Optimal Routing of Multi-Modal Wide Energy and Infrastructure Corridors

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Optimal Routing of Multi-Modal Wide Energy and Infrastructure Corridors

by

Mehdi Salamati

A THESIS
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Abstract

A multi-modal corridor is intended to accommodate multiple modes of energy and transportation infrastructure within the same right-of-way. The existing literature on corridor routing often focuses on one mode with no consideration to the width of a corridor. In particular, most of the existing routing methods assume that least-cost-paths are purely linear with zero widths. This is not a realistic assumption if multiple infrastructure modes are to co-exist within the same right-of-way. Even newer routing methods that consider the width of paths, can not take multi-modality of or mode arrangement within a corridor into account. Integrating multi-criteria analysis and GIS techniques is a well-known method for finding least-cost-paths. In this thesis, using the well-known multi-criteria analysis and Geographical Information System (GIS) techniques, a multi-modal wide corridor routing method is proposed. In this method, a multi-directed graph is defined in which the weight of each of the edges is calculated using different layers of cost data based on the direction of that edge and the desired width of the corridor and the arrangement of its modes. In addition, an important factor in routing a corridor is consideration for future plans. In this thesis, the importance of considering the locations of renewable energy sites nearby a corridor in its routing process is investigated. Moreover, a method is proposed for aligning a multi-modal corridor and its powerline branches to renewable energy sites with the minimum cost. The numerical results show the effectiveness of the proposed method compared to other applicable methods in routing of both multi-modal and single-modal, wide corridors. Furthermore, through a numerical experiment, it is shown how the proposed method can help find opportunities for cost reduction by considering the locations of renewable energy sites in the corridor routing process.
Acknowledgements

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5.9 The flow chart of the CST method

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# List of Symbols, Abbreviations and Nomenclature

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<td>Analytic Hierarchy Process</td>
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<td>CAES</td>
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<td>CC</td>
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<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>FLSG</td>
<td>Finding Least cost path for a Single mode and Generalizing to other modes</td>
</tr>
<tr>
<td>FWLA</td>
<td>Finding a Wide LCP on the Accumulated Cost raster</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gases</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GNWT</td>
<td>Government of Northwest Territories</td>
</tr>
<tr>
<td>INSTC</td>
<td>International North-South Transport Corridor</td>
</tr>
<tr>
<td>JP</td>
<td>Junction Point</td>
</tr>
<tr>
<td>LAPSSET</td>
<td>Lamu Port-South Sudan-Ethiopia-Transportation</td>
</tr>
<tr>
<td>LCP</td>
<td>Least-Cost-Path</td>
</tr>
<tr>
<td>LSO</td>
<td>Lost Saving Opportunity</td>
</tr>
<tr>
<td>MADA</td>
<td>Multi-Attribute Decision Analysis</td>
</tr>
<tr>
<td>MCDA</td>
<td>Multi-Criteria Decision Analysis</td>
</tr>
<tr>
<td>MDTG</td>
<td>Multi-Directed Transformed Graph</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>NADC</td>
<td>Northern Alberta Development Council</td>
</tr>
<tr>
<td>OBOR</td>
<td>One Belt One Road initiative</td>
</tr>
<tr>
<td>PSH</td>
<td>Pumped Storage Hydropowers</td>
</tr>
<tr>
<td>ROW</td>
<td>Right-OF-Way</td>
</tr>
<tr>
<td>SAMC</td>
<td>Shared Area of Multiple Corridors</td>
</tr>
<tr>
<td>SAW</td>
<td>Simple Additive Weighting</td>
</tr>
<tr>
<td>SGP</td>
<td>Slave Geological Province</td>
</tr>
<tr>
<td>STC</td>
<td>Substation To Corridor</td>
</tr>
<tr>
<td>TC</td>
<td>Total Cost</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Technique for Order of Preference by Similarity to Ideal Solution</td>
</tr>
<tr>
<td>TUC</td>
<td>Transportation and Utility Corridor</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>WECC</td>
<td>Western Electricity Coordinating Council</td>
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</tbody>
</table>
Chapter 1

Introduction

1.1 Background and Importance of the Research

In an article published in the Right of Way magazine, corridor is defined as “a long, narrow strip of land or real property rights for which the highest and best use is to provide an economic or social benefit by connecting the end points, and sometimes serving intermediate points along the way” [3]. Moving from the right-of-way context to the transportation context, a transportation corridor could be defined as “a route along which trade travels. It is based on geography and traffic flows comprising the links, nodes, and transfer points, which serve outbound and inbound movements.” [4]. Countries use the development of their transportation corridor as a means of enhancing their regional integration and expanding their economy. Generally, International communities help countries to invest in their large infrastructure transportation projects to create economical and social advantages [5]. Economical and social goals are not the only reasons behind these investments. Geopolitical goals such as strengthening national sovereignty in remote areas, and enhancing the quality of life for the populations living in those areas are among other potential purposes.

Canada is a vast country with specific geographical and economical conditions. The country’s economy heavily relies on trade and 53% of the country’s gross domestic product was gained by Canadian goods trade in 2016. Geographically, Canada is the second largest country in the world and the northern parts of the country are full of resources and opportunities but with a very low population density [6]. Making life easier for the northern and indigenous people, also connecting the northern resourceful lands to the southern part and tidewaters make the development of transportation corridors a crucial task for Canadian policy makers.

While there are some national single-mode transportation projects connecting Canada from coast to coast in southern regions such as Canadian National Railway, Canadian Pacific Railway
and Trans-Canada Highway, there is no nation-wide corridor in the northern and near northern parts. The idea of a National corridor which connects Canada northern regions from coast to coast was first presented by Mr. Richard Rohmer in late 1960s. This idea was not supported by the federal government possibly due to its complexity, scale and also insufficient potential economic benefit at that time. After about half a century, the idea of Canadian Northern Corridor was raised again by Mr. Andrei Sulzenko and Mr. Garret Kent Fellows in 2016 [6] and [7].

The Canadian Northern Corridor presented by [7] is assumed to accommodate various transportation modes such as road, railway, pipeline and power transmission line. This multi-modality makes it technically complex and complicated. While routing of narrow corridors has been studied very well, there are few papers studying the routing of a wide corridor. The lack of literature is even more noticeable for routing of a wide and multi-modal corridor.

Routing a corridor is a decisive step in its planning. Choosing a path for a corridor has significant influence on its financial, social and environmental impacts. Finding an optimal path, wide enough to be able to accommodate and be acceptable for all different modes is a complicated and vital task. While an optimal route can minimize the cost of a corridor as well as its environmental impacts, a path which does not consider different modes’ movement constraints when moving together, has the potential to make the corridor costly infeasible.

It is worth mentioning that in this thesis and some other papers, the phrase “multi-modal transportation corridor” simply means a transportation corridor that contains two or more parallel transportation modes, whereas, other papers have used the phrase in a different context. For example, the “international multi-modal transportation” in the article 1 of the “United Nations Conference on a Convention on International Multimodal Transport” is so explained: “The carriage of goods by at least two different modes of transport on the basis of a multi-modal transport contract from a place in one country at which the goods are taken in charge by the multi-modal transport operator to a place designated for delivery situated in a different country ” [8]. Multiple expressions have been used so far to refer to the concept of placing several transportation modes in a same corridor.
Multi-use right-of-way, integrated service corridor, sharing of right-of-way, energy corridor, multiple occupancy of right-of-way, multi-purpose corridor, joint-use corridor, multiple-use corridor, joint acquisition of rights-of-way, common corridor and multi-modal transportation corridor are known expressions for a right-of-way shared among two or more transportation modes such as road, railway, pipeline, and power transmission line [9], [10], [11].

Population and technology growth as well as discovery of various natural resources, have increased demands for utility accommodation and transportation facilities during the past decades. As a result, the cost of buying right-of-way for these infrastructures has been increasing. Besides, the crowded right-of-ways for different facilities and their growing needs for expansion and further developments have made their management, detection and relocating very complex and costly. In order to answer these difficulties several methods have been developed such as trenching, joint utility trenching, and utility corridors. The effort to find better solutions for transportation and utility right-of-way is not limited to urban areas. Although attempts to locate power transmission lines in the right-of-ways of US federal-aid highways date back to 1916, comprehensive studies about joint-use of right-of-way for different transportation modes started in late 1960s and 1970s [12].

1.2 Research Objectives

This thesis has three main objectives. The first objective is to review engineering challenges, particularly the routing ones, related to the Canadian Northern Corridor. In this context, the optimal arrangement of different modes within the corridor will be suggested and discussed. Main criteria influencing the Least-Cost-Path (LCP) for each mode are also investigated. Moreover, compatibility of different transportation modes located in a relatively narrow path and reliability and safety issues are discussed and some important Canadian and US standards regarding the compatibility issues are introduced. The potential benefits of using a same right-of-way for different modes over some individual paths are identified as well.
The second objective is to propose a new routing method which is able to take into account both the width of the corridor and the multi-modality of it. A multi-modal corridor has two characteristics that makes its routing different from finding a simple least-cost-path. Firstly, it needs to be wide enough to be able to accommodate all modes. Secondly, the modes within the corridor have a certain arrangement that needs to be maintained in the routing process. To achieve this objective, firstly, the challenges of the existing methods for routing multi-modal corridors are investigated. Then, a new method is proposed to overcome them.

The third objective is to propose a method that considers the locations of renewable energy sites in the routing process to minimize the total cost. The total cost is the cost of the multi-modal corridor itself plus the cost of a powerline branch from the corridor to one of the interconnected substations located at the renewable energy sites.

1.3 Research Challenges

The challenges of this research are divided into the two following main categories. Firstly, the issues regarding routing of multi-modal corridors and secondly, challenges related to its feasibility. In the domain of corridor routing research, some subjects have been extensively studied whereas, issues such as multi-modality and width of a path have not been adequately addressed. Most of the literature in the areas of concept and feasibility are not new; nor do they offer any solutions to routing problems.

For the routing challenges, issues such as weighting of suitability criteria, algorithms to find shortest path, and finding alternative paths are widely studied, while little attention has been paid to the width of paths[13]. Most of the routing studies seem to have assumed the routes as purely linear. Furthermore, methods such as [1], and [2] that have so far been devised to find a wide path do not take into account multi-modality. In general, compatibility of different modes in a same right-of-way and routing of multi-modal corridors are among the most important technical challenges. While the former issue has been studied well in many research or guidelines such
as [14], [15], [16], [17], the routing problems have not been given enough consideration. In this thesis, the routing challenges are reviewed in detail in Chapter 3 and new routing methods, taking the multi-modality and width of corridors into consideration, are suggested in Chapter 4. It also presents a new perspective on some particular challenges such as lateral arrangement of modes in corridors and suggests a general parallel arrangement.

Most of the studies about the concept, potential benefits and challenges and in general, the feasibility of multi-modal corridors are not novel; some were published in 1970s and 1980s including [11], [9] and [18]. These reports discuss different aspects of multi-modality and they are not limited to only technical challenges. Their goals are mostly not suggesting solutions for specific issues, but mainly to identify them. In Chapter 2, some reports and literature related to the particular planned or built multi-modal projects such as [19] or [20] or [10], [21] are reviewed. These reports discuss the constraints regarding compatibility or routing issues but they do not suggest any methods to solve them. They only introduce their proposed routes or in the case of [20] criticize the previous suggestions.

1.3.1 Early Studies On Joint-Use

“Combined transportation corridor” presented by Joseph D. George in convention of road and transportation of Canada 1971 [22] is one of the earliest papers on the issue. He defines combined transportation corridor as road allowance used for two or more transportation systems. He considered utilities such as gas and electricity as transportation systems. He stated that combined corridor can be beneficial both inside and outside of urban areas to connect communities. This paper emphasizes on the necessity and potential benefits of multi-purpose corridors and its main idea is to use right-of-way of roads, especially ring roads, to accommodate utilities like water, electricity and gas. Although it highlights the need for a wider path for multi-modal corridors, it does not investigate the optimality of the route for all different modes. Issues related to the safety and reliability of multi-modal corridors are not discussed in this work as well.

Another major study performed in Canada is Athabasca oil sand study with eight volumes of
report investigating many aspects of a multi-purpose corridor which connects Athabasca oil sand region to Edmonton. This study states “A Transportation Corridor can be defined as a continuous strip of land of varying width, connecting two or more facilities for the conveyance of people, energy and/or materials” [10], [23]. Different considerations and controlling factors affecting the optimal route for each mode are mentioned in the study. However, the route selection does not seem to be based on a composite criteria map. Nor does it use computerised and optimal algorithms. The design team, however, took into consideration some controlling factors such as land use, water bodies, and already existing modes for determination of possible alternative routes.

Advantages, disadvantages and challenges of the concept of transportation and utility corridor have been studied in a master thesis in the University of British Columbia [18]. Klassen pointed to the difficulties of routing a multi-modal corridor and categorized the existing methods for determining the location and width of the corridor into three groups. First, using the existing right-of-way such as road or railway to accommodate other facilities. The second technique which is primarily suitable for urban areas, is setting additional lands beside the road grids of these zones. The third method determines unsuitable areas for corridor crossing and suggests the remaining areas as potential locations for the route. The need and benefits of a national transportation and utility corridor over federal lands in the United States was studied at the request of the Congress by the Department of Interior, Bureau of Land Management in 1975[11]. Both [18] and [11] list the problems and considerations of a joint-use corridor but neither offers a solution for routing.

The concept of multi-purpose-corridors with its pros and cons has always been a discussion topic for transportation experts and policy makers. An example is, Utility-transportation corridor study of Montana, published in 1981 [9]. In this study, three approaches for designating corridors are discussed namely, direct, indirect and mixed approaches. Generally, these approaches are based on classifying lands into three groups on a case by case basis: avoidance lands, suitable lands and unclassified lands. These are not computerized methods using optimization algorithms to find the best route for a corridor. Another report provided for the Northern Alberta development council,
investigated the economic, social, and environmental impacts of a multi-purpose corridor from Fort McMurray to Peace River in 2014. This report reviewed prior studies proposing a route for the corridor. According to this study, little considerations had been paid at the time to multi-modality of the corridor. Offering a solution, however, was not among the objectives of the study.

1.3.2 The Canadian Northern Corridor

The necessity of developing a corridor in mid-Canada for the country’s prosperity is not a new topic. In early 1967, Richard Rohmer brought up this idea and emphasized on the effects of mid-Canada development on the country’s future. Transportation and accessibility were known as a key factor in the development of the zone. The Mid-Canada corridor was supposed to connect areas with certain characteristics such as abundant resources, acceptable climate for working and living, accessible and suitable terrain for development, high potential for urban development, and an already existing north-south transportation connection. The idea, however, did not gain enough attention from policy makers at the time.

Canadian Northern Corridor (CNC) is “about establishing a new multi-modal (road, rail, pipeline, electrical transmission and communication) transportation right-of-way through Canada’s north and near north.” During the study, CNC was recognized as a potential response to contemporary economic, political and geographical challenges of Canada. Integrating Canada’s economy and enhancing its connectivity from coast to coast to coast as well as diversifying Canadian goods market are among CNC’s huge potentials.

It has been estimated that the Northern Corridor would start from west and traverse easterly, through the boreal forests located between the western provinces and northwestern territories. A branch of the corridor would connect it via the Mackenzie Valley to the Arctic Ocean. The main stem of the corridor would then continue southeasterly towards northern Ontario, connecting the Churchill area to the James Bay wetlands. The latter is home to the “Ring of Fire” mineral deposits which offers great development opportunities. It would be a 7000 km multi-purpose corridor with parallelly located roads, railways, pipelines, and power lines and Telecommunication systems. The
width of the corridor may vary along its length up to several kilometers. A preliminary estimation of the capital cost of the corridor for building all of its modes was about $100 billion in 2016. The project is assumed to be funded by both public and private sectors [7].

Diversifying Canadian goods market, absorbing international investment, consolidating of Canadian Sovereignty on neighboring land and sea areas in the arctic region and reducing the load on the existing southern transportation system are among the strategic benefits of this corridor. Facilitating inter-regional trade, improving regional development and enhancing social and economical conditions of remote northern areas and indigenous communities are other potential benefits [7].

Legal, administrative, social, environmental, financial and technical challenges are a number of potential issues faced by the Canadian northern corridor project. Co-locating all different transportation modes in a single corridor needs many technical considerations to evaluate their compatibility and ensure their safety and reliability both during service and contingencies. Identifying risks and measures to mitigate them, finding the best route which is not only feasible for lodging all different elements, but is also maximally beneficial for communities and resources, and reducing financial costs and environmental impacts are some of the challenges making the project technically complicated. Many rivers, lakes, wetlands, muskeg soils, permafrost zones, environmentally sensitive areas, environmentally protected areas, heritage sites, indigenous reserves, wildlife migration routes, and mountains are of geographical barriers ahead of constructing the corridor [6], [7], [11].

As it was mentioned before, the Canadian northern corridor is a complex and costly mega-project. Coordinating this project with various stakeholders among several ministries at different levels poses great challenges. These include federal, provincial, territorial and local governments, public and private funders, various industry and agriculture sectors, landowners, indigenous communities and environmental groups with potential contradictions in views, priorities and interest needs.

The Standing Senate Committee on Banking, Trade and Commerce published two reports in
June 2016 and June 2017 on the corridor. “Tear down these walls” is the title of the 2016 report which had aimed to recognize Canada’s internal trade barriers and actions needed to be taken by the federal and provincial/territorial governments to overcome them. This committee recommended that “The federal government support the creation of a “national corridor” that would allow transportation of goods and services to tidewaters through pipelines, railways, fibre optic cables, transmission lines and any other appropriate means.” [26].

The Senate committee studied the proposed Canadian national corridors and published its report titled “National corridor enhancing and facilitating commerce and internal trade” in June 2017. This study indicates that limited access to tidewaters due to insufficient east-west transportation facilities is a limitation for export of Canadian products to the international markets. The current regulatory process is inefficient and causes delays in transportation infrastructure projects. The report emphasizes on the leadership role of the federal government and participation of Indigenous peoples in the project since early stages. This report also confirms that the proposed corridor by Mr. Sulzenko and Mr. Fellows has potential to address some of Canada’s current challenges such as limited access to tidewaters and the obstacles to building a national transportation corridor and developing northern parts of the country.

[7] recognizes routing as an initial step in the establishment of CNC. It also gives a rough estimation of a potential path for CNC which is greatly in accordance with the suggested Mid-Canada corridor development in [24]. [7] also introduces some avoidance areas with environmental and social significance such as wetlands, permafrost zone, and the lands under Indigenous title. It also emphasizes on the role of topography, water bodies and landownership considerations on the final routing process. Overall, this study points out the necessity of extensive studies taking into account geographical and economic issues for any route determination for CNC. Although the [7] shed light on some important criteria and considerations about engineering complexities and routing challenges of the CNC, their main goal was to introduce the CNC concept and its potentials to address Canada’s socioeconomic and sovereignty challenges at a strategic level. They suggest
engineering challenges and routing options as potential areas for future studies.

1.3.3 Optimal Multi-Modal Routing

A road, railway, power line or in general, a transportation corridor is a continuous strip of land which connects an origin point to a destination point. When finding the best path, several conditions are needed to be considered which can influence the cost of the corridor either directly or indirectly. Here, the term “cost” is not limited to the financial cost, but also includes the environmental and social costs [27][1]. For example, topography, soil conditions, land use, number of rivers, existing networks, environmentally sensitive areas, and heritage sites have significant impacts on the cost and thus, can affect the best route or the LCP. Routing simply is the process of finding the most suitable areas for the corridor to pass with the minimum overall cost and the maximum benefit. Therefore, routing is a key stage in planning a corridor that can determine its viability.

Corridor routing can be divided into two phases. Finding a general alignment which is acceptable for all stakeholders is the first phase. The second phase includes, engineering design and route refinement with consideration of all of the standards and codes related to the route curvatures and geometry. Finding a general path able to receive all the stakeholders’ approvals (the first phase) is the most challenging phase. Using Geographical Information System (GIS) to make a model for finding the optimal path focuses on this first step [28].

The focus of this thesis is on the first phase. To find a general alignment for a corridor using computerized algorithms four major steps are needed to be followed. The first step is identifying the objectives and criteria important for the project stakeholders. The second step is gathering data on important factors, which can influence the routing process, in the form of a square grid cells (Raster data). The third step is to assign a suitability value to each cell which represents how easy that cell is to be traveled across, with minimum environmental and social barriers. The more suitable the means, the less cost and negative impact on the environment and the society. The final step is to apply a Shortest Path Algorithm such as Dijkstra to the scored grid network to find the
shortest path which connects an origin to a destination [27].

Using cost raster data along with GIS has been widely used for routing linear features such as railways and pipelines, or siting wildlife corridors. Many algorithms and GIS tools assume the width of the route to be zero and unimportant compared to the raster cell size. This assumption is not realistic when high resolution data with smaller cell size is available or when routing a wide path (corridor) is desired. Surprisingly, only a few studies have been done on finding wide corridors [13].

Reference [29] introduces a method for finding wide wildlife corridors. His method includes these following step: First, for each cell within the study area the LCP and the accumulative cost of the LCP from the start point is calculated. The same process is done with respect to the ending point. These two least costs (from start point and from end point) are added up to construct a third cost map. In this new map, each cell value shows the minimum cost of connecting that point to both the starting and ending points. In the next step, a threshold is defined and cells with accumulated costs less than the threshold are selected. These cells are deemed as suitable to traverse. Evidently, the number of the selected cells increases as the threshold is raised. This last step is repeated until a continuous swath with a minimum acceptable width is produced. One problem with this method, however, is that the obtained width is not consistent and changes significantly along the path.

Reference [30] used a buffering method around LCP. They simply find the traditional LCPs and then widen them to the desired widths to find the most suitable corridor for cougar movement. This method results in a corridor with a fixed width. However, the problem with this method is that the costs of the cells neighbouring the center line of the LCP are not considered during the routing process. Therefore, the wide corridor found here could include cells with very high costs and result in a non-optimal route. This method also does not consider multi-modality of corridors.

The differences between the outputs of conventional methods and what is needed as a wide path is discussed in [2]. During the last decade, a few routing methods have been developed which take account of the width of corridors in more sophisticated ways [13], [2], [1]. The methods which
can consider the width of corridor do not limit the cost of each cell to its own cost. They generally create a new network in which the costs of neighbouring cells are also important in the cost of each cell. \[1\], \[13\] and \[2\] are among the most important works having been done so far for finding an optimal wide path. However, according to what is explained in Chapter 3, they have limitations in addressing the multi-modality issue. When the goal is to accommodate various transportation modes such as railway and pipeline within a wide single right-of-way the routing becomes more complicated. In this case, not only the width of the corridor is a problem but also the different movement characteristics of the various modes can be an issue, being able to reduce the optimality of the found route. For example, while gradient of terrain is very important for railway routing, it is not a big issue for power transmission line. These diverse tastes of various modes to find an easiest path can not be addressed by the existing methods.

1.4 Thesis Contributions

This thesis makes three contributions: Firstly, it presents a comprehensive literature review on technical challenges arisen by co-locating all different modes within a same right-of-way. These challenges include, issues related to routing, compatibility, and general arrangement of parallel modes within a corridor. Furthermore, lessons learned from the related studies are mentioned. Also, some Canadian and US guidelines and codes regarding the most important compatibility issues are highlighted. Besides, the potential benefits of putting all modes in a single right-of-way and its advantages for Canada are discussed here.

Secondly, this thesis suggests four methods for routing a multi-modal wide corridor. The first, second and third methods use the existing methods with some extra steps to find LCPs. However, the fourth method, called MDTG, has fundamental difference with the existing methods and uses multiple layers of cost raster directly for calculating weights in its connectivity graph. The MDTG method considers both the width and the multi-modality of corridors. In addition to a starting and an ending point, this method takes accounts of three input elements: 1) different cost surfaces for
different modes based on their movement characteristics and suitability criteria, 2) the width of each mode based on the number of cells in cost rasters, 3) the arrangement of different modes within a corridor. The model then creates a graph on the study area. The nodes of the graph are on the centers of the cells. The weights of the connecting edges are calculated based on the three above-mentioned elements. Then by applying an LCP algorithm the optimal path is found.

