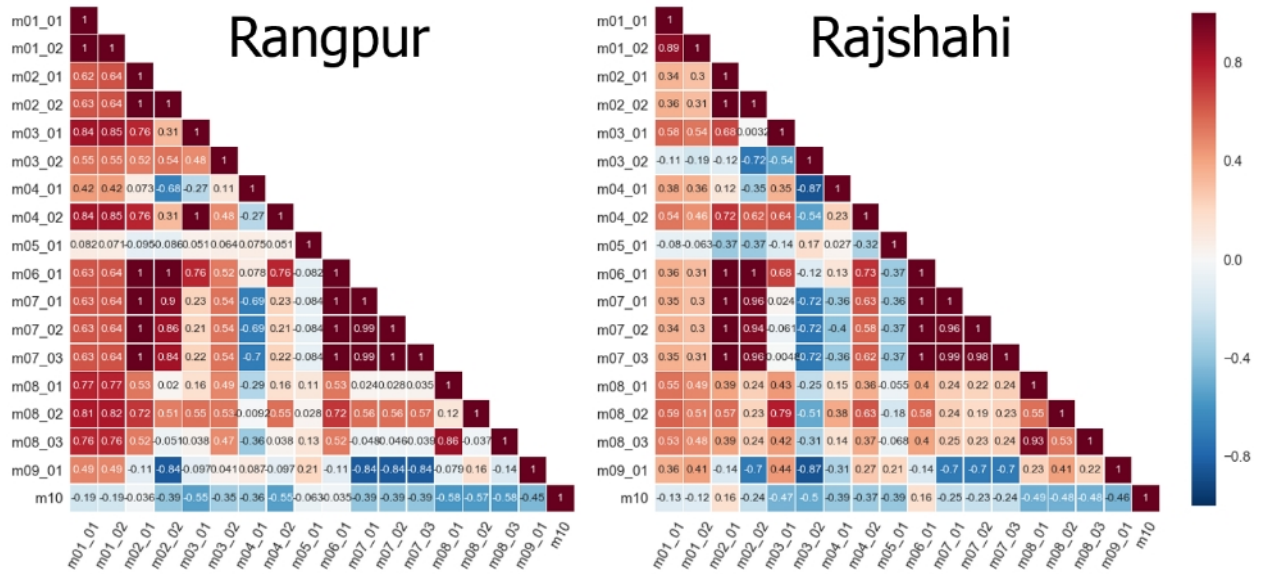


Figure 54 Spearman-rank correlation heatmap for subnetworks (3)

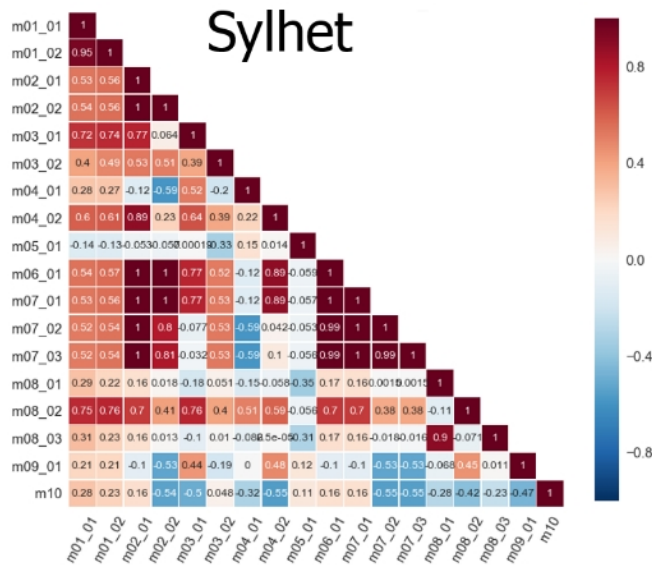


Figure 55 Spearman-rank correlation heatmap for subnetworks (4)



## Appendix F : Summary of the Metrics Choice Sets

In this appendix, all the metrics choice sets presented in Section 6.2. are summarized in tables. There are three tables as displayed in the following pages. The metrics choice sets are summarized from three viewpoints: their technical aspects, the conceptual criticality aspects they represent, and the metrics category they represent.