Thirdly, a method is suggested to connect an origin to a destination via a multi-modal corridor and also to connect this corridor to one of its nearby renewable energy sites with the minimum cost. It is assumed that renewable energy sites are interconnected. As such, connecting one of them to the corridor in fact connects all of them. The proposed method addresses the three following main questions: i) which renewable energy site is optimal for being connected to the corridor? ii) Where is the point at which the corridor and its power branch to the optimal site meet? iii) What is the least-cost alignment for the corridor and the mentioned powerline branch? A numerical experiment shows how the proposed method can help find opportunities for saving costs via considering the locations of renewable energy sites in the process.

1.5 Thesis Organization

Some important or similar projects are chosen and briefly reviewed in Chapter 2. Also, their technical challenges and lessons learned from them are mentioned, and some suggestions have been made based on these reviews. In Chapter 3, the existing methods for routing process using integrating Multi-Objective Decision Making tools and Geographic Information System (GIS) are reviewed. The effectiveness of these methods for finding a wide corridor is challenged. Moreover, the most recent methods for finding the best path for a wide corridor, and the reasons why they cannot take multi-modality into account have been reviewed. In Chapter 4, a new method is suggested for addressing these issues. This method obtains various cost-surface maps for each mode in the form of raster data and makes a network (graph) based on these maps. The weights of the links (edges) of this graph are defined based on both width of each of the modes and their parallel
arrangement. Finally, a least-cost-path algorithm such as Dijkstra is applied to the constructed network (graph) to find an optimal route. This method is applied to some random made synthetic data sets and the results are compared with those of the previous methods. In Chapter 5, the negative impact of neglecting the locations of renewable energy sites in the routing process on the costs is investigated. Moreover, a method is proposed to align a multi-modal corridor and its powerline branches to the renewable energy sites with the minimum cost. Finally, a summary of the findings of this thesis as well as some suggestions for future studies are mentioned in the last chapter.
Chapter 2

Historical studies, technical challenges and standards

This chapter has two main sections. In the first section, some international as well as Canadian transportation corridors specially those having similarities, in terms of multi-modality, to the Canadian Northern Corridor (CNC) are reviewed. The objectives, financial and physical characteristics and route planning process of these projects as well as the lessons learned from them are reported where the data is available and relevant. In the second section, the feasibility of multi-modal corridors and their technical challenges are discussed. For example, co-locating different modes, with interactions and compatibility issues, in a same right-of-way (ROW) is among the most important challenges. The most significant compatibility issue is between power lines and pipelines [20], [11]. Some international and Canadian standards related to the compatibility of power transmission lines and pipelines are reported in this chapter. After discussing the technical challenges and routing problems of a multi-modal corridor, a general lateral arrangement is proposed.

2.1 Review of some International and Canadian corridors

2.1.1 Overview

For numerous socio-economic benefits, many countries invest in transportation corridors. China’s One Belt One Road initiative (OBOR), Europe’s TEN-T projects, International North-South Transport Corridor (INSTC) connecting India to Europe via countries such as Iran and Russia, the Lamu Port-South Sudan-Ethiopia-Transportation corridor in the Eastern part of Africa and a number of infrastructure corridors in Australia are among them. The projects reviewed in this chapter are selected based on their importance or similarities to the CNC. Reasons for selecting them for being reviewed are listed in Table 2.1. Most of these projects are similar to the CNC in terms of multi-modality.
<table>
<thead>
<tr>
<th>Corridor name</th>
<th>linear components</th>
<th>Including a multi-modal corridor</th>
<th>Length and width</th>
<th>Reason for review</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAPSSET [LAPSSET.C.D.A., 2019], [MBARAGA,2016], [Japan Port Consultant Ltd, 2011]</td>
<td>Highway Railway Crude oil pipeline Product oil pipeline Power transmission</td>
<td>Yes</td>
<td>Length: 1774 Km Width: 200-500 m</td>
<td>1-Join-use of right of way 2-Considerable scale 3-Involvement of different countries with different priorities and policies</td>
</tr>
<tr>
<td>China One Belt One Road OBOR [Baker and Mckenzie, 2017]</td>
<td>Railway Highway Pipeline Powerline Maritime Silk Road</td>
<td>N/A</td>
<td>The project scope is not fixed.</td>
<td>1-Importance of the project 2-Emphasize on the role of Asia pacific in the future global trade</td>
</tr>
<tr>
<td>Australia infrastructure programs [Queensland Government,2012]. [Australia Investment Program, 2021]</td>
<td>Different modes in different locations</td>
<td>An example project for joint-use is the Callide Infrastructure Corridor which includes several buried gas pipelines</td>
<td>N/A</td>
<td>1-Political, geographical, and economical similar conditions between Australia and Canada. 2-Considerable sizes of projects. 3-Looking at the Callide Infrastructure Corridor as a joint-use corridor</td>
</tr>
<tr>
<td>Government of Northwest territories (GNWT) strategic infrastructure projects [GNWT, 2019]. [Aurora Geosciences, 2020]</td>
<td>All season gravel roads. Transmission lines and communications infrastructure are also included in Slave Geological Province Corridor</td>
<td>Only Slave Geological Province Corridor is multi-modal including: Road, transmission lines and communications infrastructure.</td>
<td>831 km= 97 km+321 km +413km Width: 60 m</td>
<td>1-Mackenzie Valley Highway has potential to be the branch of the Canadian northern corridor which goes through North west territory. 2-Some goals, benefits and challenges are the same in these projects and the Canadian northern corridor</td>
</tr>
<tr>
<td>Edmonton and Calgary transportation and utility corridors [Alberta government , 2020]. [Brian De Jong,2018]</td>
<td>Road Power lines Pipelines Regional water lines Sewer lines Telecommunication lines</td>
<td>Yes</td>
<td>167 km=Anthony Henday Drive (80 km) in Edmonton and Stoney Trail (87 km) in Calgary The maximum width: 800 m</td>
<td>1-A successful implemented join-use corridor in Canada 2-the concept of preserved right of way in this project is the same with Canadian northern corridor</td>
</tr>
<tr>
<td>Athabasca Oil Sands Multiple Use Corridor Study [Weir et al., 1973]. [A.F.L.W.R.P., 1986]. [A.C.S.G., 1974]</td>
<td>Pipelines Power lines Highways Railroads Telecommunication lines</td>
<td>Yes</td>
<td>386 km The maximum width : 1600 m</td>
<td>This corridor has some similarities with the Canadian northern corridor in terms of concept, goals, advantages disadvantages, engineering challenges, geography, and environment</td>
</tr>
<tr>
<td>Peace River – Fort McMurray Transportation and Utility Corridor [M.B.E.Ltd., 2014]</td>
<td>Road Railway Power lines Oil and gas Pipelines Telecommunication</td>
<td>Yes</td>
<td>444 km Width: 300 m</td>
<td>This corridor has some similarities with the Canadian northern corridor in terms of concept, goals and has potential to be a part of Canadian Northern Corridor.</td>
</tr>
</tbody>
</table>

Table 2.1: Reviewed corridor characteristics
2.1.2 International corridors

China’s One Belt One Road initiative (OBOR), Australia infrastructure programs and Lamu Port-South Sudan-Ethiopia-Transportation (LAPSSET) Corridor are discussed in this section. To the best of our knowledge, LAPSSET is the largest transportation project which used the concept of shared ROW with a length of about 2000 km [19]. Because of similarities to the CNC and also the availability of their data, these projects are reviewed in more detail.

In 2013, President Xi Jinping announced one of the biggest infrastructure initiatives in the modern history which has so far included more than 60 countries with 69% of the world’s population, and 51% of the world GDP [31]. Because of its massive scale and importance a brief review of this project is included in this chapter. This ambitious project called One Belt One Road (OBOR) or Belt and Road Initiative (BRI) consists of two main elements: a Silk Road Economic Belt and a 21st Century Maritime Silk Road. China’s OBOR is more a strategic approach than a project. Its scope, timeline, budget and involved countries are not fixed. The huge scale and potential influences of this initiative indicate the increasing importance of the Asia Pacific on the future of international trade [31], [32].

The Silk Road Economic Belt consists of six Overland corridors including Bangladesh-China-India-Myanmar, China-Mongolia-Russia, China-Central Asia-West Asia, China-Indochina Peninsula, China-Pakistan and New Eurasian Land Bridge. These corridors are planned to connect developed areas in China to less developed areas in the west and the north of this country, then proceed to the central Asia and Europe. The 21st Century Maritime Silk Road travels across the Indian ocean and tries to connect Southeast of Asia to South Asia, Africa, and Europe via the Suez Canal. There is a wide range of estimations for China’s investment in OBOR. Although the program is mostly referred to as the 1-trillion-dollar project, the estimations at times rise to 8 trillion dollars. This ambitious infrastructure development will not be limited by geography. Since its announcement in 2013, the project has also stretched to the Caribbean and Latin America as well as the Arctic [33].
Studying Australia’s infrastructure programs could provide some insights for the CNC because of similarities between the two countries. There is political, geographical, and economical resemblance between them. Both countries have a federal governmental system, and an economic superpower neighbour (US and China). Natural resources are a main part of their economies. Moreover, most of their populations are settled in limited geographical zones despite the vast lands and territories. Additionally, they both have Indigenous populations who mostly live in remote areas with harsh climates and no sufficient infrastructures [32].

The Australian government has committed to invest $110 billion in infrastructural projects to be carried out over a 10-year period from 2020. This is in addition to the country’s last decade huge investments in this area. Investment in new road and rail programs as well as upgrading the existing networks, bridges renewal programs and increasing safety in Australian road networks are parts of the new programs. One important sector is the Roads of Strategic Importance initiative which will fund regional and inter-regional projects as well as national highways. Key freight corridors which are necessary for removing bottlenecks in mining and agricultural resources are parts of these projects [34]. Among the Australia transportation projects, Inland Rail and Callide Infrastructure Corridor are reviewed briefly in this chapter. Inland Rail has comparable goals to the CNC and Callide Infrastructure Corridor is an example of sharing ROW.

Inland Rail, previously known as Australian Inland Railway Expressway is a 10-billion-dollar project with 1700 km freight railroad which will connect Melbourne to Brisbane along the Australia’s East coast. Some of the most important goals of this project are: improving the national freight network connections, increasing the capacity of coastal transport networks, boosting the Australian economy, providing an alternative for the existing north-south freight link, creating jobs, improving safety and reliability and lowering emissions. This railway goes through Victoria, New South Wales and Queensland and will connect national producers to national and international markets via a safer and faster transportation mode. Both public and private sectors are in partnership in this project. This mega project increases Australia’s reliance on railroad and re-
duces the role of road networks in freight movement. It also creates more than 16000 jobs during construction. It reduces carbon emissions and injects about 16 billion dollars to Australia’s GDP during the next 50 years [34], [35].

Among many transportation projects and heavy investments planned for the next decade in Australia, it seems that only the Callide Infrastructure Corridor uses the concept of shared ROW. The possible geographical reason behind it is discussed as well. Callide Infrastructure Corridor State Development Area (CICSDA) is a shared ROW for buried gas pipelines between Callide and the Gladstone State Development Area. In September 2012, the government of Queensland published a development scheme for CICSDA. Its first goal was to provide, manage and plan the land for the development scheme, including detailed regulations and procedures for land use approval and evaluation of every development in the CICSDA. This corridor saves time and cost for pipeline applicants interested in participating in the corridor. Moreover, landlord disruptions and environmental impacts would be minimized by avoiding several pipeline alignments for multiple users [36].

Lamu Port-South Sudan-Ethiopia (LAPSSET) Infrastructure Corridor located in the East Africa is planned to connect countries of Kenya, Ethiopia and South Sudan. Of all the projects reviewed in this chapter, the LAPSSET corridor appears to be the most similar to the Canadian northern corridor in terms of multi-modality, goals, social and geographical challenges. Its main linear components are highways, railways and crude oil pipelines which will be constructed in a same ROW. It is the most ambitious infrastructure project in the Eastern Africa. After completion, it enhances regional economic integration and inter-connectivity and facilitates trade in Eastern Africa. Amplifying economic activity in Kenya, especially in the Northern and Eastern parts, is of the major objectives of this project. This mega project consists of seven main projects in Kenya, Ethiopia and South Sudan. Three international Airports, three resort cities, a multipurpose dam over the Tana river, a 32-berth port at Lamu (Kenya), several inter-regional highways, a crude oil pipeline and several international railways are the seven key elements of this mega project [37], [38], [19].
Natural, environmental and socioeconomic conditions as well as the existing networks and future plans are the most important factors influencing the routing of LAPSSET corridor. Terrain, geology, hydrology and natural resources are examples of the significant natural conditions. Geography determines the need for building bridges, extra structures and earthworks as well as the achievable gradient. Terrain is of crucial importance, especially for railway routing. Paying attention to rivers, swamps, and areas with high risk of flooding is also vital. Erosion control and elevating the road to higher than flooding level is a necessity in some parts. The allocated ROW to the modalities is as follows: 100 m for highway, 60 m for railway, 30 m for oil pipeline and 10 m for utilities. It appears that in the subsequent studies, the total ROW was reported to have increased to 500 m and a power transmission line was also included in the corridor [19], [37].

The prospect of oil, gas, coal, and other natural resources was one of the most significant factors influencing the LAPSSET corridor routing. One of the main goals of the corridor was to enhance economic situation in the region. Connecting populated communities with economic importance was a key factor in the planning process. Therefore, socioeconomic profile of the region, its population, potential employment growth and economic activities, and the potential for trade, imports and export were all considered when planning the project.

Cultural heritage sites and national reserves were avoided. Also the natural environmental sites such as environmentally sensitive areas, wildlife migration routes, national parks, sanctuaries, ramsar sites and conservation areas were excluded where possible.

Ease of construction, length of planned route, the number and specifications of main water crossings, land acquisition, maintenance and operation costs are parts of a project’s direct costs. The estimated cost and financial benefits of each part determine feasibility. For a new infrastructure project or its future expansions, land acquisition is an inevitable process that can affect the cost as well as easiness of implementation of a project. As mentioned in the JPC report, public are easier to be acquired than private lands. Moreover, military lands and their vicinities need to be avoided as much as possible [19], [37].
Existing infrastructure projects and future plans are very important during the planning of a new corridor. A new corridor and existing network can potentially influence each other. They can affect the traffic, importance, maintenance and construction costs of each other. These interaction effects play important roles in corridor routing [19].

2.1.3 Canadian Experiences

In this section, some infrastructure projects in Canada are reviewed. These have been selected due to their similarities to the CNC in terms of joint use of ROW, challenges and environmental situations they are located in. Comparing the rough estimation of the CNC route in [7] with the proposed routes for Mackenzie valley highway [39] and Peace river-Fort McMurray corridor [20] shows there are potentials for these projects to become include in the CNC. The Mackenzie valley highway route is roughly similar to the location of a CNC branch which stretches to the arctic. Also, the Peace river-Fort McMurray corridor can be considered as the route of the CNC in northern Alberta. However, this potential alignment is only based on visual comparison of the data of these projects, meaning that further comprehensive studies are required for any future decisions.

Poor infrastructure systems are barriers to unlocking potentials of Northwest Territory. Some areas are accessible only via winter roads whose reliabilities are speculated to become challenging with the climate change. To address these issues, Government of Northwest Territories (GNWT) planned some infrastructure projects. Tlicho All-Season road, Mackenzie Valley highway and Slave Geological Province (SGP) corridor are a number of these projects.

The objectives and challenges of these three strategic transportation corridors are similar to those of the CNC, as enlisted in Chapter 1. Enhancing connectivity among communities, decreasing the cost of living and improving the economy in the territory are some of the aims of the Northwest Territories projects. Additionally, maximizing accessibility to potential mineral sites while minimizing negative effects on the environment are among the goals and challenges. A long-term vision of SGP is to link Canada’s highway network to the Arctic Ocean in Nunavut. Harsh weather, permafrost zones, huge number of river crossings, wildlife habitat issues and in-
sufficient available data are a number of the problems common between the GNWT corridors and the CNC [40], [39].

Some engineering, environmental and socioeconomic considerations were important in the routing process of these three corridors. In the routing process of the SGP corridor, data regarding archaeologically sensitive sites, caribou core ranges, caribou utilization distribution, esker deposits, waterbodies, watercourses, digital elevation model, wetlands, saturated soils and raptor nest and wolf den sites was collected from various sources. Traditional land use areas, mineral deposits, caribou habitats, lands with more technical challenges and costs are need to be avoided where possible. According to a report published by Aurora Geosciences for SGP [40], the best route for the corridor was determined using multi-criteria evaluation techniques to create a multi-factor cost layer. A comparisons done in 2015 and 2019 between this new route (2020) and each of the two other alignments showed that despite the slightly longer path, the new version seems to be superior since it travels through less steep areas and avoids all water crossings. Among all the GNWT strategic corridors, SGP is the only one including energy and telecommunication in addition to road.

Among all the Canadian multi-modal projects, Alberta Transportation and Utility Corridors (TUCs) are of the most successful ones that have been built so far. In the mid-1970s, the Government of Alberta determined three restricted development areas to be reserved for ROWs of TUCs. The TUCs are defined around the two major cities of Edmonton and Calgary and also, along the west side of Sherwood park. These areas accommodate major power lines, pipelines, regional water and sewer lines, and telecommunication lines. The TUCs are a long-term solution for land use and ROW issues for major linear infrastructures. Any purchase, sell, and use of lands within the TUCs by any individual, organization or company are regulated by Alberta Infrastructure.[41].

Anthony Henday Drive (80 km) in Edmonton and Stoney Trail (87 km) in Calgary are two ring roads located in the middle of TUCs’ components such as pipelines and transmission lines. The maximum widths of these corridors are along the East side of Edmonton with a 0.5-mile width.
Long term planning helps Alberta Infrastructure to control and manage land use within the TUCs in effective and efficient ways. Limiting the environmental footprints, administrative efficiency, synergy of monitoring and higher safety level, land use certainty and secure alignments for future users are among the advantages of the TUCs. [42].

A land within a TUC can be used at various levels. It can be used at above the surface (transmission lines), surface (ring roads) or underground (pipelines) levels. This makes it possible for different users to utilize the land simultaneously. Generally, three categories of use of a land are defined within the TUCs: primary use, secondary use, and original use. Examples of primary use include, ring roads and other linear utilities such as powerlines or petroleum pipelines. The roadside areas under powerlines or above pipelines can be allocate to secondary uses such as parking lots or agricultural, recreational or commercial activities. These secondary facilities are not permanent and can be displaced or altered to make space for primary uses. It takes time for the TUCs to completely develop. While the primary and secondary uses are being developed, there are lands such as residential, industrial or agricultural areas that have kept the original uses they had before the designation of TUCs [41].

In the 1970s and 1980s, the Alberta government performed a number of comprehensive studies to identify the environmental, social, and financial impacts of multi-modal transportation corridors in northeastern Alberta. Examples include the studies prepared for Alberta Forestry, Lands and Wildlife [21] and Alberta Environment [10] and [23]. Athabasca Oil Sands Multiple Use Corridors have some similarities to the CNC in terms of concept, goals, advantages, disadvantages, engineering challenges, geography, and environmental issues. The main goal of these projects was to connect Athabasca oil sand resources to a new major provincial terminal which was a hub for exporting products to the neighbouring terminals.

The approximate length of the Athabasca Oil Sands Multiple Use Corridor was estimated to be 240 miles. An over-estimation of the corridor elements included: sixteen pipelines with various sizes, two power transmission lines, four-lane highways, one railway spur with about fourteen
miles length and several other utilities such as sewer, water and gas in the section of the corridor close to Edmonton. The corridor was supposed to accommodate linear pipelines, highways, railroads and communication facilities and power transmission lines. The ROW needed for the mentioned features was estimated to be 800 m. However, for being more flexible in case of emergence of unexpected obstacles during actual routing process, the corridor width was increased to 1600m [10].

The corridor study group considered various factors to plan this corridor such as the social and environmental effects, engineering and economic consideration, hydrocarbon supply and demand, decentralization of urban development, the location constraints of each facility and potential for export. Eight volumes of reports were published which cover different aspects of this corridor. The planning and designing of the corridor were affected by the number of the transportation modes, social and environmental considerations, engineering and design factors, safety and security, land use, topography, zoning, legal factors, economics, and future expansions [10] [23]. In [23] a comparison matrix is made for evaluating different environmental impacts of powerline, pipeline, highway and railway. Weakness of this comparison matrix are lack of sufficient data and subjectivity of the method used for evaluating the importance of environmental impacts.

The width of the corridor varies from several hundred meters to several kilometers along its course. A multi-disciplinary approach was taken to evaluate different alternative routes. The main considerations for choosing the best route are: economic, engineering, environmental, legalistic, socio-cultural and political aspects [10]. In the process of routing, the existing oil sand developments and related lands were tried to be avoided. Water crossing and going through natural resources such as wildlife habitats, timber, surface mineable oil sand deposits, gravel and sand deposits were tried to be minimized.

The data gathered for these studies includes: natural resources, human settlement and infrastructure such as transportation/communication facilities, physical characteristics of the study area, rivers and streams, soil erodibility, land use, soil type, drainage characteristics, steepness of slopes,
vegetation and wildlife habitat. The alternative paths for the corridor were studied and compared in terms of their impacts on the following factors: Surface mineable oil sands deposits, wildlife habitat, water crossing, existing infrastructure and visual amenities \[21\]. Ease of construction, length of planned route, the number and specifications of the main water crossings, land acquisition, maintenance and operation costs are components of the direct cost of a project. The estimated cost of each part and its financial benefits determine its viability. For a new infrastructure project or its future expansions, land acquisition is an inevitable process that can affect the cost of a project as well as its easiness of execution. As mentioned in the JPC report, public lands have less problem to be acquired than private properties. Moreover, military lands or their vicinities need be avoided as much as possible. Existing infrastructure projects and future plans are very important when planning a new corridor. A new corridor and an existing network can potentially influence each other. They can affect the traffic, importance, maintenance and construction costs of each other. These interaction effects play central roles in corridor routing \[21\].

Another multi-modal corridor locating in the northern part of Alberta is Peace River – Fort McMurray Transportation and Utility Corridor. The goal of this project is to help sustainable development in northern Alberta by connecting Fort McMurray to Peace river area. In this project, a Transportation and Utility Corridor (TUC) which contains two or more linear infrastructures such as road, rail, water line, power, telecommunications cable, and oil/gas pipeline is aimed to be built. This project has 444 km length and can be divided into two parts. The west portion from Peerless Lake to Peace River which are already connected via Highway 986 and the east portion from Fort McMurray to Peerless Lake with no roads.

The number of the components of the corridor and the sections of it where these components go side by side can result in several scenarios. These include minimal, partial, and full TUC scenarios. An analysis done for The Northern Alberta Development Council (NADC) shows the benefit-to-cost ratio for minimal, partial, and full scenarios to be 1.88, 1.69 and 1.67, respectively. The costs of the project for the minimal, partial and full scenario sections are 357,1054 and 2909 million
dollars, respectively.

The study [20] shows that, in that project, the overall cost of a multi-modal corridor is less than the accumulative cost of single mode corridors for each linear facility. The mentioned study also shows that the multi-use corridor has more social and environmental benefits than multiple single use corridors. It is worth mentioning that even in the full scenario, oil and gas and water pipelines are present only in half of the total 444 km length of the corridors.

2.1.4 Discussion

This section talks about the lessons learned from the reviewed literature as well as some suggestions. These points are discussed under two main categories: first, the high level policy perspectives and considerations of a multi-modal corridor and second, the engineering contexts. Also, a general suggestion for the lateral arrangement of multi-modal corridors is proposed, which is very general and therefore, needs re-evaluation for each specific project.

In Canada, despite many studies on multi-use transportation corridors, only a few have been implemented in a large scale project so far. Seemingly, there are barriers prohibiting corridor users or governments from changing their approach from conventional single mode to multi-modal transportation corridors. These challenges, the reasons behind them and the ways to solve or minimize them need to be studied. One possible major challenge is to direct a multi-modal transportation corridor project, forming an integrated and cooperative team from different levels of federal and providential governments and industries, including various ministries such as aboriginal relations, environment and sustainable resources, energy, transportation etc., is needed.

Having different and sometimes contrary interests and concerns, policies, priorities and plans as well as dissimilar legal systems in different provinces and territories is another serious challenge. Moreover, technical standards and codes vary from province to province. Different parties may have unlike priorities in choosing the first mode to be built. Connection points where the corridor traverses from one province to the other is another potential point of argument. There are barriers that can be overcome only by strong coordination among different levels of the government and
industry as well as the public.

Raising public awareness, sharing information, and using local and aboriginal people’s capacity is necessary in governmental and private major infrastructure project. It is recommended that this approach be taken from the early stages of the projects. If positive communications among stakeholders are established in earlier steps, the weak points of a project become more transparent and it becomes possible to redesign a project if necessary. This ultimately leads to lower cost and delay.

All possible users of different modes of a multi-user corridor have to be considered in the planning and routing process. Focusing on only the first mode to be built, can decrease the total benefits of the corridor in the long run.

Multi-modal transportation corridors are generally feasible, and their advantages outweigh the disadvantages. But to determine the feasibility of each project, its specifications such as designs, physical and environmental conditions need to be individually studied.

The location of a multi-modal corridor ROW is in general a compromise among the optimal locations of the ROWs of its various components; particularly if the origins and destinations of the modes are not similar.

The construction cost (not overall cost including maintenance, Right-of-Way acquisition costs, etc.) of a multi-modal transportation corridor could be higher than the sum of construction costs of building conventional individual corridors. The first reason is the precautionary measures needed to be taken to make adjacent facilities, such as pipeline and transmission lines, safe and reliable. In other words, putting all facilities in the same ROW needs taking extra measures, evidently with extra costs, to make them safe in one another’s proximity and also to make sure that in case of contingencies in one mode, the rest of the modes remain functional. The greatest concern regarding interference between different systems is about power transmission line and its effects on its neighboring facilities.

Another reason is that the location of a multi-use corridor is a compromise among optimal lo-
cations of each component of a corridor. This may result in a longer path or undesirable conditions for some facilities. For example, collocating a pipeline with a railroad in a same route may result in a longer path for the pipeline because railroads need smoother turn curves and lower gradients.

These extra construction costs may be compensated by a reduction in the required land for ROW, using a same access road, reducing the time to get permissions and minimizing delays for various modes and other benefits of a multi-use corridor. It seems that saving time and money required for obtaining projects permits is one of the greatest advantages of a multi-modal approach, especially in Canada.

Consistency in land-use planning at local, regional, provincial and national levels and considering future infrastructure and transportation plans, especially at the early stages of a project, is a necessity for a multi-use corridor design and routing. Adequate data bases, including of natural resources and their values and the required future ROWs for transportation and utilities should be known and coordinated among national, provincial, local governmental and industrial organizations.

In general, locating highway in the middle of a corridor makes accessing railroad and pipeline for operation and maintenance more convenient. The route of pipeline is more flexible than that of highway or railway. Therefore, being positioned on one side of the corridor makes it possible for the pipeline to deviate away from the corridor where it is not financially viable to follow its path. This would also make it more accessible in case of an accident. Railway is greatly sensitive to the terrain gradient and also needs room for smooth turns. Therefore, locating it on the edge of the corridor provides extra room for its movements. Putting highway between pipeline and power transmission line helps reduce the incompatibility of these two. Regarding these points, the proposed arrangement is as Figure 2.1. This suggestion is very general and only based on gradient sensitivity of modes and their compatibility. For each project the lateral arrangement needs to be studied specifically considering geographical and technical condition of the project.
2.2 Discussions on Corridor Development Challenges

2.2.1 Overview

The balance between the severity of challenges posed by multi-modality and the potential advantages determines the viability of a project. Identifying the challenges and considering them in planning, construction, operation and maintenance is a necessity for the success of a project. These challenges are broadly categorized into: managerial and governance, legal and administrative, financing, land acquisition, technical, social and environmental.

In this thesis, the focus is on technical challenges, particularly routing of a multi-modal corridor. Common technical challenges which are not caused or exacerbated by multi-modality, such as soil stabilization for highway construction, are not discussed here. Purely technical challenges include routing, compatibility and reliability, whereas, social, environmental and financial challenges have the potential to influence routing a project and determine its feasibility. Significance of each of the challenges varies from one project to another. The arrangement and specifications of a corridor elements, terrain, environment, Social consideration and available alternatives need to be studied for every project for feasibility determination.

The goal of this section is to identify and explain routing, compatibility, reliability, financial, environmental and social challenges generated or intensified by multi-modality of a corridor. The
special considerations for the routing of each mode is discussed and a reasonable arrangement for a typical corridor based on these consideration and compatibility issues is suggested.

In general, if technical challenges are not serious enough to completely halt a project, they can be addressed by spending extra money. In other word, If the available technology is not a limiting factor for a project, every technical challenge can be translated to cost. These extra expenses are required for adopting extra measures that are necessary for mitigating risks or taking other actions to make a project physically possible. For example, in a corridor with multiple transportation systems, influencing one system by another during a contingency is a potential challenge. As an example, derailment of a train can cause serious problems for the pipeline or highway in its proximity. In this case, the risk of damage can be mitigated by allowing sufficient space between the rails and other systems.

Looking at previous similar projects is a way to find out the seriousness of the challenges of joint using ROW. In (U.S.D.I, 1975) study, many cases of joint-use of ROW were examined. Despite a number of problems, most systems in the joint-use were operating satisfactorily. In addition, as reviewed in Section 2.1, the general concept of sharing ROW for different systems is used for planning some mega international projects. Therefore, it seems that joint-use method does not make a project categorically impossible and its challenges can be translated to cost.

The severity of technical challenges raised by co-locating all transportation modes in a same ROW is different from one project to another. It depends on many factors such as properties of each mode, physical circumstances of a project location and the lateral and longitudinal arrangement of different modes. For example, as mentioned in [17] and [16] studies, parameters such as soil resistivity, load current magnitude, type of pipeline coating, pipeline diameter and depth of cover, etc., are deemed as important in the severity of AC interference on pipelines.

It is possible for a transportation project that the specifications and surrounding conditions change along its path. Therefore, even if building all transportation modes within a corridor is not feasible for the whole path from the start to the end, it may still be feasible for parts of it. If
so, different scenarios can rise and the best combination can be chosen based on the cost-benefit analysis of each. For example, in Peace River – Fort McMurray transportation and utility corridor study [20], three different scenarios i.e., minimal, partial and full, were developed and the cost-benefit of each was analysed. The percentage of participation of each mode was different in each scenario. In the minimal scenario, rail and power were not included, power was added to the partial scenario and both power and rail were included in the full scenario. In this report, even in the full scenario, the pipelines accompanied the corridor in merely half of the path length.

A joint-use ROW project is financially preferred over a series of individual projects for each transportation mode if its financial benefits outweigh the extra costs imposed by technical challenges. The balance between these two factors can determine whether bundling all modes in a same ROW is financially feasible. Both benefits of joint-use and expenses of the extra measures are controlled by project specifications and environment. Therefore, every joint-use ROW project has to be studied on a case by case basis regarding its conditions. [11] and [23] introduced the important factors that need to be considered to identify the feasibility of a joint-use project. Herein, we review these factors under the following headlines:

- Routing challenges
- Compatibility challenges
- Financial benefits and challenges
- Reliability challenges
- Environmental considerations
- Social considerations

2.2.2 Routing Challenges

Routing process is discussed in detail in Chapter 3. In summary, routing of a corridor encompasses three major phases. firstly, collecting geographical data on a squared grid, next, allocating weights
to each grid cell and finally, applying a shortest path algorithm to the weighted grid from a starting point to a destination point [27].

Specific criteria such as slope, hydrology, soil type, terrain, vegetation, and land use which vary based on the geography of the area are important in routing a linear infrastructure. The degrees to which they impact routing of each of the individual transportation modes are not the same. For example, crossing a river is much more convenient for a powerline than a railway. In other words, after defining criteria related to routing of each mode, these criteria should be weighted by multi-objective decision making system. These weights basically define how the routing parameters are comparatively important. The sum of all weights on a map shows the cost of traveling through each area. These costs are not the same for various transportation modes. Therefore, the least-cost-path is different for each modes.

Physical phenomena which control and limit the movement of each transportation mode are different. While sharp turns and steep paths could be tolerated by powerlines and pipelines that is not the case for railways or roads. Different routing factors and the importance of each are studied in [23] according to which, while topography and river crossing are major factors for railway and highway, they are not so much so for powerline and pipeline. Based on the same report, geology, and soil type play less important roles in overhead transmission line than in other systems such as railway, highway, or buried pipeline. It seems reasonable since for example, the limitations of movements for a train are much more restrictive than for a power line tower. In addition, cut and fill and ground conditions can affect the cost of building a railway, a highway, or a pipeline more greatly than that of an overhead powerline.

In general, a route is ideal for a corridor when its construction, maintenance, operation, and compensation costs are minimum. In addition, it needs to have the least possible footprint on the nature, the maximum safety and reliability, the maximum ability to serve the public and resourceful areas and the highest possible social satisfaction. Moreover, an ideal route has the shortest length with the lowest gradient and the least curvature.
As it was mentioned before, railway movements are restricted both horizontally and vertically. Therefore, railway needs a lot of space for winding to be able to meet the codes related to the maximum allowed gradient and acceptable curvatures. The latter helps with its safe and comfortable horizontal turns. Moreover, since overcrossing is highly costly and has a lot of safety issues, it seems that the railway cannot be situated among other transportation modes. This research proposes that in a cross section of a multi-modal corridor, a railway is probably best to be located adjacent to either of the edges.

Avoiding corrosive areas like saturated sands and zones with high potential for landslide such as hillsides are important in pipeline routing. In pipeline alignment, horizontal turns and vertical gradient are not as important as they are for road or railway alignment. Although, as mentioned in [11], pumping cost increases where there are slopes and bends.

Although Pipeline does not have many gradient restrictions per se, the maximum movable slope for heavy vehicles required to carry pipes and construction materials to the field is a limiting factor. According to [23], although pipelines are not prohibitively sensitive to grades, this can nevertheless become an issue for oil pipelines. Moreover, rocky soils, muskegs and soils with high water level, fault zones, high steep canyons and hillside areas, corrosive soils, locations with potential tread for pipeline coating and permafrost zones need to be avoided where possible [23]. Additionally, it is better that pipeline routes be kept away from urban areas due to safety issues.

A main part of a pipeline construction cost is the cost of its materials. This is directly a function of the length and the size of a pipeline. As pipeline is not sensitive to gradient, its co-location besides railway or highway in steep terrains can result in a dramatic increase in costs. Moreover, its target usually differs from those of railway and highway. While railway and highway tend to go through community settlements and populated areas, pipelines are preferentially kept far from those regions. In considerations of all these factors, this research proposes that pipeline be located on one of the corridor edges rather than its middle.

Both gradient and horizontal curvature play a role in road routing. These roles, however, are
not as significant as in railway routing. For road construction, soil that can be easily excavated with good permeability condition is desirable. Wetland areas, permafrost zones, solid rock areas, river crossings and deep organic soils must be avoided as much as possible.

Powerline route is not sensitive to gradient or horizontal turns. However, similar to pipeline, access road can be a limiting factor. Transmission line must be built on stable grounds and be well designed to stand extreme weather conditions. Due to safety issues and the negative effects of high voltage powerline on neighbouring facilities, adequate spacing should be allowed between transmission line and pipeline or railway.

2.2.3 Compatibility challenges

Different systems located laterally in a same ROW might undesirably affect one another. These potential effects can jeopardize the functionality of the systems or increase their maintenance costs. In addition, when two neighbouring systems are technically incompatible, they can pose a risk to users, workers, environment, and assets located in their vicinity. The magnitude of these potential incompatibilities depends on a number of factors including the specifications of the systems, modes distancing, the length of paralleled systems and environmental conditions.

Reference [20] considers only one technical incompatibility within a corridor comprised of six systems (Road, railway, powerline, metal pipeline, fiber optic cable, plastic waterline). This is between powerline and pipe line. The BC HYDRO RIGHTS OF WAY GUIDELINES, addresses the issue as follows: “BC Hydro has found that for a 30 kA median lightning current and an average soil resistivity in B.C. of 1000 ohm-m, the minimum separation distance to prevent arcing is 30metres. If BC Hydro is to reduce the minimum separation, a soil resistivity test will need to be performed at the specific location for which the calculations are being done. BC Hydro will consider a reduced separation if a technical analysis shows that it is feasible. This test analysis must be reviewed and signed by a Professional Engineer registered in the province of British Columbia and reviewed and accepted by BC Hydro”. Besides, [20] suggests cathodic protection as a means of resolving the issue, where the proposed spacing is not plausible.
Reference [11] discusses technical compatibility amongst five different modes (Road, railway, powerline, pipeline, communication lines). According to this report, although all these systems influence one another to some degree, the most problematic one is the transmission line. If the induced current and voltage from a transmission line into its nearby metallic objects are not considered in design process, serious consequences could ensue. The induced current and voltage also can negatively affect the cathodic protection of the pipeline.

Reference [14] investigated interference of different systems in a corridor and provided a matrix of interactions between different utilities. This matrix offers a comprehensive view about any possible interference in a corridor. This is important because most of other references limited their studies to merely the problems caused by powerlines. For instance, railroads and highways can pose safety issues for other systems within a corridor. These issues include potential accident and derailment. In addition, fire and explosion hazards are the main risks of pipeline for its neighbouring systems.

Issues related to powerline have been well studied in the literature. Electric Power Research Institute (EPRI) and the Pipeline Research Committee of the American Gas Association conducted a study which investigated mutual Design Considerations for Overhead AC Transmission Lines and Gas Transmission Pipelines [43]. In addition, effects of high voltage powerlines on railroad tracks are studied in [15].

A/C interference guideline provided by Canadian Energy Pipeline Association (CEPA) [17] and “criteria for pipeline co-existing with electric power lines” prepared by the INGAA foundation ([16] explain different risky interactions between powerlines and pipelines in detail. These guidelines introduce three modes of interference that can damage pipeline facilities or pose the risk of electrical shock to the pipeline personnel or the public. The interferences are: inductive, resistive (conductive) and capacitive (electrostatic) coupling. Five major factors determining the severity of AC interference are: separation distance, powerline current, length of shared ROW, soil resistivity and collocation or crossing angle [16].
Where powerlines and pipelines are to be installed in the same ROW, the Canadian standards set by C22.3 NO. 6-13 (R2017) must be met.

2.2.4 Financial challenges

The construction cost of a multi-modal corridor is higher than the sum of the construction costs of all the individual modes. This is due to the cost of risk mitigation measures to make all neighbouring systems safe to one another. Another reason is related to the location of the corridor which is a compromise among different modes and thus is a sub-optimal route for each individual mode[11]. However, a multi-modal corridor has the potential to compensate for these extra costs and also save money. Potential areas of saving include sharing access roads, less amount of required land for ROW, integrated planning, saving money and time in negotiations and legal works with land owners and indigenous communities and maybe the most importantly, shortening the time to obtain approvals and permission forms from organizations and officials in charge.

It seems that saving time and money in procuring permits for projects is one of the greatest advantages of a multi-modal approach, especially in Canada. With regards to dealing with construction permits, the World Bank’s report[44] ranked Canada 54th among 190 assessed countries. While obtaining a construction permit takes 249 days in Canada, it takes 80.6 days in the USA and only 64 days in Denmark[44]. Moreover, this report mentions that construction permits and obtaining site plan approvals are also expensive in Canada. There are many studies and proposed infrastructure projects which have never been built due to various barriers, with delays in many approval procedures being of the major ones. Some of them such as Athabasca oil sand corridor or Peace River – Fort McMurray were either only partially built or not approved at all. Some others such as Mackenzie Valley Pipeline project were canceled because the approval was issued many years after the submission of the project proposal, at a time when it was no more financially viable.
2.2.5 Reliability challenges

The reliability can be negatively affected by co-locating various systems in a relatively narrow passage. It is a main concern for infrastructure users but it has additional importance when it comes to power transmission lines. Any accidents rendering a power transmission line out of service could impose extra loads to neighbouring electrical transmission or generator facilities. In a worse case scenario, a domino effect can result in a cascading outage.

A number of reliability issues were reviewed in the section related to the technical compatibility of a multi-modal corridor. There are other potential reliability issues as well such as accidental damages to neighbouring facilities by active personnel or machinery in the corridor. An accident or a natural disaster could also hit the systems located close to one another. Generally, the systems are more vulnerable to Sabotage and terrorist attacks if situated side by side. A passive defence study seems to be necessary for a corridor with this significance.

Integrated monitoring systems and easy and fast accessibility to all modes (for example to a pipeline by a highway) are of the potential positive aspects of multi-modality. Allowing sufficient space among different modes, taking required risk mitigation measures, smart monitoring and governing the corridor and effective and adequate communication and cooperation among different corridor participants are imperative.

2.2.6 Environmental and social considerations

The environmental impact of joint-use approach needs to be studied on a case by case basis as it is hard to draw a general conclusion. The present local environmental characteristics and the availability of alternative solutions for a joint-use corridor can determine whether it is environmentally beneficial. It can reduce the total environmental impact of the system in comparison with implementing several modes separately. Besides, less area clearance and environmental disturbances are expected. Where traversing a relatively wide clearing becomes problematic for a predominant species, ecological buffer zones are necessary to mitigate the problem. It seems crucial to
build wildlife corridors where wildlife migration routes are crossed by the transportation corridor. While highways and railways are barriers for wildlife movements, except during the construction phase, powerlines and pipelines seem to be less of an issue.

Different transportation modes have different levels of social acceptance. A highway may provide better connectivity and lower living cost and therefore be more acceptable for local population than a pipeline with pollution or explosion risks. The change of sceneries local people use to see, the risks of negative impacts on their health and environment may make a corridor socially unacceptable. Raising public awareness, sharing information, and using local and aboriginal people’s capacity and including them in different levels of project is suggested.

2.3 Summary

Multi-modal transportation corridors are generally feasible, and their advantages outweigh the disadvantages. But to determine the feasibility of each project, its specifications have to be studied individually. There are two possible reasons that make the construction cost of a multi-modal corridor higher than the sum of the construction costs of all the individual modes. Firstly, the location of a multi-modal corridor ROW is in general a compromise among the optimal locations of the ROWs of its various components. Secondly, putting all facilities in the same ROW needs taking extra measures, evidently with extra costs, to make them safe in one another’s proximity. A joint-use ROW project is financially preferred over a series of individual projects for each transportation mode if its financial benefits outweigh the extra costs.

The main compatibility issue for sharing ROWs is about locating powerlines in the proximity of pipelines. In this case, A/C interference guideline provided by Canadian Energy Pipeline Association (CEPA) [17] and “criteria for pipeline co-existing with electric power lines” prepared by the INGAA foundation ([16] are among the important guidelines needed to be considered.

In general, locating highway in the middle of a corridor makes accessing railroad and pipeline for operation and maintenance more convenient. The route of pipeline is more flexible than that
of highway or railway. Therefore, being positioned on one side of the corridor makes it possible for the pipeline to deviate away from the corridor where it is not financially viable to follow its path. This would also make it more accessible in case of an accident. Railway is greatly sensitive to the terrain gradient and also needs room for smooth turns. Therefore, locating it on the edge of the corridor provides extra room for its movements. Putting highway between pipeline and power transmission line helps reduce the incompatibility of these two.
Chapter 3

Multi-Modal Corridor Routing

As reviewed in Chapter 2, one of the important engineering challenges related to multi-modal corridors is routing. The route of a corridor significantly influences its economic, environmental, and social impacts. A road, railway, power line or in general a transportation corridor is a continuous strip of lands connecting a start point to an end point. There are bilateral impacts both on the corridor and on the traversed lands. The topography, soil conditions, land use, number of rivers and many other factors of the lands affect the cost and geometrics of corridors. On the other hand, a corridor has environmental, social, and economic effects on its neighbouring areas. Routing is simply a process to find the most suitable areas for the corridor to pass through with minimum overall cost and maximum benefit. These considerations make routing a key stage in designing a corridor, capable of rendering a project viable. Finding an optimal path for a multi-modal corridor is more complicated than a single-mode narrow path. A multi-modal corridor needs to be wide enough to accommodate all transportation modes. In addition, its path has to be acceptable for all different modes even though various modes have different movement constraints and different impacts on their environment.

Finding an optimal path, wide enough to be able to contain, and be acceptable for all different modes is a complicated and vital task. While an optimal route can minimize the cost of a corridor as well as its environmental impacts, a path which does not consider different modes’ movement constraints when moving together, has the potential to make the corridor costly infeasible.

The process of routing a corridor can be divided into two phases. In the first phase, a general alignment that is acceptable to all stakeholders is found. This phase is the most challenging phase and is the focus of this thesis. This phase is broken into four steps explained in Section 3.1. The second phase includes engineering design and route refinement. Standards and codes related
to the route curvatures and geometry are considered in the second phase. However, this phase is not within the scope of this thesis.

In this chapter, firstly, the method of corridor routing by integrating multi-criteria analysis and GIS techniques is reviewed. This method encompasses four steps: identifying objectives and criteria, data gathering, making a composite cost-surface by weighting criteria and combining them, and applying a least-cost-path (LCP) algorithm to find an optimal path. Furthermore, the problem of routing a corridor when its width is considerably larger than a cell size in cost raster is explained in this chapter and the existing relevant methods are reviewed. Finally, the complexity and applicability of the existing routing methods with respect to both the width and multi-modality of the corridor are discussed.

3.1 Integrating Multi-criteria Analysis and GIS to Find an Optimal Corridor

Various factors can determine the suitability of a path, including terrain, geology, soil type, waterbodies, slope, land cover, land use, endangered species habitats, etc. [45] [28]. For example, considering terrain factor, Western Electricity Coordinating Council (WECC) recommends that based on the difficulty of the terrain, a cost multiplier should be applied on the construction cost of power transmission lines. While flat lands are the most suitable terrain with the cost multiplier equal to one, the forested areas are the most expensive one with the cost multiplier equal to 2.25 [46].

In his book, Design with Nature, Ian McHarg [47] was one of the pioneer scientists who devised the method of overlaying monochrome maps for finding a best route. In this process, for every criterion impacting the cost of traveling, a monochrome shaded map is provided with darker colours representing higher costs and lighter colours representing lower costs. These transparent maps are then overlaid on a light-table and an optimal route is determined visually by going trough the lighter areas and avoiding the darker ones as much as possible [47]. Today, with the availability of advanced computers, this method can be implemented in a more automated way with the help
of GIS tools to provide a composite cost-surface and to apply an optimal routing algorithm \[28\].

Most of the computerized corridor routing models go through four major steps for finding a general alignment i.e. the first phase mentioned above. The first step is identifying the objectives and criteria important for the project stakeholders. The second step is data gathering around the important factors influencing the routing process in the form of a square grid cells, i.e., raster data. The third step is to assign a suitability value to each cell, representing how easy that cell is to be traveled through with regards to the physical, environmental, and social barriers. The more suitable means less cost and less negative impact on the environment and society. The final step is to apply an LCP algorithm, such as Dijkstra \[48\], to the scored grid network to find the shortest path that connects an origin to a destination \[27\]. These four steps are shown in Figure 3.1 schematically.

3.1.1 Identifying Objectives and Criteria

The first step is to identify the main objectives and goals based on which the routes are evaluated. These goals represent the most important categories of factors impacting the suitability of route alternatives. They determine the criteria and sub-criteria that control the whole routing process in further steps. These often common goals are discussed in the previous routing literature. \[49\] chose economic and environmental impacts to evaluate alternative routes. \[28\] introduced economic cost, environmental impact, proximity to population centers and accessibility for maintenance as potential objectives. \[50\] used economic, ecological, and technical factors for a railway alignment. \[51\] categorized the objectives into four dimensions, including economic, environmental, social acceptance and existing infrastructure for a High Voltage Direct Current electrical power transmission line routing study in Europe.

Each of the objectives mentioned above can be broken down into multiple criteria and sub-criteria. The criteria as well as each criterion’s relative importance may vary from one project to another. Identifying important criteria and sub-criteria for routing of different transportation modes and weighting them has its own area of research. For example, \[52\] determined the criteria for transmission lines routing and \[53\] focused on identifying and weighting the geotechnical and
Figure 3.1: Integrating multi-criteria analysis and GIS for finding the least-cost-path
soil condition criteria in a study of routing a road in Sumatra.