Table 19 compares the technical aspect of each metrics set in terms of the data requirements and the computation cost. The data requirements for a metrics set may be compulsory or optional. Some data become optional because some metrics sets give flexibility to the practitioners to select among several possible metrics, which may relax the data requirements. Therefore, this table is to be consulted altogether with the data requirements of each metric presented in Table 15. The computation cost is ranked between one to six, with one being the lowest computation cost. The computation cost is derived from the individual computation cost of each metric in the metrics set.

In Table 20, the conceptual criticality factors combinations (combinations of the underlying paradigm factor and the functionality factor) represented by each metrics set are summarized. Since there are two possibilities from the underlying paradigm factor (user equality or total performance) and three possibilities from the functionality factor (accessibility, total travel cost, or connectivity), there are six combinations of criticality factors on a conceptual level. The yellow color on the table means that only either one of the criticality aspects can be represented by the metrics set, since the corresponding metrics set itself entails a selection between several metrics. For instance, if metrics set A1-01 is used, only either user equality – accessibility or total performance – accessibility aspects are represented. The green color indicates that the combination of criticality aspects is definitely represented by the metrics set. As an example, metrics set A3-01, A3-02, and A3-03 represent all six combinations of criticality aspects.

Rather than seeing only from the conceptual level, it is empirically found from the case study that the aggregation factor (network-wide or localized) also influences the criticality outcomes. A permutation of the three factors results in ten combinations of these factors, which are basically the ten metrics categories enumeration from M1 to M10 as discussed in 3.3.4. Therefore, as an addition to the previous table, it is also interesting to see which metric categories are represented by each metrics set. This information is displayed in Table 21.

The three tables complement the informed criticality metrics selection method described in Section 6.2. Along with the nested decision tree in that section, these three tables can help practitioners in assessing whether the metrics set of interest suits the data availability and the policy question that they want to address by conducting a criticality analysis.

Table 19 Metrics sets technical aspects summary

Metrics Set Code	Data Requirements					Computation Cost (1 = very low, 6 = very high)
	Transport Network	Average daily travel distance	Economic production and attraction factors	Administrative boundaries	Natural hazard map	
A1-01	Required	Optional	Optional			2
A1-02	Required	Required	Optional			3
A1-03	Required		Optional			2
A1-04	Required		Optional	Required		5
A1-05	Required				Required	2
A1-06	Required		Required		Required	3
A2-01	Required	Optional				2
A2-02	Required	Required				3
A2-03	Required					2
A2-04	Required			Required		3
A2-05	Required					1
A2-06	Required					2
A3-01	Required	Required	Required		Required	3
A3-02	Required	Required	Required		Required	4
A3-03	Required	Required	Required	Required	Required	6
A4-01	Required	Required				3
A4-02	Required	Required				4
A4-03	Required	Required	Required			5

Table 20 Criticality aspects conceptual level representation of metrics sets summary

Metrics Set Code	Criticality Aspects on Conceptual Level					
	User equality - Accessibility	User equality - Total travel cost	User equality - Connectivity	Total performance - Accessibility	Total performance - Total travel cost	Total performance - Connectivity
A1-01	Yellow			Yellow		
A1-02	Green			Green		
A1-03		Green			Green	
A1-04		Green			Green	
A1-05			Green			Green
A1-06			Green			Green
A2-01	Yellow			Yellow		
A2-02	Green			Green		
A2-03		Green				
A2-04		Green				
A2-05			Green			
A2-06			Green			
A3-01	Green	Green	Green	Green	Green	Green
A3-02	Green	Green	Green	Green	Green	Green
A3-03	Green	Green	Green	Green	Green	Green
A4-01	Green	Green	Green	Green	Green	
A4-02	Green	Green	Green	Green	Green	
A4-03	Green	Green	Green	Green	Green	

Table 21 Criticality aspects representation of metrics sets summary

Metrics Set Code	Metric Categories									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
A1-01	Yellow					Yellow				
A1-02	Green					Green				
A1-03		Green					Green			
A1-04		Green	Green				Green	Green		
A1-05				Green	Green					Green
A1-06				Green	Green				Green	Green
A2-01	Yellow					Yellow				
A2-02	Green					Green				
A2-03		Green					Green			
A2-04		Green	Green				Green	Green		
A2-05				Green	Green					
A2-06				Green	Green					
A3-01	Green	Green		Green		Green	Green			Green
A3-02	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
A3-03	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
A4-01	Green	Green		Green		Green	Green			
A4-02	Green	Green	Green	Green	Green	Green	Green			
A4-03	Green	Green	Green	Green	Green	Green	Green			