The physical conditions of a project such as its size and length, the type of infrastructure that is located in the route, the surrounding condition of the location and the availability of data are important in determining the criteria. A comparison between [51], which is a power line routing study in Europe, and [54] that focuses on an arctic road study in Canada, shows how the criteria can vary based on the type, location, goal and other conditions of projects. [51] divided the economic objective into the length of route, the underlying terrain, and the land ownership; the terrain factor can further be broken down into elevation and slope. In the same paper, environmental objectives include landscape aesthetics, areas under protection and river courses. The negative impact of power lines on social acceptance is determined by population density. In this study, the existing of infrastructure, such as railways, motorways and high-voltage power line, were also considered. [54] determined two objectives for routing an arctic all-weather road: engineering and environmental factors. Surficial material, esker distance, rock distance, slope and streams are amongst engineering criteria, while wolf den sites and archaeological sites are among the environmental criteria.

3.1.2 Data Gathering and Processing

The second step is collecting data on the routing goals. The data may include land-use, elevation, slope, land-cover, geology and soil type, permafrost zones, location of existing roads, railway, transmission lines and other networks, habitats of endangered species, wildlife migration routes, environmental sensitive areas, first nation reserves, heritage sites, wetlands, locations of power substations and generators or power storage systems [28] [27] [49] [54].

Because of the diversity of the parameters which can affect the suitability of a route, route planning typically is a multi-objective task [49]. A common solution is to weight objectives and make a single objective cost raster for routes alignments [28]. The study area considered for building the corridor is divided into squared cells and a cost value is assigned to each cell depending on its suitability for being part of the corridor.
To use an optimal route-finding algorithm in GIS applications every geographical feature needs to be converted to raster data format with a specific cell size. In conversion process from vector data that includes points, lines and polygons to raster format choosing the cell size is important. To save greater detail in the conversion process, a smaller cell size is needed which results in a higher resolution raster. In other words, to minimize the problem of losing accuracy, the size of each cell should not be too large [49]. On the other hand, selecting a very small cell size or a very high-resolution raster data may dramatically increase the computation time as well as the cost of data acquisition. Therefore, an acceptable compromise between the level of detail, i.e., cell size, and the processing time needs to be made depending on availability of computing resources and the width of the study zone [54] [27]. For example, [55] considered a 1 km by 1 km cell size as a low resolution and a 5 m by 5 m cell size as a high resolution data source for power transmission routing. [56] used a 90 m cell size for an LCP analysis for a power transmission line routing where the route length is about 140 km. [27] used a 610 m cell size raster data for a power line routing study in Maryland, United States. [54] used a raster with 20 m pixel size in an area with 200 km width for routing an arctic all-weather road in Northwest Territories of Canada. [51] converted their 100 m resolution original raster data to a 500 m raster to reduce data file sizes and processing time for a high voltage power line routing analysis in Europe.

The resolution of collected data for various criteria may vary from one criterion to another. In this case, the resolutions can be converted into the resolution of the target composite map in a data pre-processing stage because the ultimate goal of this step is to provide a cost-surface for further routing analysis. Many government agencies’ spatial data bases such as maps, aerial photograph and remote sensing data can be used to create the needed raster data sets [54] [27].

3.1.3 Weighting and Combining Criteria Maps to Create a Composite Cost-Surface

After gathering data in raster format for various important factors it is needed to assign a cost-value to each cell. Low cost-value cells mean suitable areas, while high cost-value cells are unsuitable locations. Combining Multi-Criteria Decision Analysis (MCDA) and GIS tools can save money
and time in route planning projects [56].

When the objectives and criteria are identified and relevant data is gathered, it is time to rank criteria and assign weights to them and then, to assign suitability score to cells based on each criterion. The next task is combining them to create a composite map that shows the accumulated cost of traversing each cell.

In a routing process, different stakeholders’ preferences can be merged and combined by integrating GIS and multi-criteria evaluation techniques [57]. Assigning weights to criteria is a very subjective task and depends on the judgments of stakeholders participating in criteria importance determination. Delphi method [58] and Nominal Group Technique [58] can be helpful in overcoming this issue as objectively as possible [27]. [59] shows how the raw data for every criterion can be scaled in a manner whereby weighting and aggregating them would be mathematically valid. In these methods, low suitability means high cost values and high suitability means low cost values [49]. In general, suitability score is the result of weighting and combining the sub-scores associated with the criteria and sub-criteria related to major objectives such as environmental or economic objectives [49].

Using a MCDA method, such as Analytic Hierarchy Process (AHP) developed by Saaty [60] for weighting criteria in routing process, is well studied in the literature. For example, [56] used this method for routing a power transmission line, and [61] for a highway alignment. To enhance the conventional AHP method in dealing with uncertainties related to participant experts’ opinions in weighting process, AHP technique can be combined with Fuzzy method to produce criterion cost layers. These two methods were implemented by [50] and [62] for railroad planning and by [63] for routing a power transmission line and also by [54] to find an all-weather road routing in Canada. Figure 3.1 shows the process of combining GIS and MCDA methods to create a composite cost raster, i.e., cost surface.

A comprehensive literature review on GIS-based multicriteria decision analysis is done in [64]. In general, a criterion may refer to an attribute or an objective. Therefore, according to [64] MCDA
can be divided into two main categories namely multi-attribute decision analysis (MADA) and multi-objective decision analysis (MODA). The MADA methods are assumed to have a predetermined, limited number of alternatives and are useful to compare these alternatives. In contrary, MODA methods are applicable to find the optimal solution among all feasible solutions. In other word, MADA methods are selection process while MODA methods are design process [64]. Simple Additive Weighting method (SAW) [65], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [66] and AHP [60] are among well-known MODA methods. Various MCDA methods are also widely explained in a book written by Jacek Malczewski and Claus Rinne [67].

The assigned weights for different criteria are not the same for various transportation modes. These variations have roots in different movement characteristics of various modes, different stakeholders participating in each mode’s routing and various economic, environmental and social impacts of each mode. For example, a highway may block a wildlife migration route while a power transmission line or an underground pipeline are not big barriers with this regard. In social acceptance the concept is similar. A highway may provide better connectivity and lower living cost and therefore be more acceptable for local population than a pipeline with pollution or explosion risks. The economic objectives also vary among various modes. For instance, a railway cost is much more sensitive to the slope than pipelines or power lines are. Proximity to aggregate deposits and remoteness from bodies of water and stream crossings have crucial effects on a road cost, while they are not as important in power line routing.

These differences among cost rasters of different modes will result in different optimal paths in further steps. Therefore, the LCPs for different modes have variations in the landscape. For example, assume that the only important criterion for routing is the gradient of the terrain and the LCPs for four different modes are shown in Figure 3.2a. Observed in Figure 3.2a that the optimal routes for the pipeline and the power transmission line are chosen in a more straight path compared to that for the highway and railway. This is due to the higher sensitivity of the two latter to the
3.1.4 Creating Graph and Applying an LCP Algorithm

After setting the objectives and criteria, gathering data related to these criteria, weighting and combining these data layers based on all stakeholders’ opinions and creating a cost surface raster
which represents the cost of traveling each square cell, it is time to find an LCP. An LCP is a route with minimum cost (impact). For this purpose, a network, also referred to as a graph, is defined on the composite cost raster, in which the nodes are the centers of the cells and the edges (arcs) are the line segments between two neighbouring nodes [27]. The allowable movement between two nodes (cells) can only be direct arc, similar to the rook’s moves on a chess board Figure 3.4a or it can be extended by adding diagonal arcs similar to queen’s moves in chess Figure 3.4c. In the latter way, every cell is connected to its eight surrounding cells. By adding arcs which link each cell to all its neighbouring cells within a ring of two cells, both queen and knight movements are possible. Figure 3.4e depicts the queen plus knight movements. Note that the links which are the repeating of simple queen moves, are not depicted in 3.4e [49] [76] [27].

As the number of accessible cells increases, the turn angle between an input movement and an output movement can be reduced and a smoother movement becomes possible [77]. On the other hand, increasing linkages between cells means increasing the number of edges and network complexity [49], which results in a higher computation time.

Orientation, elongation, and proximity distortions are three kinds of possible geometry distortions that may occur during a path finding [27]. Figure 3.3 shows how when merely rook movements are permitted, the shortest path from point A to point B will be an stair steps shown in red. Whereas, when diagonal movements are allowed as well, the shortest path will be the green path. The orientation errors are caused by the difference between the real shortest path and the alignment of the grid [27]. [78] defined the elongation distortion as the length of the found shortest path, i.e., the red path, to the length of actual shortest path, i.e., the green path, which is equal to $\sqrt{2}$ in the example shown in Figure 3.3. Radius of linked neighbours, referred to as $r$, determines the allowable directions of movements. $r$ and the cell size of constructed grid can affect Elongation and Orientation errors. In Figures 3.4a, 3.4c and 3.4e $r$ is equal to 0, 1 and 2, respectively. The constructed grids using these three kinds of connectivity are shown in Figure 3.4b, 3.4d and 3.4f in the same order. These grids show that higher $r$ results in more allowable movements and thus,
Figure 3.3: Direct path versus stair step path

less distortion and elongation error.

The impacts of various allowable movements on LCP analysis are studied in [27], [79], [76] and [77].

The impact, i.e., cost, of a corridor can be identified by summation of its footprint from an origin to a destination. This cost is a function of the costs of cells which are traversed by the corridor and the area of those cells which is occupied by the corridor, as depicted in Figure 3.5 and can be calculated by (4.4) where A and C are the occupied area and the cost of the cell $ij$, respectively. [27] [49]. When the width of the corridor is assumed to be zero then the cost of a path is just a function of length of the path within each cell and the costs of traversed cells. In this case, the weight to go from cell i to cell j for an orthogonal and diagonal move can be calculated by the (4.5) and (4.6), respectively [56]. Figure 3.6 shows a 3 by 3 cost raster with three specified cells A, B and C. As an example, the costs of a diagonal edge, AB, and an orthogonal one, BC, are calculated in Figure 3.6.
Figure 3.4: a) accessible cells via Rook’s pattern (4 blue cells) and b) constructed grid based on them. c) accessible cells via Queen’s pattern (8 blue and red cells) and d) constructed grid based on them. e) accessible cells via Queen’s plus Knight’s pattern (16 cells) and f) constructed grid based on them.
Figure 3.5: The total impact of a corridor in a grid

\[
\text{Total Impact} = \sum_{i=0}^{9} \sum_{j=0}^{9} A_{ij} \times C_{ij} \quad (3.1)
\]

\[
w_{ij} = \frac{c_i + c_j}{2} \quad (3.2)
\]

\[
w_{ij} = \sqrt{2} \frac{c_i + c_j}{2} \quad (3.3)
\]

After defining the graph on the cost raster where the centers of cells are nodes and the allowed movements are edges and the cost values of the traversed cells are the weight of each edge, an LCP algorithm can be applied to find a set of nodes that illustrate an LCP \[80\]. Dijkstra algorithm \[48\] and A* algorithm \[81\] are two well known algorithms for finding LCP \[82\]. The Dijkstra is the most widely used algorithm for a single origin shortest path problem because of its simplicity and efficiency \[28\]. The different steps of application of Dijkstra algorithm for finding LCP is well explained in \[78\], \[79\] and \[13\].

The original Dijkstra algorithm in a graph with \( n \) nodes and \( m \) edges, when a naive data structure is used, has a complexity of \( O(n^2) \). However, the complexity can be reduced by using modern
Figure 3.6: Cost of edge AB i.e. diagonal move = $1.4142 \times \frac{1}{2} \times (4 + 2) = 4.2426$

Cost of edge BC i.e. orthogonal move = $\frac{1}{2} \times (5 + 2) = 3.5$

data structures such as Fibonacci heaps, double buckets and approximate buckets to $O(m + n\log n)$ and computation time remarkably decreases in this way [28]. The Dijkstra algorithm with a modern data structure is the preferred algorithm for non-real-time applications when the origin point is fixed and high accuracy is demanded [82]. In this thesis the goal is finding a shortest path from a certain source (origin) to a destination for right-of-way alignment which is not a real-time application; therefore, Dijkstra algorithm is used for this purpose. In ArcGIS the width of path is assumed to be zero and queen movements to the eight neighbouring cells are allowable [49]. Furthermore, Dijkstra algorithm is used to find the LCP in ArcGIS Network Analyst extension [83].

3.2 Wide Corridors Alignment

Geographic Information System software packages assume that the width of path is zero and they cannot take the width of corridor into account [28]. However, this is a natural assumption that the width of the path should be equal to the width of the right-of-way needed for the linear infrastructure being routed [27]. Even for a corridor with a width equal to or less than one cell size, neglecting the width may result in finding undesirable routes similar to what was explained above.
To show how the unrealistic assumption of zero width could lead to a non-optimal path, a cost raster and the found least-cost-path using ArcGIS is shown in Figure 3.8. Figure 3.8a shows a synthetic cost surface and an origin and a destination point colored in blue. The LCP found using ArcGIS connecting the origin and the destination is the black path in Figure 3.8b, whereas the real shortest path is the brown path shown in Figure 3.8b. The reason of finding the black path is that in ArcGIS the path is just a line connecting centers of cells, thus, the weights of two cells with high cost values, highlighted by H, were not taken into account during the diagonal movements. If the width of the path is considered, these two cells make the cost of the black path higher than the cost of the brown path.

The problem of considering the width of the path in LCP finding process in conventional GIS packages is even more significant when the width of the path is considerably larger than a cell size. Although finding an LCP with considerable width in a raster space might seem similar to the classic LCP methods, using the same method can result in unrealistic LCPs. The weakness of the classic GIS packages is that they do not consider the weight of neighbouring cells around the centre line of the path. The first idea probably is to find an LCP and then buffer that path to make as proximity distortion.
Figure 3.8: Zero-width LCP versus 1-cell-wide LCP

it as wide as the desired corridor [2].

Figure 3.9 illustrates the found LCP which starts from cell A and ends in cell B in blue. If the desired path is five times larger than the cell size, the orange wide path can be produced by buffering the blue centerline to 2.5 cell size in each direction. However, the suitability scores of two rows of cells around the centerline’s cells did not affect the classic LCP method in our grid. This basically means that our method of buffering is completely blind to the neighbouring cells. [84] showed that buffering method may include extremely expensive cells in a wide corridor.

Another method is to enlarge the cell size by resampling it to achieve a cost raster whose cell size is equal to the width of the required path. [1] applied resampling method to a cost raster where the required path’s width was 2 times larger than the original raster’s size. He re-sampled the original cost raster which was an artificial 10 by 10 cell cost raster and doubled both width and height of original cells. [1] pointed out that both one-cell-wide path found on the original cost surface and the path found on the resampled cost surface with two-cell-wide, followed very different routes to the optimal two-cell-wide path which his method provides. To better illustrate the resampling method a schematic LCP is shown in black in both original grid 3.10a and resampled double size.
To consider the cost of neighbouring cells and reduce the proximity distortion, [27] used a smoothing approach. In their experiment, they calculated a weighted average of the neighbouring cells’ costs in a certain radius and assign it to each cell to make a new cost surface. They introduce three methods of weighting. In the first method, the costs of neighbouring cells matter equally, while in the second and third ones, the importance of further cells’ costs are reduced by applying inverse distance or inverse-square distance functions, respectively [27]. By implementing the smoothing method, the costs of cells located in each other’s proximity affect each other and thus, the neighbouring cells are more similar to each other. In this way, for example, canyons and cliffs will be turned into hills and valleys. Since smoothing can reduce the resolution of data, the degree of smoothing (the radius and weighting multipliers) needs to be chosen conservatively [27]. It is not claimed by [27] that this method results in a more or less realistic solution; rather it is a way to control the output of the conventional LCP. [2] points out that the smoothing method works if the original cost raster is a uniform cost surface with some obstacles with very high values on it. [13] implemented the smoothing technique using a conventional GIS software to make an efficient and simple method for routing of wide corridors. However, it seems that the drawbacks of smoothing
Reference [1] developed a sophisticated method to find a wide LCP by creating a specific graph on the original cost raster made by w-nodes and w-edges. "W-nodes" are combinations of contiguous cells from original cost raster which make a "path front" with specific criteria such as geometry and length. These valid path fronts (w-nodes) are connected to each other by some valid transitions called "w-edges". Applying an LCP algorithm to the described graph gives a sequence of valid path fronts which construct a wide path with a specific width. In general, this approach transforms the conventional graph described in Section 3.1.4 and finds the LCP on this transformed graph. The final wide LCP could be construed by following the neighboring cells (w-nodes) on the original raster. As reviewed in [2], this method would be very complicated when the width of a corridor is relatively large in comparison to the cell size, because the number of w-nodes increases exponentially as the length of path front increases. Further more, this method keeps the number of cells fixed in the path but not the Euclidean distance representing the width of the path.

Shirabe (2016) introduced a method to find a wide LCP with a width equal to a fixed Euclidean distance. The graph of this method is constructed of a certain form of neighbouring cells ("neighborhoods") as nodes and possible transitions between adjacent neighborhoods. A certain
cell called “focus” of neighbourhood and a fixed arrangement of its surrounding cells make a neighbour-
hood. The arrangement is defined by the desired width of the path. For example, for creating a 2-cell width path a two by two block could be the arrangement, and the upper left cell of each block could be considered the focus cell working like a pen tip. In this transformed graph, two adjacent foci make two adjacent neighbourhoods (nodes) and are connected to each other by edges (transitions). The weight of an edge is equal to the difference of two accumulated costs of cells within two adjacent neighbourhoods which are connected by the edge. After applying an LCP algorithm on this transformed graph, a set of foci and their neighbourhoods will be found. The sequence of neighbourhoods in a landscape is like the movement of a pen tip on a paper which makes a relatively fixed Euclidean distance path.

Although LCP finding in raster data format is studied well in many researches for different applications such as highways or pipelines alignments, surprisingly the number of studies considering the width of path is low [13]. To find an LCP for a multi-modal corridor the importance of considering the width seven higher than a single-mode corridor because a multi-modal corridor is generally wider due to its different included transportation modes and the safety distances designed between each two neighbouring modes. The method described above could respond to the width of a multi-modal corridor. However, they cannot consider the multi-modality of the corridor. This problem is addressed in the following section.

3.3 Multi-Modal Corridor Alignment

A multi-modal corridor has two characteristics that make its routing more complicated than a conventional LCP problem. These include: (i) being wide, and (ii), collocating different modes with different movement criteria in a same path. Since the various modes within a multi-modal corridor have different criteria with varying levels of importance, finding a wide path for one of them and assigning it to the others can result in a very costly path for the rest of modes.

One approach would be to weight the different modes and then to make a single cost raster for
each of the modes and finally, to find a wide path on an aggregated cost raster. However, using this method can result in the contrary criteria dissolve the impacts of one another. Moreover, the lateral arrangement of the modes would not be taken into account. In other words, making a composite cost-surface for all of the modes located in a corridor and constructing a wide path front[1] or a neighbourhood [2] leads to losing some data accuracy and a non-optimal path for the multi-modal corridor.

To illustrate this problem, an example is depicted in Figure 3.11. Figures 3.11.a and 3.11.b show two cost-rasters for highway and pipeline, respectively. Blue and orange colors are used to show the costs of these two rasters. More saturated colors represent the more costly cells, while the less saturated ones show the relatively less costly ones. The cost of the cells is written on them. The goal is to find a 2-cell-wide path for a multi-modal corridor which collocates both highway and pipeline. For simplicity, it is assumed that (i) these two modes have the same importance, (ii) each of them needs a one-cell path, (iii) only rook movements are allowed. The starting points for the highway and the pipeline are specified by SH and SP, respectively. In the same manner, end points are EH and EP.

According to the assumption (ii), each of the cost-rasters takes 50% of the weight. Therefore, the value of each cell in the combined cost-raster will be the average of the two modes’ rasters as shown in Figures 3.11.c and 3.11.d. Finding an optimal two-cell-wide path in this combined raster will result in the yellow path shown in Figure 3.11.c, where the highway and pipeline paths are shown with blue and red arrows, respectively. The cost of all of the cells constructing the yellow path in the combined cost-raster is equal to 28, whereas the cost of the green path shown in Figure 3.11.d is 32.5. Therefore, in this method, the yellow path is more optimal than the green path with respect to the accumulated cost. However, if the cost of each of these two paths was calculated on the original cost-rasters, the accumulated cost of the yellow path would be 28 as shown in Figure 3.11.e and the optimal path would be the green one with a cost of 20, as shown in Figure 3.11.f. Note that the values of the blue and the red arrows are taken from the cost-raster of highway Figure
3.4 Conclusion Remarks

In this chapter, routing a corridor, in a raster data format, by integrating GIS and multi-criteria analysis was reviewed. This process includes four major steps: 1-identification of the objectives and criteria, 2-data gathering, 3-making a composite cost-surface using the weighting criteria and combining them and 4- applying a least-cost-path (LCP) algorithm to find an optimal path. Furthermore, the assumptions of conventional GIS applications such as ArcGIS was explained. One of these assumptions is related to the width of a path that is assumed to be zero. This assumption is not applicable to a wide multi-modal corridor. To address this issue, a number of solutions are suggested in the literature. Although these solutions are helpful for optimally routing a wide single-mode corridors, they cannot take into consideration the multi-modality and the arrangement of different modes within a wide corridor.
Figure 3.11: a) A synthetic cost raster data for highway, b) A synthetic cost raster for pipeline, c) The optimal 2-cell-width path on combined cost raster i.e. yellow path, d) A non-optimal 2-cell-width path on combined cost raster i.e. green path, e) The cost of the yellow path on the original cost rasters, f) The cost of the green path on the original cost rasters
Chapter 4

Multi-Modal Corridor Routing the Proposed methods

Being wide and having a certain arrangement of modes make routing of multi-modal corridors a complicated task. To overcome this complexity, in Chapter 4, four different methods are proposed. The first, second and third method use the existing methods with some extra steps. The fourth method has fundamental difference with the existing methods and uses multiple layers of cost raster directly for calculating weights in its connectivity graph. The first and second methods use the existing methods for finding an LCP that is both wide and multi-modal. The first method, finds a path for the mode with the highest priority and then widens it to accommodate other modes. In this thesis, this method is referred to as: Finding Least cost path for a Single mode and Generalizing to other modes (FLSG). Finding an LCP for the first mode is based on the conventional methods for pure linear paths. The second method is referred to as Finding a Wide LCP on the Accumulated Cost raster (FWLA). In FWLA, all of the cost surfaces related to different modes within the corridor are combined and then, a wide LCP is found in the combined cost surface. In FWLA, finding a wide path on the combined cost surface can be done by methods discussed in Section 3.2, including buffering, re-sampling and using the neighborhood concept. The further steps are combining cost surfaces and accommodating all modes in the found wide path.

The third method, referred to as Shared Area of Multiple Corridors (SAMC), takes all the individual cost rasters related to the corridor elements and creates a wide corridor for each mode. The shared areas of these corridors are then used to align the multi-modal corridor. In the SAMC method, for each cell, the cost of the LCP starting from the corridor’s start point and ending at the corridor’s end point, with inclusion of this cell, is separately calculated for each mode. Then the cells are categorized by setting an increasing upper bound for their LCP cost. These upper bounds are increased for different modes to make wider and wider corridors until the shared cells of the
corridors of different modes provide a wide enough path.

The fourth method, referred to as Multi-Directed Transformed Graph (MDTG), also takes different cost rasters related to the various modes to make a transformed multi-directed graph constructed of neighbourhoods, i.e. sets of cells. Each neighbourhood has a reference point and takes its weight from the layers of cost rasters related to different modes. In this graph, the nodes, edges and weights work like Lego pieces. Each piece is comprised of different coloured segments related to each mode that take their weights from the corresponding cost rasters. The weights are calculated based on the direction of each edge and the desired width and arrangement of the corridor modes. After finding the LCP on the transformed graph, a list of reference points is determined that can be transferred to the original graph to align the actual path of the corridor. This method is not only applicable to routing of a multi-modal corridor but also to a single-mode wide path with the desired width in every direction. A comprehensive comparison of this method and other methods is presented in this chapter for both multi-modal and single-modal wide paths.

The advantages and drawbacks of all methods are discussed in related sections. Also, the methods mentioned above are applied to a synthetic data set to find a multi-modal corridor and the results are discussed. In addition, the applicability of the MDTG method to a relatively large area is tested and discussed.

4.1 Route planning by Finding a Least cost path for a Single mode and Generalizing it for other modes (FLSG)

The proposed FLSG method is the simplest method among all four methods since it uses the conventional methods available in most GIS applications. This method assumes one mode as the most important one in terms of the cost or priority. The LCP found in this method is only based on the suitability for this mode. This mode could be the most expensive one, the widest one or the mode that is going to be built first. After finding the pure linear LCP for this mode, the neighbouring lands are reserved as the right-of-way for the future modes. The process is shown in
Figure 4.1 and it can be divided into the following steps:

- Defining the mode with the highest priority which most probably will be built first.
- Aligning the first mode defined in the previous step using the existing methods.
- Preserving enough lands in the proximity of the route found in the previous step for the ROWs of the other modes of the corridor.

As an example, assume that points A and B are, respectively, the origin and destination points of the corridor shown in Figure 4.2 and a highway is the most prioritized mode going to be built. In the first step, the LCP for the highway, i.e. the grey path, is found. Then, the neighbouring lands of this path, i.e. the blue areas, are reserved for the ROWs of the remaining modes.
Figure 4.2: The corridor path is defined based on the first mode, i.e. Highway, and lands in a certain proximity are reserved for future expansions for the ROWs of the remaining modes.

The most advantageous feature of this method is perhaps its simplicity. Inclusion of all of the modes in the routing process means involvement of a series of various stakeholders who need to compromise on many issues such as, the respective weight of each mode, the main criteria and finally the acceptable common route for all modes. This issue could make the routing process a time-consuming and technically challenging process.

The other potential advantage is that the aligned route is mostly in favour of the prioritized mode, meaning less cost for the first mode and less investment in the beginning of a huge project. Moreover, if the remaining modes of the corridor are decided not to be built, the cost of building the first mode would not increased as a result of compromise on the route with other modes. However, this advantage can turn into a disadvantage if the other modes are to be built.

The drawback of this method is that during the routing process only the first mode cost raster is taken into account. As a result, the reserved neighbouring lands may not be suitable enough for the other modes just as in a group trip where the leader does not take the opinions of the other teammates into account and plans the trip only based on his/her preferences. For example, assume that the first mode to be built is a pipeline and the future mode is a railway. In this case, since
the materials, i.e. the pipes, are the most costly elements of the first mode and also due to low sensitivity of pipelines to terrain gradient, the selected path will most probably be a straight route with the shortest possible length. Whereas, railway is highly sensitive to gradient and thus, a lot of civil work such as excavation, filling, tunneling and bridge making is needed to flatten the ground to make it suitable for the railway. Depending on a number of technical parameters, a maximum allowable gradients of 1 to 2.2% for railway and 13 to 16% for oil and gas pipeline are mentioned in the literature [14][11]. The East portion of the Peace River – Fort McMurray Transportation and Utility Corridor (TUC), which is reviewed in Chapter 2, is an example of a route that was mostly selected based on the preferences of the first mode, and therefore, is not ideal for all modes [20] recommends to “review the route for the east portion of the corridor based on a comprehensive analysis of all the requirements of all potential users for TUCs, not just the road”.

4.2 Route planning by Finding a Wide LCP on the Accumulated Cost raster (FWLA)

In this method, to take all modes into account, a composite cost surface is built by aggregating the cost rasters of all of the modes. Then, an LCP as wide as the multi-modal corridor is found using an existing method. Finally, considering the desired arrangement of modes, all modes are accommodated within the corridor. Figure 4.3 shows the flowchart of FWLA method.

The FWLA method, summarized in Figure 4.4, is defined in the following four steps: (i) Creating a cost-raster for each mode (ii) aggregating all of the cost rasters into one composite raster (iii) finding a wide path on this cost raster and (iv) locating the desired multi-modal corridor within the path found in (iii). It is notable that in step (iii), all wide LCP techniques such as Buffering method, Re-sampling method and the Neighbourhood concept can be applied to the created composite cost raster as in Figure 4.4b. In this chapter, the methods introduced by [2] and [1] as the most advanced existing methods are used for finding the wide path on the aggregated cost surface.

The general problem of this method is that in Step (iii), the path finding algorithm uses ac-
Figure 4.3: The flow chart for the FWLA method
cumulated cost of the cells, whereby all cells in the path should be low cost for all modes. This issue imposes unnecessary constraints on the algorithm. For example, Two synthetic cost rasters are shown in Figure 4.5a and Figure 4.5b. The goal is to find a two-cell-wide path that is subsequently divided evenly among the modes. The weights of these modes are assumed to be the same and equal to 0.5. Their aggregated cost raster is shown in Figure 4.5c. As it is shown, the costs in row C are lower than those of rows A and B because both highway and pipeline have relatively low costs in this row. The Optimal two-cell-wide path found by this method is shown in the red box in Figure 4.5c. However, if the average cost is not considered and the original rasters are used, the optimal path would become as in Figure 4.5d where the row A costs are important in highway cost raster and the row B costs are important in pipeline cost raster.
Figure 4.4: a) Cost rasters for n different modes. b) Composite cost raster for all modes. c) Finding the wide LCP. d) Fitting the multi-modal corridor into the found wide path.
Figure 4.5: a) A synthetic cost raster for a highway b) A synthetic cost raster for a pipeline c) The weighted average cost raster for the highway and the pipeline where the optimal two-cell-wide path found on this composite cost raster is highlighted in the red box d) The actual 2-cell width LCP considering the weights of the original rasters
4.3 Route planning by using the Shared Area of Multiple Corridors (SAMC)

The disadvantages of using a composite cost raster are explained in Section 4.2. and 3.3. Generally, it imposes unnecessary constraints on the LCP by not considering the arrangement of modes within the corridor. In this chapter, two methods are proposed to face this problem i.e. the SAMC and MDTG methods. The SAMC method produces a corridor for every mode and then makes them wide enough to the level that the cells shared among all corridor layers can accommodate the desired multi-modal corridor. The flowchart of this method is shown in Figure 4.6.

Using LCP methods for designing wildlife corridors is widely studied in the literature. Examples include, [85], [86] and [87]. [29] developed a method to find wide corridors for the movements of animals. In this method, accumulative cost-distance for each cell is defined as the lowest possible cumulative cost of a path connecting that cell to both terminuses. In Figure 4.7 the yellow and green paths are two LCPs connecting the specified cell, i.e. the blue cell, to the origin and destination points respectively. The accumulative cost-distance of the blue cell is the summation of the costs of these yellow and green paths. The steps applied in [29] method can be summarized in the following two major phases.

In the first phase, the accumulative cost-distances of all cells can be calculated following these steps:

1. The cost-distances of all cells from the origin point are calculated using an optimal routing algorithm such as Dijkstra.

2. The cost-distances of all cells are calculated from the destination point as well.

3. Adding the two values calculated in the previous steps to obtain an accumulative cost-distance for all the cells.

These steps are depicted in Figure 4.8 for a hypothetical cost raster. The cells with lighter colors have lower accumulative cost-distance than cells with darker colors. The value of each cell
Figure 4.6: The flow chart for the SAMC method

1. Cost layers for different Modes
2. For each mode: Calculating the Accumulated Cost Distance (ACD) for each cell from the origin and destination
3. For each mode: Creating a corridor by setting a threshold equal to the cost of the conventional LCP for the mode and filtering the cells with ACD equal or less than the threshold
4. Overlaying the corridors found for different modes and finding the common area among them
5. Is it in accordance with the desired corridor
6. For each mode: Adjust the threshold (increase if it is not wide enough or decrease if it is too wide) by trial and error and filter ACD values again to found the adjusted corridors
7. Accommodate all modes within the common area
8. Multimodal corridor
Figure 4.7: The accumulative cost-distance of the LCP which starts from the black point, passes through the blue point and ends at red point can be calculated by summation of the two LCPs shown in yellow and green in Figure 4.8.a and Figure 4.8.b are equal to the accumulative cost of the yellow and green path in Figure 4.7 respectively.

It is notable that the cost of each cell in a cost raster is an attribute of that cell and depends on how easy that cell is to pass. Therefore, it is only an internal characteristic of that cell. However, the accumulative cost-distance of a cell, as shown in Figure 4.8.c, is a cell attribute resulting from not only that cell cost but also the cost of a chain of cells, i.e. the costs of the yellow and green paths in Figure 4.7 that connect that cell to both terminuses [29].

The second phase can be implemented in a loop following three steps:

1. A threshold is defined. Then, the cells with an accumulative cost-distance less than the threshold are selected to make a wide path, i.e. the corridor.

2. This corridor does not have a fixed width in the whole landscape. Therefore, the
minimum width of this corridor needs to be checked with the desired width of the corridor. If the minimum width is large enough, the process stops. Otherwise, it proceeds to the next step.

3. The threshold in the first step is increased to make a wider path and this loop is continued until the desired path is found.

Note that the minimum value of the threshold is equal to the cost of the conventional LCP that connects the origin to the destination. As by definition, the LCP is a chain of cells with the minimum accumulative cost-distance, the amount of increase in the threshold to achieve the desired width is not predictable. It differs case by case and depends on the geographical distribution of the costs within the study area. The amount of increase can be determined by trial and error. As a rule of thumb, it can be set at 1% of the cost of the LCP. If the shared area is larger than the desired corridor, it can be reduced; otherwise it needs to be increased.

In Figure 4.9, the threshold increases from left to right and the white cells have an accumulative cost-distance below the threshold. As it is shown, higher thresholds result in wider paths.

To use this method for finding a multi-modal corridor, the first phase explained above needs to be done individually for each mode. The second phase can be done following these steps:

1. For each mode, a threshold equal to the cost of the conventional LCP of that mode
Figure 4.9: Widening the corridor by increasing the upper bound is defined.

2. For each mode, the cells with an accumulative cost-distance less than or equal to the threshold are selected to make a corridor.

3. The corridors are then overlaid to find the cells shared by them.

4. If the cells found in the previous step create a continuous swath of cells with minimum width equal to the desired width of the multi-modal corridor, the process stops. otherwise it proceeds to the next step.

5. Increase thresholds and repeat the process from Step 2.

There are a few notable points about raising the thresholds. Increasing the threshold of a mode means relaxing the constraint in Step 2, which results in a wider path for that mode. It essentially means a compromise in that mode in favour of the rest of the modes. After increasing the threshold, the amount of widening is not equal for all modes. Some modes are more sensitive and become wider than others by the same amount of increase in their threshold. The increments do not need to be equal for all modes. They can be defined based on several criteria such as the construction cost of each mode per unit of length, the sensitivity of modes to cost changes and other agreements made by the stakeholders.

The widening process for a hypothetical 3-mode corridor is shown in Figure 4.10. The three corridors found in Figure 4.10b became wider by increasing their thresholds in Figure 4.10c. This
The process is continued until the shared cells create a continuous path with enough width as shown in Figure 4.10d.

Some of the advantages of this method are as follows:

- This method can be implemented using the existing conventional GIS softwares.
- Because the widening process and the sensitivity of each mode is visible, it is easy to have a general understanding of what goes on behind the results and how the behaviours of different modes change by spending more money.
- The overlaid corridors and the area of shared cells show the areas where a corridor has more options and flexibility, as well as the bottlenecks and narrow paths. This
can help designers to align corridors that are partially parallel in places where the shared cells are accessible with little increase in thresholds.

- This method can be used along with the other three methods described in this chapter. The corridor found by this method can be used as a mask to limit the search area for other methods. This can dramatically decrease computation time. This concept is shown in Figure 4.11.

Figure 4.11: a) The output of this method is filtered and shown in white within a cost raster. b) The white area in (a) used as a mask c) The searching area for a path is limited to the masked area by creating the graph and finding an LCP only within this area.

Some of the disadvantages of this method are as follows:

- The method does not create a wide path with a fixed width. There are some bottlenecks as well as flexible areas.

- There is no mathematical way to calculate the appropriate increment of thresholds. In each loop the right amount can only be found by trial and error.

- To align a corridor with a certain width further implementation of other methods is needed to find an LCP in the too wide areas.
4.4 Route planning by using a Multi-Directed Transformed Graph (MDTG) which takes the weights based on the direction of the edges and the arrangement of the Modes

The MDTG method, similarly does not mix the cost rasters of all modes. It uses a multi-directed transformed graph with specific defined neighborhoods. The weight of each edge in the transformed graph is calculated directly from multiple cost rasters based on the locations of the linked nodes, the direction of movement, and the desired arrangement of the modes. In other words, the structure of this model allows it to choose different neighbourhoods depending on the direction of movement and calculate the weights of these neighbourhoods directly from the related cost rasters. Therefore, this model can preserve the arrangement of the modes. Also, it does not impose the unnecessary constraints mentioned previously. The numerical results, discussed in 4.5, show that this method outperforms the other three not only in multi-modal corridor path finding but in finding a single-modal wide corridor.

In Reference [27], the concept of using a sequence of rectangles to make a path was introduced. Their method transforms the original cost grid into a graph in which the centers of the cells are the nodes. An arc is a rectangle connecting two nodes with a width of $w$. The weight of a rectangle arc is equal to the sum of the costs of the cell fractions from the original grid that it occupies. Consider the two nodes $P(i, j)$ and $Q(u, v)$. The cost of the arc connecting them $arc_{pq}$ can be derived from (4.1) [27] where $C(x, y)$ is the cost of the cell located at $(x, y)$. An example of using the latter equation is shown in Figure [4.12]. The A1, A2, A3 and A4 are the intersected areas of the rectangular arc with the cells shown in Figure [4.12]. The concept is, when the path has a width of $w$, the cost of the path equals the sum of the weights of the rectangles creating it.

$$arc_{pq} = \sum_{x=i}^{u} \sum_{y=j}^{v} C(x, y) \times A(x, y)$$ (4.1)

There are some challenges to this method, even for a single mode corridor. The first one, also mentioned by [2], is that on taking turns, each two adjacent rectangles of the path will have both
Figure 4.12: An example of a rectangle arc with a width of $w$ connecting the node $p(1,1)$ to the node $q(2,3)$. The occupied areas within each cell are shown in different colors.

\[
    \text{arc}_{pq} = \sum_{x=1}^{3} \sum_{y=1}^{3} C(x, y) \cdot A(x, y) = C(1,1) \cdot A_1 + C(1,2) \cdot A_2 + C(2,2) \cdot A_3 + C(2,3) \cdot A_4
\]

Figure 4.12: An example of a rectangle arc with a width of $w$ connecting the node $p(1,1)$ to the node $q(2,3)$. The occupied areas within each cell are shown in different colors.
overlap and gap. This error increases with growing $w$. Other challenges include, the complicated geometry of the arcs and also difficulty tracking the path and calculating the weights with this model. For example, calculating A1 to A4, as shown in Figure 4.12, is not straightforward even for a single arc from a single mode path with a $w$ less than one cell size. Another problem, when using this model for a multi-modal corridor, is its simple edges (i.e. not directed). According to the [27], the edge which connects $p$ to $q$ has the same weight as the edge connecting $q$ to $p$. In other words, $arc_{pq}$ is equal to $arc_{qp}$. In a multi-modal corridor, maintaining the arrangement of the modes when taking turns is crucial to avoid over-crossing of the modes and also to create a continuous path for each mode. Therefore, it is necessary for the arrangement of the modes in perpendicular sections of the corridor that are in opposite directions to be in reverse order. This would make the $arc_{pq}$ and $arc_{qp}$ different, making the use of a multi-directed graph necessary.

As an example, the challenges of the method introduced in [27] for a two-mode corridor is shown in Figure 4.13. This figure shows a path consisting of three rectangles for a two-mode corridor which connects a Start point to an End point. Each rectangle is in turn composed of a series of smaller rectangles connecting adjacent cells in a same direction. One mode is depicted in blue and the other in red. The overlaps, gaps and over-crossings are shown in Figure 4.13.

In the MDTG method, a transformed multi-directed graph is used to find the LCP. A multi-directed graph is a graph in which more than one edge can exist between every two nodes, with their weights varying in various directions. It is a transformed graph because the value of an edge connecting two nodes is a function of the neighbouring cells of those points. The concept of neighbourhood is derived from [88], which defines a neighbourhood as ”a set of locations that are at specified cartographic distances and/or directions from a particular location”. In the MDTG method, a neighbourhood is a non-empty set of cells or fractions of cells with a certain arrangement from different cost layers corresponding to different modes located in the corridor. The neighbourhoods can function like pieces of a Lego creating a complete path when put together.

There are two types of neighbourhoods: i) moving neighbourhoods and ii) turning neighbour-
Figure 4.13: The overlaps (the inner corners of turns) and gaps (the outer corners of turns) problem of using adjacent rectangles is shown in the figure for a simple path of two modes. The nodes within the path are shown with small black circles and each mode is depicted in a different color, i.e. blue and red. As it is shown, with the same order of modes for the opposite directions (here, left to right vs right to left), over-crossing is inevitable.
hoods. A moving neighbourhood is a section of the corridor with the length of one unit moving in a certain direction (i.e. not turning) whereas a turning neighbourhood is a piece of Lego that fills the gap between two moving neighbourhoods. To preserve the arrangement of modes in the corridor and avoid overlapping, two sets of turning neighbourhoods are defined for turning clockwise or counter-clockwise. The total cost of a path is equal to the costs of the neighbourhoods which construct the path. It can be derived from (4.2), where the path consists of \( N \) neighbourhoods including \( M \) moving neighbourhoods and \( T \) turning neighbourhoods. Therefore, \( N = M + T \). \( C_n \) is the cost of \( n \)th neighbourhood which is equal to a \( C_m \) or a \( C_t \) depending on its type. \( C_m \) and \( C_t \) are used for the costs of moving and turning neighbourhoods, respectively.

\[
\text{Total cost of path} = \sum_{n=1}^{n=N} C_n = \sum_{m=1}^{m=M} C_m + \sum_{t=1}^{t=T} C_t
\] (4.2)

Here, the moving neighbourhoods are discussed in more detail. Different notations for both moving and turning neighbourhoods are shown in Table 4.1. The same notations are used for edges. The MDTG model allows control over the direction of the moves and makes it possible to take different widths for different directions. The moving neighbourhoods can be defined such that the number of cells be consistent in each direction, as in the model introduced by [1], or in a way that the Euclidean distance of two edges of the path be consistently similar to, but more precise than, the model introduced by [2]. To make the geometry simpler, in this chapter, the length of moving neighbourhoods (sections) are equal to one cell size for orthogonal moves and \( \sqrt{2} \times \text{cell size} \) (diameter of a cell) for diagonal moves. The \( \sqrt{2} \times (\text{cell size}) \) by \( \sqrt{2} \times (\text{cell size}) \) blocks constructing diagonal moves will soon be discussed. Each moving neighbourhood has a reference cell, which is needed for tracking the sequence of the path. Moves to eight directions are allowed in the MDTG method, making possible eight moving neighbourhoods. The concept of moving neighbourhoods as sections of the path is shown in Figure 4.14 for a sample three-mode corridor. The orthogonal and diagonal neighbourhoods are labelled with a two-letter and a four-letter name, respectively.

The ultimate goal in finding a route for a transportation corridor is to have a consistent width in
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<td></td>
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<td>Right Down</td>
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<td>Clockwise turns (only 45 degree turns)</td>
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<td>LURD</td>
<td>LRtoLURD</td>
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<td>RDLUtoDU</td>
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<td>LDRU</td>
<td>LR</td>
<td>LDRUtoLR</td>
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<tr>
<td>Counter-clockwise turns (only 45 degree turns)</td>
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<td>LDRU</td>
<td>LRtoLDRU</td>
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<td>LDRU</td>
<td>DU</td>
<td>LDRUtoDU</td>
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<td>DUtoRDLU</td>
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<td>RDLU</td>
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<td>RDLUtoRL</td>
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<td>LURD</td>
<td>LR</td>
<td>LURDtoLR</td>
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Table 4.1: Notations used in the MDTG method for direct moves and turns
Figure 4.14: A sample three-mode corridor path modeled with sequences of moving neighbourhoods connecting the Origin to the Destination. The modes are depicted in green, red and blue. The concept of defining one unit length section in each direction as moving neighbourhoods is depicted for seven directions. These seven moving neighbourhoods are 1: Up to Down(UD), 2: Down to Up(DU), 3: Left to Right(LR), 4: Right to Left(RL), 5: Left Down to Right Up(LDRU), 6: Right Up to Left Down(RULD), 7: Left Up to Right Down(LURD). The only moving neighbourhood being missed is the Right Down to Left Up(RDLU) because the path does not move in that direction.

terms of the Euclidean distance. Also, the corridor width needs to remain the same in all directions. To satisfy these goals, the eight-directional multi-layered rotating neighbourhoods is introduced. Four orthogonal neighbourhoods and four diagonal neighbourhoods are defined, as shown in Figure 4.15. The reference cell is marked in the middle of the picture with a black dot. The dotted lines mean that the number of modes, cells or blocks in each mode can vary. One orthogonal, Left to Right, and one diagonal, Left UP to Right Down, of these neighbourhoods are explained in more detail, the others are basically the same with repeated 90 degree rotations.

Taking the cost of a neighbourhood rather than the weight of one cell allows to find a wide LCP
Figure 4.15: Eight rotating neighbourhoods are defined in each cell of the study area
rather than a narrow path. Moreover, taking the costs of neighbourhoods from different cost layers allows to consider the costs of all modes individually, and avoid problems related to the use of the accumulated cost of all modes, as discussed in Section 4.2. In addition, using a multi-directional graph makes it possible to define the oppositely directed neighbourhoods in a way that the desired arrangement of modes be preserved while avoiding over-crossing. Therefore, $arc_{pq}$ and $arc_{qp}$ are no more equal.

As it can be seen in Figure 4.14, there are gaps in the path at the turning points. These gaps can be filled with turning neighbourhoods as depicted in Figure 4.16. Each turning neighbourhood is a sector of a full circle, constructed from different layers depending on the arrangement of the modes within a multi-modal corridor. To illustrate how the turns work, a three-mode corridor taking two turns is shown in Figure 4.17, with each mode in a different color and a different width. Figure 4.17a shows an LR moving corridor turning to RDLU, while Figure 4.17b connects the same neighbourhood (i.e. LR) to LURD. The turning neighbourhoods related to the Figures 4.17a and b are depicted separately in Figure 4.17c and Figure 4.17d, respectively. Similar to the composition of the moving neighbourhoods in opposite directions, for example LR and RL, the composition of turning neighbourhoods clockwise or counter-clockwise are different.

The complete circles of turns for both clockwise and counter-clockwise turns are shown in Figure 4.18b and Figure 4.18a, respectively. To make the geometry simpler and calculating the weights easier in this chapter, the two turning circles are modeled as two octagons as shown in Figures 4.18c and d. In each turn there is an input moving neighbourhood and an output one. For example, in both Figure 4.17c and d, inputs are LR while the outputs are RDLU and LDUR. The compositions of all turning neighbourhoods in this example can be derived from Figure 4.18e and f. For each input and output moving neighbourhood there is a sector in each octagon that can be used depending on the turning direction. For each mode, if the number of blocks in its diagonal moves is equal to the number of cells in orthogonal moves, the octagon will turn into a square shape. This happens when the width of a mode is less than three cells, whereas for a wider
Figure 4.16: The incomplete path shown in Figure 4.14 is completed by adding turning neighbourhoods
Figure 4.17: Two turns for a three-mode corridor are depicted in a) and b) with each mode in a different color. The desired arrangement of the modes is such that when moving from left to right, the first mode (i.e. black) is on the top. The two turning neighbourhoods are separately shown in c) and d). The input moving neighbourhood for both a) and b) is LR while their outputs are different as shown in figure.

corridors, it would be octagon. Figure 4.19a and b shows the clockwise and counter-clockwise square turns for a 3-mode corridor when the width for the first, the second and the third mode is one, one and three cell-size, respectively.

For each turning neighbourhood, there are two reference cells corresponding to the input and output neighbourhoods. In counter-clockwise turns these two cells are the same while in clockwise turns they are different. It is notable that in counter-clockwise turns the input neighbourhood turns on its own reference cell, while in clockwise turns the input turns over the cell on the opposite side of its reference cell. This is shown in Figure 4.20. The cost of a turning neighbourhood is
Figure 4.18: Turning cycles and octagons for a 3-mode corridor with each mode in a different color. The desired arrangement of modes is in a way that when the corridor moves from left to right, the black mode is on the top. a) and b) are complete cycles while c) and d) are complete octagons. In this chapter we use circumscribed octagons instead of circles to make the geometry simpler. The eight direction of moves are also depicted in e) and f). a), c) and e) are for counter-clockwise turns, while b), d) and f) are for clockwise turns. The turn between each input and output moving neighbourhoods is similar to a chunk of pizza.
equal to the accumulated cost of the cells or the fractions of cells constructing it. In a clockwise
turn, this cost is for i) moving from the input reference cell to the output reference cell and ii)
changing the direction of the move. In the counter-clockwise turns, the reference cell does not
change and the cost is only for changing the direction. For each 45 degree turn in the MDTG
method, there is one orthogonal and one diagonal moving neighbourhood. If the centre line of an
orthogonal neighbourhood and its diagonal counterpart is chosen, the area swept by them when
moving toward each other will construct the turns between them. Turns greater than 45 degrees
could be created by the summation of their sequential 45-degree components. For example, in
Figure 4.20b, if the $C_{LRtoRDLU}$ is the cost of turning from LR to RDLU, it can be calculated from
the costs of its 45 degree components by the equation (4.3). The same concept applies to clockwise
turns. This characteristic is useful when defining turning edges in a transformed graph and will be
discussed in the following sections.

$$C_{LRtoRDLU} = C_{LRtoLDRU} + C_{LDRUtoDU} + C_{DUtoRDLU}$$ (4.3)

Figure 4.19: Turning squares for a relatively narrow corridor. The width of the first mode (black)
is one cell-size while for the second (yellow) and the third (orange) modes it is one and three times
the cell-size, respectively. a) is for counter-clockwise and b) is for clockwise turns

Calculating the costs of the moving neighbourhoods is explained in this part. The cost of each
neighbourhood is equal to the summation of the costs of cells located in that neighbourhood. In
a multi-modal corridor, the cost of each cell in a neighbourhood is derived from the value of cost
Figure 4.20: Two turns of a 3-mode corridor are shown. a) shows a clockwise turn and b) shows a counter-clockwise turn. The inputs are LR for both. While outputs are LUDR and RDLU for a and b, respectively. a) has different input and output reference cells, while in b), like other counter clockwise turns, they are the same.
Consider a multi-modal corridor consisting of \( M \) modes (Mode\(_1\), Mode\(_2\), ... Mode\(_M\)) where the width of \( m \)th mode is equal to \( w_m \) and the cell – size of the cost rasters is equal to \( cs \). The required number of cells for each mode \( n_m \) that create \( w_m \) can be derived from \( \text{(4.4)} \). \( n_m \) values do not need to be integers. The orthogonal neighbourhoods can be made up of full cells or fractions of cells. However, in this chapter, for the sake of simplicity, the \( w_m \) values are assumed to be a factor of \( cs \) and thus, the \( n_m \) values are integers. The total width of the corridor in terms of the number of cells is equal to \( T_{wn} = \sum_{m=1}^{M} n_m \) and in terms of the Euclidean distance is \( T_{we} = T_{wn} \times cs \).

Assume a one-cell section of the corridor moving from left (i.e. West) to right (i.e. East). This section is a Left to Right (LR) moving neighbourhood. The origin of the Cartesian coordinate system is at the top left corner of the study area and the longitude (i) and latitude (j) increase from left to right and from up to down, respectively. The order of modes in LR neighbourhoods from Up to down is 1 to \( M \) with their corresponding cost layers being \( C_1, C_2, ..., C_M \) and the corresponding \( n_m \)s being \( n_1, n_2, ..., n_M \). The number of cells from the reference cell to the start of each new mode \( m \) is equal to \( N_m \) \( \text{(4.5)} \). The cost of each neighbourhood is equal to the sum of the costs of cells existing in that neighbourhood from their corresponding cost layers. For LR neighbourhoods the reference cell is the top cell while for Right (R) to Left (L), Up to Down (UD) and Down to Up (DU) neighbourhoods the reference cells are the lowest, the leftmost and the rightmost cells, respectively, as depicted in Figure \( \text{4.15} \). This way, the order of the modes from the reference cell will be consistent in all moves and the reference cell is always the beginning cell of the first mode (\( M_1 \)).

The LR neighbourhood is shown in the Figure \( \text{4.21} \). The cost of this neighbourhood for each cell located at \( (i, j) \) can be calculated using \( \text{(4.6)} \). In this equation \( CLR_{ij} \) is the cost of LR neighbourhood at cell \( (i, j) \) and \( C_m(i, j) \) is the value of cell \( (i, j) \) on the cost raster of mode \( m \). It is assumed that the study area consists of \( I \) cells in width and \( J \) cells in height. Limitations of a study area need to be considered when creating the neighbourhoods why the end cell of the neighbour-
hoods are not allowed to be over the borders of the study area. The conditional term before the (4.6) to (4.9) is added to control enough room in the study area for move in that direction. This constraint basically means that at these cells the corridor does not have enough room to move in the direction of that neighbourhood. For example, assume that the study area is 100 by 100 cells and the total width of the corridor derived from (4.5) is 10. In this scenario, left to right moves are not allowable for \( j > 100 - 10 + 1 = 91 \). The costs of RL, UD, and DU, i.e., CRL, CUD, and CDU neighbourhoods can be calculated in a similar way, using the (4.7) to (4.9). These equations basically calculate the cost of the area covered by each neighbourhood in the corresponding cost layers and the concept is the same with the Equation (3.1) for the total impact.

In multi-modal corridors preserving the designed arrangement is crucial because changing the arrangement of the modes means over-crossing of transportation modes that is both costly and risky. For example, if a highway needs to cross over a pipeline or a railway, tunnels or bridges are probably needed and extra safety measures are required.

\[
n_m = \frac{w_m}{cs} \quad (4.4)
\]

Number of cells before mode \( m = N_m = \sum_{1}^{m-1} n_m \) By definition: \( N_1 = 0 \) (4.5)

If \( j =< (J - Twn + 1) \) : \( CLR_{ij} = \sum_{m=1}^{M} \sum_{n=1}^{n_m} C_m(i, j + N_m + n - 1) \) (4.6)

If \( j => (Twn - 1) \) : \( CRL_{ij} = \sum_{m=1}^{M} \sum_{n=1}^{n_m} C_m(i, j - N_m - n + 1) \) (4.7)

If \( i => (Twn - 1) \) : \( CUD_{ij} = \sum_{M=1}^{m} \sum_{n=1}^{n_m} C_m(i - N_m - n + 1, j) \) (4.8)

If \( i =< (I - Twn + 1) \) : \( CDU_{ij} = \sum_{M=1}^{m} \sum_{n=1}^{n_m} C_m(i + N_m + n - 1, j) \) (4.9)

The concept and definitions of the diagonal moving neighbourhoods used in the MDTG model are similar to those explained for the orthogonal moving neighborhoods. The few differences are discussed here. Also, the Left Up to Right Down (LURD) neighbourhood is explained in more detail. The other diagonal neighbourhoods are the same with repeated 90 degree rotations.
Figure 4.21: A general left to right neighbourhood is depicted. The coordinate axes are shown with black arrows and their origin is located on the top left corner. The reference cell of the neighbourhood is marked with the black circle in the top cell of the neighbourhood. The modes $M_1$ to $M_M$ are shown in different colours. The first mode (Mode$_1$) is in blue and the last one $M_M$ is in green. The location of the reference cell of the neighbourhood is $i$ and $j$ in the coordinate system. The cost of each cell is written to the right of the cell. For example, $C_{M_11}$ is the cost of the first cell from the first mode and $C_{M_M n_M}$ is the cost of the $n_M$th cell (the last one) from the last mode ($M_M$). The $n_m$s are derived from the (4.4).
Because the proposed model in the MDTG method has control over the moves and turns, the diagonal neighbourhood can be defined in a way that creates the exact Euclidean distance as the orthogonal ones. However, since the Euclidean distance of the two diagonal cells from center to center is $\sqrt{2}$ times the cell size, the geometry is more complicated. It is worth mentioning that the [1] model fixes the number of cells in diagonal moves and [2] model fixes the Euclidean distance with two limitations. First, the diagonal width should be a factor of $\sqrt{2} \times Cell – Size$. Secondly, the diagonal width fluctuates by $\sqrt{2} \times Cell – size$, i.e. the diameter of one cell, and the edges of the found path are indented with a zigzag shape. The second issue is non-significant with a path whose width is considerably larger than the cell-size or with a smooth cost surface where there are no sharp changes in the cost of adjacent cells. However, when the width of path is not large enough in terms of cell size or when there are dramatic changes in the cost of adjacent cells, the fluctuation could become more significant, leading to finding a non-optimal path. This issue will be explained using a numerical example in Section 4.5. The diagonal width of the paths created by the two aforementioned existing methods are shown in Figure 4.22.

To avoid the complex geometry for calculating the exact Euclidean distance in the MDTG method, the diagonal neighbourhoods can be imagined to be constructed of a number of blocks with the same geometry. The first block consists of four half cells one of which is taken from the reference cell itself. The other three half cells are determined based on the direction of the moves. For example, in the LURD neighbourhoods the three other half cells are cell$(i+1, j)$, cell$(i, j+1)$ and cell$(i+1, j+1)$ where $i$ and $j$ indicate the location of the reference cell of the neighbourhood. This way, the width of each block is equal to $\sqrt{2} \times cell – size$. These blocks can be considered to have rotated 45 degrees with respect to the original grid. The concept of constructing one block in LURD neighbourhood using only four half cells without rotating the axis is shown in Figure 4.23. The reference cell is shown in black. Using this method, indentations and fluctuations of the path width are avoided, making it possible to create a path with a constant width in diagonal moves. The constraint of being a factor of $\sqrt{2} \times cell – size$ for diagonal width can be solved with more
Assume that $w_m$ is the desired width of the mode $m$ in a multi-modal corridor. To guarantee the minimum width of $w_m$, the number of blocks from each mode $d_m$ is calculated from (4.10) and considering (4.4) will result in (4.11). The order of the modes is the same as the order of the orthogonal moves. The reference cell is one of the cells of the first block of the first mode. For LURD, the coordinate system, the composition of blocks and some other variables are shown in Figure 4.24. The other three diagonal neighbourhoods are its rotated versions. The total width of the corridor in diagonal moves, in terms of number of blocks, is equal to:

$$T_{wd} = \sum_{m=1}^{M} d_m$$

and in terms of Euclidean distance is:

$$T_{wed} = \sqrt{2} * T_{wd} * cs$$
The ratio of the width of the corridor in diagonal moves to orthogonal moves is:

\[
R = \frac{T_{\text{wd}}}{T_{\text{wn}}} = \frac{\sqrt{2} \sum_{m=1}^{M} d_m}{\sum_{m=1}^{M} n_m}
\]

which approaches one as the width of the corridor increases. The number of blocks from the reference cell to the first block of each mode \( m \) is \( D_m \) and is derived from (4.12). The cost of each neighbourhood at point \((i,j)\) for four diagonal moves: LUDR, RULD, RDLU, and LDRU is referred to as \( CLURD(i,j) \), \( CRULD(i,j) \), \( CRDLU(i,j) \) and \( CLDUR(i,j) \), respectively, and are derived from (4.13) to (4.16).

\[
d_m = \left\lfloor \frac{w_m}{\sqrt{2} \cdot cs} \right\rfloor + 1 \quad \text{(4.10)}
\]

\[
d_m = \left\lfloor \frac{n_m}{\sqrt{2}} \right\rfloor + 1 \quad \text{(4.11)}
\]

The number of blocks before the first block of mode \( m \) is \( D_m = \sum_{1}^{m-1} d_m \) (4.12)

By definition: \( D_1 = 0 \)

if \( i >= (T_{\text{wd}} - 1) \) and \( j <= (J - T_{\text{wd}}) \):

\[
CLURD_{ij} = \sum_{m=M}^{m=M} \sum_{d=d_m}^{d=d_m} \sum_{ii=0}^{j+1} \sum_{jj=0}^{1} 0.5 \cdot (C_m(i - D_m - d + 1 + ii, j + D_m + d - 1 + jj))
\]

(4.13)

if \( i >= (T_{\text{wd}} - 1) \) and \( j <= (J - T_{\text{wd}}) \):

\[
CRULD_{ij} = \sum_{m=M}^{m=M} \sum_{d=d_m}^{d=d_m} \sum_{ii=0}^{j+1} \sum_{jj=0}^{1} 0.5 \cdot (C_m(i - D_m - d + 1 - ii, j - D_m - d + 1 + jj))
\]

(4.14)
if $i \leq (I - Twd + 1)$ and $j \geq (Twd)$:

$$CRDLU_{ij} = \sum_{m=1}^{M} \sum_{d=d_m}^{d} \sum_{ii=1}^{d} \sum_{jj=0}^{j} 0.5 \times (C_m(i + D_m + d - 1 - ii, j - D_m - d + 1 - jj))$$

(4.15)

if $i \leq (I - Twd)$ and $j \leq (J - Twd + 1)$:

$$CLDRU_{ij} = \sum_{m=1}^{M} \sum_{d=d_m}^{d} \sum_{ii=1}^{d} \sum_{jj=0}^{j} 0.5 \times (C_m(i + D_m + d - 1 + ii, j + D_m + d - 1 - jj))$$

(4.16)

How the MDTG method distinguishes turns to add appropriate turning costs is explained in this part. The explained turning neighbourhoods are defined so to avoid overlapping. Also, by adding them, a continuous path for every mode will be created without any gap or over-crossing. Therefore, the only issue is for the routing algorithm to understand the locations of turns and direct moves. The Dijkstra algorithm which is used in the MDTG method, does not differentiate between direct moves and turns. In other words, Dijkstra uses only nodes and linking edges to find an LCP without considering whether the path is turning or is continuing the same direction. To solve this problem, in the MDTG method, the graph is transformed in a way that the turning costs are added only if the path turns and so, when it continues to move straight in the same direction there will be no turning cost. To do so, each cell is considered as a graph with eight nodes corresponding to its eight possible inputs and outputs. Each of these eight nodes works as a terminal for input and output edges as shown in Figure 4.25.

In the MDTG method, there are three types of edges. The first type connects two corresponding nodes, i.e. terminals, from two adjacent cells. These edges are for straight moves with no turning cost and thus are called direct edges. Following these edges, the path can go only in the same direction as its previous move. Each node, i.e. terminal, has one input and one output direct edge. The direct edges are shown in Figure 4.26.

The second type of edges are those related to counter-clockwise turns. There are eight nodes in each cell. Therefore, for each input node there are seven other nodes (i.e. terminals) which can be reached by seven edges turning counter-clockwise. These seven edges are shown in Figure 4.27a for LR node. Because there are eight nodes in each cell, there could be $8 \times 7 = 56$ edges.
Figure 4.24: A general LURD neighbourhood for an $M$-mode corridor is depicted here. Each mode is in a different color and the reference cell of the neighbourhood is in black.
Figure 4.25: One cell with its centre shown with a black square is divided into eight nodes corresponding to its eight allowable moves. These eight nodes are shown in different colors surrounding the black center.

as shown in Figure 4.27b. However, as mentioned before in Figure 4.20b, bigger turns are made up of smaller 45 degree components, making it unnecessary to add all these 56 turning edges. All these types of turns are created by connecting each node (terminal) to its neighbouring node in a counter clockwise direction. This concept is depicted in Figure 4.27c. This way, for example a 90 degree counter-clockwise turn from LR to DU can be created by two 45 degree turns: first from LR to LDRU, and then from LDRU to DU. There are eight counter-clockwise turning edges in each cell. It is notable that because turning costs are large for the turns over 180 degrees, the routing algorithm (i.e. Dijkstra) would rather create them by clockwise turns which are the third types of edges.

The third and the last type of the edges are the clockwise turning edges. They change not only the direction but also the reference cell of the neighbourhood. Similar to the counter-clockwise turning edges, there are eight clockwise 45 degree turns and the larger turns can be created by adding these sequential 45 degree turns. For clockwise turns, the input neighbourhood turns around the cell on the opposite side of the reference cell. Again, the turns more than 180 degrees are not
Figure 4.26: In this 3 by 3 cell grid, each cell is divided into eight nodes. The input and output direct edges for the nodes in the central cell are shown. The counterpart nodes and their linking edges are in the same color and these colors are the same as in the previous figure.
Figure 4.27: a) Eight counter-clockwise turning edges for LR. b) 56 counter-clockwise turning edges for all 8 terminals in a cell. c) The edges in b) can be made by the 8 sequential edges shown in c.

used by the Dijkstra because of their large costs and the availability of less costly paths found by counter-clockwise turns. In Figure 4.28, a complete cycle of clockwise turns is shown. As an example, if the turn starts from the LR node it will go to the LURD node which is the next node in the clockwise direction. Note that this is not LURD node from the same cell because the output reference cell is different from the input reference cell for clockwise turns (Figure 4.20.a). The cost and the jump of reference cells depend on the number of cells and blocks in moving neighbourhoods as explained before.

In summary, in the MDTG model, each cell is divided into eight terminal nodes. Each node has three input and three output edges. Input edges include: i) a direct edge from the counterpart node from the previous cell in that direction, ii) a counter-clockwise turning edge from the previous node in counter-clockwise cycle in the same cell, and iii) a clockwise turning edge from the previous node in clockwise cycle from another cell. Similarly, the three output cells are: i) a direct edge to the counterpart node to the next cell in that direction, ii) a counter-clockwise turning edge to the next node in counter-clockwise cycle in the same cell and iii) a clockwise turning edge to the next node in a clockwise cycle to another cell. these edges are shown in the Figure 4.29. Assume a study area with $N$ cells. In the conventional methods, the graph would have $N$ nodes and $E$ edges,
while in this model, it has $8 \times N$ nodes and $3 \times E$ edges. This means that the MDTG model has the same complexity as the routing algorithm i.e. Dijkstra and the running time grows linearly and not exponentially, with the size of the grid.

The weight of an edge is the area covered by the neighbourhood or neighbourhoods making that edge and can be calculated from their corresponding neighbourhoods. In the MDTG method, the edges link the central points of the cells. Therefore, considering the moving and turning neighbourhoods, the weights of the edges for all three types of the edges and eight kinds of terminals at cell $(i, j)$ can be derived from (4.18) to (4.41), where $WX_{ij}$ is the weight of the moving or turning edge of X in cell $(i, j)$. To illustrate the start and end point of each edge, $E_{(i,j,n1)\rightarrow(p,q,n2)}$ is used where the start point is node (terminal) $n1$ from cell $(i,j)$ and end point is node $n2$ from cell $(p,q)$. The term $CX_{i,j}$ represents the cost of neighbourhood X at cell $(i,j)$. The $CX_{i,j}$s are derived from (4.6) to (4.9) and (4.13) to (4.16). Basically, the neighbourhoods are defined such that the cost of their area from different layers is equal to the weight of their corresponding moves or turns. The only exceptions are the four orthogonal moves (i.e. (4.18) to (4.21)) where the weight of these edges are an average of the weights of the starting and ending neighbourhoods. In the following equations (4.18) to (4.21) are for orthogonal edges and (4.22) to (4.25) are for diagonal edges. (4.26) to (4.33) and (4.34) to (4.41) are for counter-clockwise and clockwise turns, respectively. Figures 4.31, 4.32 and 4.33 show one orthogonal, one diagonal and one clockwise turning edge.

An LRtoLURD turning neighbourhood is depicted in Figure 4.33 as an example, with more detail to show how the weight of a turning edge can be calculated using the geometry defined in this chapter. The input and output neighbourhoods are also depicted. In general, the areas covered by each turning edge from each mode can be divided into three separate areas, called W1, W2 and W3. In this figure, these three areas are shown for the first mode, i.e. the blue one. The summation of these three areas for all modes from their corresponding cost rasters would result in the weight of turning neighbourhood. The terms used in this figure are the same as Figure 4.21 and 4.24. The total area of the neighbourhood is enclosed in a solid violet line. It is notable that
Figure 4.28: Eight sequential clockwise turns for eight cells are depicted. Each node within a cell has its own cycle of clockwise turns which are not shown here to make the figure more simple.
Figure 4.29: For LR node in the central cell of a 3 by 3 grid, all three input edges and the three output edges are depicted. The three input edges are in solid lines and the three output edges are in dotted lines. The colors of the edges are the same as their start nodes. Direct edges only change the cells and not the type of nodes. The counter-clockwise turning edges change the type of nodes within a cell. The clockwise turning edges changes both the nodes and the cell.
in counter-clockwise turns, the reference cell of the input neighborhood needs to be eliminated from the weight of the turning neighbourhood. Similarly, the opposite cell of the reference cell needs to be eliminated in clockwise turns. The reason is that half of the cell is covered by the input neighbourhood, here LR, and the other half is covered by the output neighbourhood, here LURD. The weight of the shown neighbourhood can be derived from (4.17) where $W_{im}$ is $ith$ W from mode $m$. For example, $W_{11}$ to $W_{31}$ are three Ws constructing mode 1. The weight of the turning neighbourhood LRtoLURD at cell $(i,j)$ is called $W_{LRtoLURD}(i,j)$ . The weights of the other turning neighbourhoods can be calculated in a similar way. An easy way to calculate the weights of the neighbourhoods for each cell using code is to create those neighbourhoods and then use them as filters to read and add the values of all the cells within them. Figure 4.30 shows an example of all 24 neighbourhoods for a three-mode corridor. In this figure, the mode 1, mode 2 and mode 3 are in blue, green and yellow with their width in an orthogonal move being 8,16 and 10, respectively. These neighbourhoods can be used as filters to calculate all 24 weights at each cell from all 3 cost layers.
Figure 4.30: a) Shows moving neighbourhoods. b) shows clockwise turning neighbourhoods and c) shows counter-clockwise turning neighbourhoods. The reference cells are located in the middle of each sub-figures and for the 3 top-left sub-figures are illustrated by a white dot. In b) the reference cell of the output neighbourhood for the top-left sub-figure is shown by a red dot.
\[ ND_m = Tw_n - Tw_d + D_m - N_m \]

\[ ND_{m+1} = 0 \]

\[ II_1 = Tw_n - N_m - 2ND_m + jj - 1 \]

\[ JJ_1 = ND_m - 1 \]

\[ W_{1m} = 0.5 \sum_{jj=0}^{jj=II_1} \sum_{ii=0}^{ii=II_1} C_m(i+ii,j+jj+N_m) + C_m(i+ii+1,j+jj+N_m) \]

\[ II_2 = Tw_n - N_m - ND_m - jj - 1 \]

\[ JJ_2 = n_m - ND_m - 1 \]

\[ W_{2m} = 0.5 \sum_{jj=0}^{jj=II_2} \sum_{ii=1}^{ii=II_2} C_m(i+ii,j+jj+N_m) + C_m(i+ii-1,j+jj+N_m+ND_m) \]

\[ II_3 = Tw_n - n_m - N_m - ND_{m+1} + jj \]

\[ JJ_3 = ND_{m+1} - 1 \]

\[ W_{3m} = 0.5 \sum_{jj=0}^{jj=JJ_3} \sum_{ii=1}^{ii=II_3} C_m(i+ii,j+n_m+ND_{m+1}-1-jj) + C_m(i+ii-1,j+n_m+ND_{m+1}-1-jj) \]

\[ WLR_{toLURD}(i, j) = \sum_{m=1}^{m=M} \sum_{i=1}^{i=3} W_{im} \]

\[ WLR_{ij} = E_{(i,j,LR)to(i+1,j,LR)} = \frac{CLR_{i,j} + CLR_{i+1,j}}{2} \]  \hspace{1cm} (4.18)

\[ WRL_{ij} = E_{(i,j,RL)to(i-1,j,RL)} = \frac{CRL_{i,j} + CRL_{i-1,j}}{2} \]  \hspace{1cm} (4.19)

\[ WUD_{ij} = E_{(i,j,UD)to(i,j+1,UD)} = \frac{CUU_{i,j} + CUD_{i,j+1}}{2} \]  \hspace{1cm} (4.20)

\[ WDU_{ij} = E_{(i,j,DU)to(i,j-1,DU)} = \frac{CDU_{i,j} + CDU_{i,j-1}}{2} \]  \hspace{1cm} (4.21)

\[ WLRD_{ij} = E_{(i,j,LURD)to(i+1,j+1,LURD)} = CLURD_{(i,j)} \]  \hspace{1cm} (4.22)

\[ WRLD_{ij} = E_{(i,j,RULD)to(i-1,j+1,RULD)} = CRULD_{(i,j)} \]  \hspace{1cm} (4.23)

\[ WLDU_{ij} = E_{(i,j,LDRU)to(i+1,j-1,LDRU)} = CLDRU_{(i,j)} \]  \hspace{1cm} (4.24)

\[ WRDLU_{ij} = E_{(i,j,RLDU)to(i-1,j-1,RLDU)} = CRDLU_{(i,j)} \]  \hspace{1cm} (4.25)
Figure 4.31: An LR edge between cell (i,j) and cell(i+1,j) is shown. The weight of this edge similar to the other three orthogonal moves is an average of the costs of the two linked neighbourhoods. The reason is that these edges connect the middles of two adjacent neighbourhoods, therefore, half of each needs to be considered.

\[
W_{LR}(i,j) = E_{(i,j)LR\to(i+1,j,LR)} = \frac{CLR(i,j) + CLR(i+1,j)}{2}
\]
Figure 4.32: An LURD edge between cell \((i,j)\) and cell\((i+1,j+1)\) and its corresponding neighbourhood are shown. The weight of this edge, similar to the other three diagonal moves, is equal to the cost of its neighbourhood.
Figure 4.33: An LRtoLURD (clockwise) edge between cell \((i,j,LR)\) and cell\((p,q,LURD)\) and its corresponding neighbourhood. The weight of this edge, similar to all 16 turning neighbourhoods, is equal to the area swept by its input neighbourhood to reach the output neighbourhood. To avoid even as much as half cell overlapping, the following considerations are needed. Since the turns are 45 degrees in the MDTG model, each turning neighbourhood has an orthogonal and a diagonal input or output neighbourhood. Half of the cost of the orthogonal neighbourhood should be included in the turning neighbourhood while the diagonal moves are excluded. In clockwise turns, Input neighbourhood turns around the opposite cell of its reference cell (the red dot) while in counter-clockwise turns, it turns around its reference cell (black dot). The cell around which turning happens, should be eliminated from the turning neighbourhoods. The LRtoLURD neighbourhood is enclosed with the solid violet line.
\[ \text{WLRtoLDRU}_{ij} = E_{(i,j,LR)\rightarrow(j,i,LDRU)} = \text{CLRtoLDRU}_{(i,j)} \quad (4.26) \]
\[ \text{WLDRUtoDU}_{ij} = E_{(i,j,LDRU)\rightarrow(i,j,DU)} = \text{CLDRUtoDU}_{(i,j)} \quad (4.27) \]
\[ \text{WDUtoRLU}_{ij} = E_{(i,j,DU)\rightarrow(i,j,RDLU)} = \text{CDUtoRLU}_{(i,j)} \quad (4.28) \]
\[ \text{WRDLUtoRL}_{ij} = E_{(i,j,RDLU)\rightarrow(i,j,RL)} = \text{CRDLUtoRL}_{(i,j)} \quad (4.29) \]
\[ \text{WRLtoRULD}_{ij} = E_{(i,j,RL)\rightarrow(i,j,RULD)} = \text{CRLtoRULD}_{(i,j)} \quad (4.30) \]
\[ \text{WRULDtoUD}_{ij} = E_{(i,j,RULD)\rightarrow(i,j,UD)} = \text{CRULDtoUD}_{(i,j)} \quad (4.31) \]
\[ \text{WUDtoLURD}_{ij} = E_{(i,j,UD)\rightarrow(i,j,LURD)} = \text{CLUDtoLURD}_{(i,j)} \quad (4.32) \]
\[ \text{WLURDtoLR}_{ij} = E_{(i,j,LURD)\rightarrow(i,j,LR)} = \text{CLUDtoLR}_{(i,j)} \quad (4.33) \]
\[ \text{WLURDtoUD}_{ij} = E_{(i,j,LURD)\rightarrow(p,q,UD)} = \text{CLUDtoUD}_{(i,j)} \quad (4.34) \]
\[ \text{WUDtoRLD}_{ij} = E_{(i,j,UD)\rightarrow(p,q,RLD)} = \text{CLUDtoRLD}_{(i,j)} \quad (4.35) \]
\[ \text{WRULDtoRL}_{ij} = E_{(i,j,RULD)\rightarrow(p,q,RL)} = \text{CRULDtoRL}_{(i,j)} \quad (4.36) \]
\[ \text{WRLtoRLD}_{ij} = E_{(i,j,RL)\rightarrow(p,q,RLD)} = \text{CLUDtoRLD}_{(i,j)} \quad (4.37) \]
\[ \text{WRDLUtoDU}_{ij} = E_{(i,j,RDLU)\rightarrow(p,q,DU)} = \text{CLUDtoDU}_{(i,j)} \quad (4.38) \]
\[ \text{WDUtoLDRU}_{ij} = E_{(i,j,DU)\rightarrow(p,q,LDRU)} = \text{CLUDtoLDRU}_{(i,j)} \quad (4.39) \]
\[ \text{WLDRUtoLR}_{ij} = E_{(i,j,LDRU)\rightarrow(p,q,LR)} = \text{CLUDtoLR}_{(i,j)} \quad (4.40) \]

The control of the MDTG method over turns allows addressing some other routing problems that arise when it is required to impose constraints to the turns. For example, when the suitability of turns varies and sharp turns are not desired, they can be penalized with applying an additional turning cost factor. The other example would be using this method to limit the turns to only the allowable ones based on the geometry design codes of the route. The flowchart of MTDG method is shown in the Figure 4.34.
Figure 4.34: The flow chart for the MTDG method

1. Calculating the weights for all 24 neighbourhoods of each cell and using these weights as weights of 8*3 edges in the next step.
2. Creating the Transformed Multi Directed Graph (TMDG): Assigning 8 nodes for each cell and connecting each node by its 3 edges (direct, clockwise turn and counterclockwise turn) to its adjacent nodes.
3. Applying an LCP algorithm on TMDG.
4. Multimodal corridor.
4.5 Numerical results

This section is divided into three main parts. Initially, the performance of the MDTG method is compared with the two other existing models: [1] for constant number of cells and [2] for constant Euclidean distance in finding a two-cell-wide single mode LCP. It is notable that although the MDTG method is created for finding multi-modal wide corridors, by assigning the same cost raster for all modes, it is applicable for finding single mode wide paths.

Secondly, the performance of the MDTG method in finding a multi-modal corridor will be compared with FLSG and FWLA methods. To find a multi-modal corridor by FLSG method, in the first step, an LCP is found for the first mode and the further modes will be located in its neighbouring areas to create the desired arrangement of multi-modal corridor. To compare the performance of MDTG with FWLA, firstly a single cost surface is created by accumulating all cost surfaces and then the [2] method for wide paths is applied.

Lastly, the MDTG method is applied to find a three-mode corridor in a study area consisting of 200 by 200 cells to show the applicability of the model. Because the SAMC method cannot create a corridor with a fixed width, its results are not comparable with the other methods. As mentioned before, SAMC is good to be used alongside the other methods for limiting the search area or for explanatory purposes.

4.5.1 The Comparison of the MDTG method with the two other existing methods in routing a single-mode wide corridor

In this part, a two-cell-wide single-mode LCP will be found on a simple ten by ten cost raster using three methods: MDTG, [1] and [2]. The data is synthetic and randomly made and is available in [1]. The costs of the found LCPs by MDTG then will be compared with those found by the two other methods.

First, MDTG is used to find a two-cell-wide path. Its width is fixed in terms of the number of cells. This is similar to the goal of [1] method. The moving and turning neighbourhoods were so defined
to keep the number of cells constant. The result is shown in Figure 4.35. Figure 4.35.a is the data used as the cost layer. Figure 4.35.b is the LCP found by [1] with the accumulated cost of 31 and figure 4.35.c is the LCP found by the MDTG method with the accumulated cost of 30. The result shows that although the purpose of this research was to find a method for routing a multi-modal corridor, the LCP found by the MDTG method for a single mode is less expensive than the LCP found by [1] when the goal is to keep the number of cells constant in all transitions.

The second comparison is between the MDTG method and the [2] method. The data is the same as in the previous experiment and the goal is to fix the width of the LCP in terms of Euclidean distance. The result is shown in Figure 4.36. In this Figure, a) is the cost values for each cell, b) is the found LCP by MDTG when the goal is to fix the Euclidean distance of two edges of the path, and c) depicts the path on the cost values. The total cost of MDTG method is 55. Fixing the Euclidean distance in [2] method for a two-cell-wide path means using a 2 by 2 block neighbourhood. As it was explained before and also shown in Figure 4.22b, the path found by [2] cannot precisely fix the width as it fluctuates by $\sqrt{2} \times \text{cell-size}$ or by one cell in terms of cell numbers. Therefore, as shown in Figure 4.22d, the path found by [2] in diagonal moves fluctuates by 1 cell (i.e. 1 or 2). To make this path consistent with its goal (2 cell width in all directions), some triangles are added wherever the width was only one cell in the diagonal moves Figure 4.22e. The modified path is illustrated on the cost values. To calculate the total cost of this path, half of the cost of a cell is added wherever a triangle of the cell is occupied by the path. The total cost of [2] is equal to 57.5 which is higher than the cost of the path found by the MDTG method, i.e. 55.

4.5.2 The comparison of the MDTG method with the FLSG and FWLA methods in routing of a multi-modal corridor

In this section, a two-mode corridor is found with the width of each mode equal to one cell size. The origin of the path is at the top left corner and the destination is at the bottom right corner. It is assumed that one of the modes is a highway and the other is a power line.

The result of the FWLA method is shown in Figure 4.37. In this experiment, for finding a wide
Figure 4.35: a) The cost raster values derived from [1], b) The single mode two-cell-wide LCP found by [1] shown in grey, c) The single mode two-cell-wide LCP found by the MDTG method with the path in green

LCP on the composite cost raster, the [2] method is used. In this figure, a) is the same data used in the previous experiment and it is used as the cost layer for the highway. b) is a data created randomly for using as the cost layer of the power line. The value of b is between 1 and 4 and the size of this data is the same as a)'s. The [2] method is designed to work on a single cost layer. To make it possible to find a two-mode corridor as described in Section 4.2 and Figure 4.3, the accumulated values of all the cost layers or their average could be used. Figure [4.37]c is the average of a) and b). Figure [4.37]d shows the found two-cell-wide path by [2] on an average layer shown in c). In the next step, d) is modified into e) to fix the issue of indented edges where the width is only one cell as explained in the previous experiment. In f), the space in the corridor e) is divided between the two modes with the desired arrangement of the corridor. It is assumed that in the desired arrangement, the first mode, i.e. the highway (yellow), should be on top of the second mode, the power line (white), when the path moves from left to right. However, this path is found on the average cost layer of the two modes, whereas the actual cost needs to be calculated on the original cost layers a) and b). In g) the path is depicted on the highway cost layer (i.e. a). The summation of values within the yellow area is the cost of the highway which is 27. In h), the f) is depicted on the cost layer of the power line, i.e. b. The summation of values within the white area
Figure 4.36: a) The cost raster values derived from [1], b) The single mode two-cell-wide LCP found by the MDTG method where the goal is to fix the width in terms of Euclidean distance. c) the path found in b) is depicted on cost values. The total cost is 55 d) The single mode two-cell-wide LCP found by [2]. To fix the issue of the indented path found in d, some triangles are added where the width is equal to one cell instead of two. The result is shown in e) and it is depicted on the cost values in f). The total cost is equal to 57.5
is the cost of the powerline on its original cost layer which is 43. The total cost of the two modes is shown in i) which is equal to 70.

The same data, same arrangement, same widths and same origin and destination as the above mentioned example are used here to apply the MDTG method. The results are shown in Figure 4.38. In this figure, the found two-mode corridor is shown in a). The cost of the highway, which is in red, is calculated in b) and is 28. The cost of the power line, illustrated in green, is shown in c) and is equal to 37. The total cost is the summation of the costs of the two modes and is 65 in total which is less than the cost of path found by FWLA (i.e. 70). This shows the MDTG method found a lower cost multi-modal path.

In this part, the performance of the FLSG method for finding a two-mode corridor will be compared with MDTG. This method is explained in Section 4.1. The weights of the moves are based on the equations 3.1 and 3.2. The same data, same arrangement, same widths and same origin and destination as in the previous example are used here. In the first stage of this part, firstly a zero-width LCP is found for the first mode (i.e highway) and then it is widened to create a path with one-cell-width for the highway. Then the second mode is allocated to the neighbouring of the first mode in a manner to maintain the desired arrangement. The cost of each mode then is calculated from the original cost rasters corresponding to each mode. The result is shown in Figure 4.39. This shows that the cost of the corridor found by MDTG, i.e. 65, is less than that found by FLSG (i.e. 70). It is notable that the performance of FLSG decreases with an increase in the number or the width of the modes.

4.5.3 Checking the applicability of the MDTG method for the routing of a three-mode corridor in a relatively larger area

To check the capability of the MDTG model for a relatively large area, a 200 by 200 cell cost raster was randomly made Figure 4.40a. To make it more natural, it was smoothed twice using a 5 by 5 filter. The first and the second smoothed surfaces are shown in Figures 4.40b and c), respectively. In this example, it is assumed that the data is a slope raster and is the only important criterion for
Figure 4.37: a) The cost raster values derived from [1] used as the highway cost layer. b) is a data created randomly for using as the cost layer of the power line. c) is the average cost raster of a) and b). d) is the found two-cell-wide LCP by [2] method. e) Some triangles are added to d) to make the width constant. f) the space within e) divided between two modes with the first mode in yellow and the second mode in white. In g), f) is overlaid on a) to calculate the cost of highway. In h), f) is overlaid on b) to calculate the cost of powerline. The total cost is the summation of g) and h) that is depicted in i).
Figure 4.38: The same data as in Figure 4.37 is used in this experiment. a) is a two-mode corridor found by the MDTG method with the paths of highway and powerline shown in red and green, respectively. b) The path is depicted on the cost layer of highway and the calculated cost of highway is 28. c) The path is depicted on the cost layer of the powerline and the calculated cost of powerline is 37. The total cost is a summation of these two costs which is equal to 65, as shown in a).

Routing of a three-mode corridor consisting of a highway, a railway and a power transmission line. Some avoidance areas such as lakes and rivers are added manually to the surface. Moreover, some suitable areas are added to see whether the model can distinguish them. Then, the values of the cells on this surface are classified into three different methods representing the three mentioned modes. As the sensitivities of these modes are different regarding the slope, the variability of the reclassified costs increase from the power transmission line to the highway and then to the railway. d) is the result of the mentioned process which is used as cost layer for the highway. Similar to d), f) is for the railway and g) is for the power transmission line. The found three-mode LCP is shown in h), where the widths of the highway, powerline and railway are 3, 1, and 2 cells, respectively. To show how the MDTG model works like a Lego, the used neighborhoods in the found LCP are shown in i). j) is an LR illustrating the desired arrangement, with the highway being on top, the powerline in the middle, and the railway at the bottom. It is notable that for finding an LCP, the MDTG model not only needs the origin and the destination points, but also the nodes or terminals.
Figure 4.39: a) shows a zero-width LCP found by the FLSG method for the highway (red line). In b), the LCP shown in a) is widened to one-cell-wide path in terms of number of cells. In c), The second mode (yellow), which is for the power line, is located on the neighbouring of the first mode in a way that the desired arrangement be preserved. In d), these two paths are modified to have a one-cell width in terms of the Euclidean distance. The wide paths created in d) are depicted on the highway and power line cost layers in e) and f), respectively. The cost of highway is 28 and the cost of powerline is 42 and total cost is equal to 70.
at those two points. In this example, the starting neighbourhood is an LR while the destination
neighbourhood is a UD. h) demonstrates how the arrangement of the modes are maintained all
along the path.

4.6 Conclusion

In this chapter, the four following methods for routing a multi-modal corridor are introduced:

1. the FLSG method uses the conventional GIS routing method by the unrealistic as-
   sumption of a zero width alongside some extra steps.

2. the FWLA method firstly makes a composite cost raster of all modes then aligns a
   wide path on this cost raster using the existing methods. Finally, accommodates all
   modes within the found corridor based on the desired arrangement of modes.

3. the SAMC method creates multiple wide corridors for various modes then selects
   the area shared by them to align a multi-modal corridor. This method cannot create
   a fixed width path alone and needs to be completed by each of the other three
   methods. It is useful for explanatory purposes to find the areas suitable or unsuitable
   for all modes and making different scenarios for partially joint-use of corridor.

4. the MDTG method uses a transformed multi-directed graph which assigns eight
   nodes to each cell and connects them by specified edges. The weights of these edges
   are calculated based on the costs of several rotating multi-layer neighbourhoods
   explained in Chapter4. After applying a routing algorithm, the sequence of nodes
   which create the multi-modal wide corridor on the transformed graph is found.
   These nodes are then transfer to the original grid to align the corridor.

The performances of these methods are evaluated in Section 4.5 and the numerical results are com-
pared. The results show that, for the randomly created datasets in this chapter, the MDTG method
Figure 4.40: Applying the MDTG method on a wide area consisting of 200 by 200 cells to find a three-mode corridor where the first mode is a three-cell-wide, the second one a two-cell-wide and the third mode an only one-cell-wide path.
has superiority over all other methods in both multi-mode and single-mode wide corridors routing. In addition to finding the lower cost LCP, the MDTG avoids two problems of the other methods by using a number of geometrical considerations and also by the way that its graph is created. These problems are 1, finding an indented path in diagonal moves and 2, having overlapped or gaped areas in turns. The MDTG method helps the routing algorithms such as Dijkstra to work in a conditional way. Wherever the path turns, the turn cost will be added automatically to avoid creating gaps. A sample multi-modal corridor also was found for a relatively larger area to show the applicability of MDTG to large areas.
Chapter 5

Considering Renewable Energy Resources in Routing a Transportation Corridor

Energy use is continuously growing due to economic growth, urbanization and international trade. This results in growing amounts of carbon dioxide (CO2) emissions globally. The latter, as the main component of greenhouse gases (GHG) emissions, has a threatening role in global warming and climate change [89]. Although using more energy seems inevitable for economic growth, a reduction in GHG production needs to be considered in any sustainable development plan. Using renewable energy is not only a viable option for supplying energy, but a way to reduce GHG emissions and prevent an environmental catastrophe[90].

Canada has set a goal of reducing 40-45 % of its GHG emissions by 2030 with respect to the level of GHG emission in 2005 [91]. The electricity sector will have to play a key role in achieving this target not only because of the need to decrease its emissions, but for the increasing reliance of other sectors on this industry in the future. A shift from fossil fuels to renewable energy sources such as wind, solar, hydro, tidal, and biofuels is necessary to meet this target. This needs to be accompanied by the newly emerging technologies to be able to manage the fluctuating nature of these energy sources. Today, various options for energy storage are available to help balance the intermittency of the renewable energies. These technologies vary in terms of maturity, price, form, potential size, response time and facility lifetime. Batteries, Pumped Storage Hydropowers (PSH) and Compressed-air energy storage (CAES) are a number of these technologies [92].

Several research works have been done on the optimal siting and sizing of renewable energy projects. For example, [93] and [94] combine Geographical Information Systems(GIS) and the Analytical Hierarchy Process (AHP) to optimize wind farms and solar farms siting, respectively. Some researches such as [95], [96] and [97] focus on co-optimization of the renewable energy
generation sites and transmission system planning. In this thesis, it is assumed that the renewable energy sites are selected and they are connected to one another by an interconnected grid. The aim is to find the best route to connect the transportation corridor to the electrical grid substations to move renewable energy. The objective of this chapter is to determine the optimal routing of the corridor considering the interconnected power substations.

5.1 Methodology

Assume a multi-modal corridor connects an origin point to a destination with \( N \) interconnected substations named \( S_n, n \in \{1, ..., N\} \) in the proximity of the intended corridor. The goal is to connect one of the substations to the corridor with minimum cost. We define the substation that would be connected to the corridor at the lowest total cost as the optimal substation. The point where the corridor and the powerline coming from the optimal substation meet is referred to as the Junction Point (JP).

We investigate three cases for connecting the electrical grid and the corridor. In all three cases, the process can be divided into two phases. Firstly, optimal substation and the location of junction point need to be found. The second phase is to minimize the overall cost of connecting the origin point to the destination point where the cost of connection to the grid is also minimized.

We also refer to the cost of the corridor connecting the origin to the destination by Corridor Cost (CC). Further, the cost of connecting the optimal substation to the junction point is referred to by Connecting Powerline Cost (CPC). The objective of the proposed methods in this chapter is to minimize the Total Cost (TC) defined as follows:

\[
TC = CC + CPC
\]  

The three different cases are build based on different assumptions, as shown in Figure 5.1a, b and c. In Figure 5.1a, a multi-modal corridor connecting an origin and a destination is shown in red. A substation demonstrated with a red dot is located nearby the corridor. In the first case,
named Substation To Corridor (STC), it is assumed that corridor routing is already done and no further routing optimization will be performed. In other words, in this method, routing the optimal corridor ignores the power system interconnection. To connect the grid to the corridor in this case, the problem is to find the location of the optimal substation and the location of the junction point that would result in the minimum cost.

In Figure 5.1.b the second case, called Corridor to Substation (CTS), is depicted. Here, it is assumed that the corridor must pass through the substation location. The question is to find the one out of \( N \) substations and its LCPs both to origin and destination such that the cost is minimized.

In the third case, called Corridor Substation Trade-off (CST), the restrictions of the two previous methods are relaxed. In CST, both corridor and substation can move towards each other and meet in a three-way junction point, creating a three way with one way going to the origin and the other two ending at the destination and the optimal substation. Basically, the CST is the general form of the problem while, STC and CTS are two limited forms of it. In this case, the question is to find the locations of the optimal substation and the junction point. It is worth to mention that although Figure 5.1.a and b look similar but in a, i.e. STC, the corridor is the optimum corridor which connects origin to destination whereas in b, the corridor changes its initial path to get closer to the optimal substation.

To investigate each case, and without losing generality, we consider two randomly created synthetic cost rasters. The assumed study area is a 20 by 20 cells surface and the cell values are between one and nine. The corridor is assumed to have two modes, one being a power transmission line, and the other can be any other transportation mode. Figure 5.2 a, shows the powerline cost raster. The cells with higher cost have darker color tones. The cost raster of the second mode is not depicted here. In Figure 5.2 b) the routed corridor by the MDTG method, discussed in Chapter 4, is shown. The powerline is in yellow, the origin, destination, and assumed substations, i.e., \( S_1 \) to \( S_4 \), are depicted in green, blue and red cells respectively. The arrangement of the two modes is assumed such that the powerline is north of the second mode when moving from west
Figure 5.1: This is a schematic figure showing the origin, destination, optimal substation and joint point. The STC method is shown in the sub-figure a. Sub-figure b Shows the CTS method. In this case, since the optimal substation acts as a middle point, the corridor cost is not the minimum as it is in a). c) The CST method is depicted in this figure.
to east and stays accordingly as the corridor turns. In future figures, to make figures simpler, only the powerline and the yellow cells, are pictured. For substations $S_1$ and $S_2$ one over-crossing is inevitable and it is assumed that the cost of this over-crossing is negligible.

Figure 5.2: a) Shows the randomly created cost raster for power transmission line on a 20 by 20 surface. b) Shows the aligned two-mode corridor between an origin, the green cell, and a destination, The blue cell. This corridor is found using the MDTG method. Four substations, S1 to S4 are shown in b as well. The goal is to connect one of these substations to the main powerline located within the corridor.

5.1.1 The Substation To Corridor (STC) Case

The STC case assumes that the corridor is already built, and the goal is to pick the substation that connects to the corridor with the least cost. In this case, to minimize TC, i.e., we need to minimize CPC. This can be done by following these steps:

- For each substation, the cost distances of all cells are calculated using the cost raster of the powerline.

- For each substation, the cost distance raster found in the previous step is masked by the cells creating the powerline portion of the multi-modal corridor.
• For each substation, the point with the minimum cost distance value is selected as the junction point. The cost of powerline connecting this point to a substation is equal to CPC of that substation.

• The substation with the minimum CPC and the associated junction point are selected as origin and destination for connecting powerline.

• The LCP between the optimal substation and the junction point shows the alignment of connecting powerline.

These steps are depicted in Figure 5.3 as a flowchart. The result of implementing this method is shown in Figure 5.4. For each substation S1 to S4, the cost-distances values for all cells are calculated with the source cell being the location of that substation and the cost raster being the cost raster of the powerline. In Figure 5.2, the cost-distance values and the locations of the substations S1, S2, S3 and S4 are shown in sub-figures a, b, c and d, respectively, with S1 to S4 in yellow cells. The darker cells represent the cells with higher cost distance for that substation. The values of the cost-distances shown in different shades of red in the sub-figures are basically equal to CPC values in 5.1. Because in this case, the corridor alignment is fixed and its cost is unchanged, by minimizing the CPC part of 5.1 the whole equation would be minimized. To find the junction point for each substation, the cost-distance rasters are masked by the layout of the power transmission line within the corridor. This is shown in Figures 5.4 e, f, g and h for S1 to S4, respectively. In these sub-figures, for every substation the cells with minimum cost-distance are depicted with a black circle. The cells within the circles are junction points for the substations. The result of cost-distance analysis is shown in Figure 5.5. The S3 has the minimum CPC from the corridor and therefore is the optimal substation. Its joint point in the corridor with minimum CPC is cell (12,3). The powerline section of the corridor and its branch to S3 are shown in yellow and orange, respectively. The total cost is 249.5 unit cost.
Figure 5.3: The flow chart of the STC method
Figure 5.4: a, b, c, and d show the cost distances from S1 to S4 respectively. Sub-figures e, f, g and h show the left side figures masked with the corridor layout. The cell with the minimum cost distance is shown in the black circles.
Figure 5.5: a) The result of cost-distance analysis shows that S3 with the minimum CPC of 5.5 has the least CPC among all substations. In b) the LCP for powerline that connects S3 to its junction point i.e. (12,3) is shown in orange, the powerline part of the corridor is in yellow, and S3 is in red.
5.1.2 The Corridor To Substation (CTS) case

In this method, instead of adding a branch from the powerline of the corridor to the substation, the corridor travels through the substation. In other word, the CPC is equal to zero and the total cost is equal to the corridor cost. The corridor alignment, contrary to the STC case, is not optimal here because going through the substation is an extra constraint on corridor routing. The question is which substation should be selected and how it should be connected to the origin and destination.

For each substation, to calculate the corridor costs (CCs) for all cells a method similar to SAMC in Chapter 4 section 4.3 in combination with MDTG method is applied with some extra considerations. The cell through which the corridor travels is like a middle point needing to be connected to the origin and destination. In Figure 5.6 the study area and a sample middle point are depicted. The CC for this point is the summation of two sub-corridors. The first sub-corridor starts from the origin and ends at the middle point, while the second one starts from the middle point and ends at the destination. To calculate the costs of these sub corridors the MDTG method is applied. In MDTG, as explained in Chapter four, every cell is divided into eight nodes. Therefore, for each node in each cell there is a least cost path from the origin to that node and from that node to the destination. As a result, eight CCs are calculated for each cell which correspond to its eight nodes and the minimum of these CCs is the CC of the cell itself. In Figure 5.6 for a sample middle point these two sub-corridors are illustrated for the LR node. The output of this part for each cell is the cost of the least cost corridor passing through that cell.

The method is explained in the following steps and the flowchart is shown in Figure 5.7:

- Calculate the minimum cost of corridor which goes through each cell using the method explained in the above paragraph. These costs are the CCs of the cells.

- Compare the CCs of the cells in which the sub-stations are located, and choose the substation with the minimum CC.

- Consider the node in the optimal substation resulting the CC of that cell. This node
Figure 5.6: This is a schematic figure showing a middle point with its eight corresponding nodes. The two sub-corridors are shown in red. There are seven other pairs of sub-corridors that are not shown here. These eight pairs of sub-corridors have eight CCs with the minimum being the CC of the middle point.
is used in the next step and it could be any of the eight nodes shown in Figure 5.6.

- For the node found in the previous step find two sub-corridors using MDTG method. The first one starts at the origin and end at that node and the second one starts from that node and ends at the destination.

- The combination of sub-corridors found in the previous step is the corridor with the minimum cost which goes through the optimal substation.

The numerical result of application of this method is shown in Figure 5.8. In this figure, the same data as the previous method is used. The sub-figure a shows the CCs of each cell and b shows the locations of substations. As it is shown, S1 has the minimum CC and is selected as the substation that corridor is going through. The corridor found in this method is shown in c and the numerical results are depicted in d. It is notable that junction point in this method is overlapped on the optimal substation and because the length of powerline branch is zero the CPCs are zero as well. The total cost is 251 as shown in d.

5.1.3 The Corridor Substation Trade-off (CST) case

This case is the general solution for the STC and CTS cases. Here, there is no constraint fixing the alignment of corridor as in STC method and also there is no constraint forcing the corridor to pass through one of the substations. Therefore, both elements of (5.1) exist and are not necessarily equal to zero. As shown in Figure 5.1c the joint point is not necessarily overlapped with the optimal substation and also is not located within the optimal corridor. The latter is shown in Figure 5.1a as a red line. In CST method, based on the cost rasters of all modes in the corridor and other specifications such as width and arrangement of modes, both the corridor and the substation move towards each other and meet at a joint point. The trade off between the cost of changing the alignment of the corridor and the cost of powerline branch from the corridor to the substation determine the location of the joint point.
Figure 5.7: The flow chart of the CTS method

1. Input
2. Substation Selection
3. Alignment of corridor which goes through the selected substation
4. Output

Cost layers for different Modes

Location of origin, destinations and substations

For each cell: Using MDTG method calculate the Accumulated Cost Distance (ACD) for the LCP that connects that cell to origin and destination.

Compare the ACDs of cells which represent the locations of substations and select the substation with minimum ACD.

Using MDTG method find the path from the origin to the selected substation and again from this substation to the destination.

The path for the corridor is the combined path created by two paths found in the previous step.

The optimum corridor which pass through one of the substations
Figure 5.8: a) shows the CCs of the cells. b) The locations of four substations and their CCs are shown. As it can be seen, S1 has the lightest color which means the lowest CC among the substations. In c, the corridor with minimum cost starting from the origin, passing through S2, and reaching at the destination is shown. The cost of this corridor is 251 as shown in d.
If the corridor is too wide, lodging several modes, it can be predicted that substation will move toward the corridor, whereas if the cost of powerline branch is high and there are other sub-optimal corridor routes available nearby, it is predictable that the corridor will choose them rather than the optimal path to minimize the total cost\(^{(5.1)}\). This will be explained with an example in the following sections.

The CST case is explained in the following steps as well as in Figure\(^{5.9}\):

- For each substation, the cost distances of all cells are calculated using the cost raster of powerline. This step is explained in STC method and its output is CPCs.
- Calculate the minimum cost of corridor which goes through each cell using the method explained in the CTS case. These costs are CCs of cells.
- For each substation and for each cell add the above, calculated CPCs and CCs to find the TCs for each cell.
- For each substation and for each cell, add the above calculated CPCs and CCs to find the TCs for each cell.
- Compare the TCs of joint points for all substations and choose the substation with the lowest TC. The junction point of this substation is the final junction point of this case.
- Using the method explained in STC, align the powerline branch from the optimal substation to the JP.
- Using method explained in STC, align the powerline branch from the optimal substation to the JP.
- The combination of the found powerline branch and two sub-corridors will construct the final solution.
Figure 5.9: The flow chart of the CST method

1. **Input**
   - Aligned Corridor
   - The cost raster of Powerline

2. **Substation selection and finding the Connection Cell (CC)**
   - For each substation: On powerline cost raster calculate the cost-distance of each cell from that substation name it Power cost(PC)
   - For each cell: Using MDTG method calculate the Accumulated Cost Distance (ACD) for the LCP that connects that cell to origin and destination.
   - For each substation and for each cell find the connection cell (CC) with minimum PC+ACD and select the substation corresponding to that minimum

3. **Alignment of corridor which goes through the selected substation**

4. **Output**
   - The optimum connection point:
     - The corridor and its optimal connection to the substations

Combine the three following paths to create the corridor and the connection line:
1) The LCP for powerline between the selected substation and CC
2) Using MDTG align the corridor from origin to CC
3) Using MDTG align the corridor from CC to the destination
Table 5.1: The numerical results of CST method

The numerical results of this method is shown in Figure 5.10 and Table 5.1. In this figure, a, b, c and d represent the cost-distances of cells for substations S1 to S4, respectively. Sub-figure e shows the CCs of each cell and f, g, h and i show TCs for each cell for substations S1 to S4, respectively. The cell with the minimum TC for each substation is depicted in violet color in sub-figures f, g, h and i. These violet cells are JPs for S1 to S4. As it is shown in the Table 5.1, S3 has the minimum TC and its junction point is the cell (12, 3) with total cost of 249.5 unit cost. This result is exactly the same as the result found in STC method. However, this is not always the case. For example, for S1 the results of CST is the same as CTS with total cost of 251 unit cost.

5.2 Discussion

The goal of this chapter is to minimize the cost of a corridor (CC) plus its connection to one of substations (CPC) as represented in (5.1). The general solution for this problem is given in the CST case. However, it is possible that two different situations with two different assumptions happen. The first one is an already built corridor with fixed routing. In this case, the CC part of (5.1) is constant and cannot be minimized. This would call for the STC method. In this method, the corridor route is fixed and is equal to the optimal multi-modal corridor found using the MDTG method. Therefore, all optimization process is about finding the substation which can be connected with a branch of powerline to the existing corridor with the minimum cost.
Figure 5.10: In subfigures a, b, c, and d the locations of S1 to S4 are shown in yellow and the value of each cell represents its CPC. In sub-figure e, the value of each cell is equal to the least cost corridor which goes through that cell i.e. CC. The summation values of left figures a to d with the e is equal to figures f to i which represents the TC of each cell. For each substation the cell with the minimum TC is shown in violet which is junction point for that substation. The total solution can be found by finding the LCP of powerline from junction point to its substation the same as STC and also finding the two sub-corridors connecting junction point to the origin and destination same as what explained in CTS method.
Another situation would be to realign the corridor to pass through one of the substations rather than to connect it to the substation via a branch. This would eliminate the cost of the access road to the substation, reduce maintenance cost and have other possible benefits. In this case, the cost of branch is equal to zero and the problem is to find the optimal substation, as a middle point, for passage of the corridor. This situation is explained in the CTS case.

The method explained in CTS case and Figure 5.6 that finds the accumulate cost distance of each cell has another application as well. The weighting of important criteria and calculating cost rasters based on that is a subjective task. Sometimes, the result is not satisfactory for stakeholders who themselves assigned the weights. Also, the least-cost-path analysis could have different results with trivial changes in weights or accepting to spend more money for a more satisfactory result. The output of the calculation method explained for the CTS case, shown in Figure 5.10e, can be used to tackle this issue. By changing the symbology of the raster shown in Figure 5.10e other potential routes for the multi-modal corridor will appear. This is similar to what happens when the threshold increases in the SMAC method, explained in Chapter 4. For example, the cost of optimal corridor was 244 unit-cost in the example given in this chapter. If stakeholders are ready to spend 250 unit-cost instead of 244 unit-cost to have more options, the Figure 5.10e could be substituted with Figure 5.11. The black route is the optimal path with the cost of 244 unit-cost and the other ones are near-optimal paths. As it can be seen in this figure, there are several near-optimal paths close to S1 and S2. So as it is summarized in Table 5.2 for S1 and S2, the optimal solution is CST or CTS. This basically means for these substations, it is better to change the route of the corridor rather than to build a powerline branch.

As it is shown in row 14 of Table 5.2 using CST method always guarantees to find the least-cost solution because it is solved based on general equation without any other constraints. Therefore, for any substation CST method is the solution with minimum cost and its total cost for substation \( n \) i.e. \( TC_{CST,n} \), is always minimum. However, in some cases the CST solution could be the same as the two other methods, i.e. STC and CTS. Based on this, three situations are possible: (i) The TC of
Figure 5.11: The optimal path for the corridor is shown in black. The near optimal LCPs are shown in other colors. As it is shown in the figure the location of S1 and S2 are close to other near optimal paths shown in blue and red.
CST is equal to the TC of STC. (ii) The TC of CST is equal to the TC of CTS. (iii) The TC of CST is equal to neither the TC of STC nor to CTS. Among these three categories, only in (i) the path of the corridor is not changed because of its connection to the substations. In (i) the solution is to connect the selected substation to the optimal corridor connecting origin to destination. However, in categories (ii) and (iii), to achieve the minimum TC, changing the optimal path of the corridor is inevitable. The optimal path of the corridor here means the LCP found by the MDTG method without considering substations. In other words, if the locations of renewable energy sites are not considered during the routing of the corridor and if categories of (ii) or (iii) happen, a potential for saving is lost. The Lost Saving Opportunity ($LSO$) for each substation $Sn$, shown as $LSO_{Sn}$, can be driven from (5.2) where $STCSn$ is equal to the TC of the method STC for substation $Si$ and $CSTSn$ is the cost of the CST method for the same substation.

\[
LSO_{Sn} = TC_{STCSn} - TC_{CSTSn} \tag{5.2}
\]

For instance, in the previous example, assume that the S2 was the only substation that should be connected to the corridor. If the location of S2 is not considered during the routing of the corridor, the corridor will be aligned as in Figure 5.2b. The JP of S2 in this example, presented before in Figure 5.5a, is the cell (18,18) and its total cost is 282.2 unit-cost. In Figure 5.12a, the corridor, the yellow cells, and its powerline branch, the orange cells, and the related costs are shown. In Figure 5.12b, the result of CST method is shown. Comparing these two solutions shows that if the location of S2 is considered during the corridor routing the TC decreases by 21.2 unit-cost, which is more than %8 of total cost. As it is shown in sub-figure b, the corridor changed its path to a semi optimal path which travels through the area nearby S2.

5.3 Summary

To connect an origin to a destination via a multi-modal corridor and connecting this corridor to one of its nearby substations with minimum cost three different cases are proposed and investigated.
Figure 5.12: a) In this case it is assumed that the corridor is aligned optimally without considering the location of S2 i.e. STC method. b) The location of S2 is considered during the routing of corridor and the problem solved by CST case. Comparing a and b shows that TC decrease from 282.2 unit-cost in a to 261 unit-cost in b.
In STC, it is assumed that the route of the corridor is fixed and the optimal substation should be chosen and connected to the corridor via a powerline branch. In CTS, corridor changes its route and goes through the optimal substation. In the general case, i.e. CST, the limitations of the two previous cases do not exist as the corridor can get closer to the optimal substation via changing its route. Optimal substation also can connect to the corridor via a powerline branch.

In this chapter, it is shown that the CST case always guarantees the minimum total cost. However, if the locations of substations are not considered when routing a corridor, the only available option will be STC method which is not necessarily the optimum solution. In this case some potential savings will be lost.

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Table 5.2: The summary of results for all substations
Chapter 6

Conclusion and future work

In Canada, despite many studies on multi-use transportation corridors, only a few have been implemented in large scale project so far. Seemingly there are barriers prohibiting corridor users or governments from changing their approach from conventional single mode to multi-modal transportation corridors. These challenges, the reasons behind them and the ways to solve or minimize them need to be studied. One possible major challenge is to direct a multi-modal transportation corridor project, forming an integrated and cooperative team from different levels of federal and providential governments and industries, including various ministries is needed. The feasibility of multi-modal corridors and their technical challenges specially routing challenges are discussed in this thesis.

6.1 Conclusions

The balance between the extra costs which multi-modality could pose to a project and its potential advantages could determine the viability of that project. Multi-modal transportation corridors are generally feasible, and their advantages outweigh the disadvantages. But to determine the feasibility of each project, its specifications such as designs, physical and environmental conditions need to be individually studied. The construction cost of a multi-modal transportation corridor is usually higher than the total cost of building conventional individual corridors. The first reason is the precautionary measures needed to be taken to make adjacent facilities, such as pipeline and transmission lines, safe and reliable. Another reason is that the location of a multi-use corridor is a compromise among optimal locations of each component of a corridor. This may result in a longer path or undesirable conditions for some facilities. These extra construction costs may be compensated by a reduction in the required land for ROW, using a same access road, reducing the
time to get permissions and minimizing delays for various modes and other benefits of a multi-use corridor. It seems that saving time and money required for obtaining projects permits is one of the greatest advantages of a multi-modal approach, especially in Canada where obtaining approvals and permits for a project is a very slow process.

Different systems located laterally in a same ROW might undesirably affect one another. These potential effects can jeopardize the functionality of the systems or increase their maintenance costs. The magnitude of these potential incompatibilities depends on a number of factors including the specifications of the systems, modes distancing, the length of paralleled systems and environmental conditions. The greatest concern related to interference between different modes is over power transmission lines and pipelines. Allowing sufficient space among different modes, taking required risk mitigation measures, smart monitoring and governing the corridor and effective and adequate communication and cooperation among different corridor participants are imperative. A/C interference guideline provided by Canadian Energy Pipeline Association (CEPA) [17] and “criteria for pipeline co-existing with electric power lines” prepared by the INGAA foundation [16] explain different risky interactions between powerlines and pipelines in detail.

For lateral arrangement of modes within a multi-modal corridor suggestions are as follows: In general, locating highway in the middle of a corridor makes accessing railroad and pipeline for operation and maintenance more convenient. The route of pipeline is more flexible than that of highway or railway. Therefore, being positioned on one side of the corridor makes it possible for the pipeline to deviate away from the corridor where it is not financially viable to follow its path. This would also make it more accessible in case of an accident. Railway is greatly sensitive to the terrain gradient and also needs room for smooth turns. Therefore, locating it on the edge of the corridor provides extra room for its movements. Putting highway between pipeline and power transmission line helps reduce the incompatibility of these two. These suggestions are very general and only based on gradient sensitivity of modes and their compatibility. For each project the lateral arrangement needs to be studied specifically considering geographical and technical condition of
the project.

Most of computerized corridor routing models go through four major steps. The first step is identifying the objectives and criteria important for the project stakeholders. The second step is data gathering around the important factors influencing the routing process in the form of a square grid cells, i.e., raster data. The third step is to assign a suitability value to each cell, representing how easy that cell is to be traveled through with regards to the physical, environmental, and social barriers. The more suitable means less cost and less negative impact on the environment and society. The final step is to apply a least-cost-path algorithm, such as Dijkstra [48], to the scored grid network to find the shortest path that connects an origin to a destination.

The existing routing methods have two weaknesses with respect to routing a multi-modal corridor. Firstly, for various transportation modes within a multi-modal corridor, the first and third step mentioned in the previous paragraph, are not the same. Therefore, the cost rasters for different modes and least cost paths found in these cost rasters have variations in the landscape. Since the existing methods only take one cost raster, to find a suitable path for all modes it is needed to add all cost raster together or getting average of them. Creating a single composite cost raster for all modes basically means losing data. In this case the arrangement of different modes within the corridor is not taking into account during the routing. Searching for the least cost path in the single composite cost raster may result in non-optimal paths.

The other weakness of the conventional GIS routing method is they assume that least-cost-paths are purely linear with zero width. They do not consider the weight of neighbouring cells around the centre line of the LCP. This is an unrealistic assumption that causes errors where the width of the path is considerable in comparison with the cell size of cost raster. Surprisingly the number of studies considering the width of path is very low. Even the new routing methods that consider the width of path, can not take the multi-modality of corridor and the arrangement of various modes within the corridor into account.

Four different methods are proposed to consider both the width and the multi-modality of
corridors. Among these methods, the fourth method, referred to by Multi-Directed Transformed Graph (MDTG), has the superiority over the other methods. It takes different cost rasters related to various modes to make a transformed multi-directed graph constructed of some neighbourhoods. In this model, a multi-directed graph is defined in a way that the weight of each edge is calculated based on the direction of that edge and the desired width and arrangement of the corridor modes. The concept of multi-layer rotating neighbourhood introduced in the MDTG method helps to find the least cost corridor without need to add all cost rasters together or getting average of them.

In MDTG method, to avoid the problem of overlapping or gap areas where the corridor turns, each cell of cost raster is assumed to be a graph itself. This small graph has eight nodes corresponding to its eight possible movements. The weights of edges in this small graph at each cell are defined in a way that they will be added to the corridor cost only if the corridor turns at that cell.

This method is not only applicable for routing of a multi-modal wide corridor but also for a single-mode wide path with the desired width in every direction. A comprehensive comparison of this method and other existing methods is presented in Chapter 4 for both multi-mode and single-mode wide path. The numerical results show that corridors found by MDTG method have the minimum cost over all other existing methods not only for multi-modal wide corridors but also for single-mode wide corridors. In addition to finding the lower cost LCP compared with the other methods, MDTG method avoids two other problems of other methods. These problems are first finding an indented path in diagonal moves and second, having overlapped or gaped areas.

The importance of considering the locations of renewable energy sites in routing a corridor is discussed and a method for connecting the corridor to these sites is proposed. It is assumed that a multi-modal corridor connects an origin point to a destination with some interconnected substations related to renewable energy sites in its proximity. The goal is to connect one of the substations to the corridor with minimum total cost. The total cost is the cost of the corridor itself plus the cost of its powerline branch to the selected substation. To do this the following process should be done for every substation.
At each cell a three-way junction is assumed. One way is a sub-corridor which starts from origin point and ends at that cell. The second way is another sub-corridor which starts from that cell and ends at destination point. Finally the third way is a powerline branch starting from that cell and ending at the substation. The accumulated cost of these three paths is the total cost that should be minimized.

A method proposed to find the optimal substation is explained in Chapter 5 and the substation with the minimum total cost is the optimal one that needs to be connected to the corridor. The cell with the minimum cost corresponding to that substation is called joint point. The two mentioned sub-corridors and the powerline branch meet at the joint point. Knowing the locations of origin, destination and joint pint allows to route all three components of the assumed three-way.

It is also discussed and shown by a numerical experiment that to achieve the minimum total cost, the locations of substations must be considered in the process of routing the corridor. This way, the corridor may choose a near optimal path which goes through a cell nearby one of the substations to minimize the total cost. If the corridor is aligned without giving any considerations to the locations of substations, this option will be lost. In this case the only option that remains is to connect the substation to a cell within the defined corridor via a powerline.

6.2 Proposed future works

This thesis sheds light on some of the areas that need further investigation in future studies. In addition to providing a basis for the future works, the achievements of this research can help some aspects of routing other than multi-modality.

In this thesis, it is assumed that \( mode_1 \) to \( mode_N \) have fixed right-of ways \( ROW_1 \) to \( ROW_N \). In this case, all \( ROWs \) are constant. Therefore, the total width of the corridor is equal to \( \sum_{n=1}^{N} ROW_n \) which is a fixed amount as well. A potential field for research is to find methods to relax this constraint up to a certain level. In this case, the \( ROW_n \) of \( mode_n \) is between a minimum \( ROW_{nmin} \) and a maximum \( ROW_{nmax} \), i.e. \( ROW_{nmin} < ROW_n < ROW_{nmax} \). As a result, the total \( ROW \) of the
corridor also varies between a minimum and a maximum value.

Since different modes have dissimilar movement characteristics, allocating flexible ROWs helps them adjust themselves in their minimum and maximum ROWs. This adjustment allows them to avoid being attached all along the path and results in a less expensive path.

The main purpose of the MDTG method is to find the least-cost-path for a multi-modal corridor. However, its ability to exert control over the turns and distances of the modes has potentials for other applications as well. Some of these applications that can be topics of future studies are as follows:

In some cases of path routing, turns and bends, especially if sharp, are undesirable. In other words, a straight path is preferred over a curved path. Using the MDTG method and defining penalties as turning costs makes it possible to find a least-cost-path with limited number of turns.

In powerline routing, when two or more parallel lines are planned to be built, it is important to allow enough separation distance, ten kilometers for example, between them. This would prevent the powerlines from being hit all at the same time by a natural disaster such as tornado or flood. This makes the system more reliable in times of contingency. The MDTG method has the potential to solve these types of problems by considering all modes as powerline and defining discrete ROWs for them.

A corridor that is fully multi-modal is not always the answer. How to route a corridor with modes having dissimilar origins and destinations can be another topic for research. Finding optimal ways to connect the modes to or separate them from a corridor, and finding a partially multi-modal scenario that maximizes a corridor’s total benefits is an interesting area of research.
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