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Incorporating the impacts of climate change in transportation infrastructure decision models

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Abstract

Historically an important transportation corridor in the Northwest Territories, climate change has shortened the duration of the Mackenzie River's navigational season. Communities rely increasingly on airlift as the growing volatility affects barging operations, leading to higher overall freight costs. Using an options approach, we present a methodological framework that supports flexible infrastructure decision making, accounting for the impacts of climate change uncertainty. We apply this method to the decision of whether to continue barging on the Mackenzie River, or connect the entire corridor by extending the all-weather Mackenzie Valley Highway, explicitly considering uncertainties in river barging conditions. We first model river open season days as a stochastic process; barging is dependent on the number of open season days, which in turn is affected by climate change. Second, we evaluate the expected cost of barging and airlift each season using a modified Black-Scholes model. Finally, we use real options to determine how long construction of the all-weather highway may be deferred. The results indicate that it is advisable to defer construction nearly a decade, in balancing the costs of construction against climate change uncertainty. This paper demonstrates that when we explicitly incorporate the impact of climate change on project valuations, particularly those in northern and Arctic Canada where these impacts are considerable, project valuations can change significantly such that all-weather road construction is supported, even if it is deferred to future years. This method can assist federal and territorial governments in communicating the impacts of climate change on communities, and provide another tool to support multi-layered, complex transportation infrastructure investment decisions that address these rapidly changing environments.

Keywords: Northern Canada; Mackenzie River barge shipping; Real options model; Climate change; Transportation investment decision analysis.

1. Introduction

The Mackenzie River is the longest river system in Northern Canada and a historically significant transportation corridor. It provides the primary mode for essential freight transport via tug and barge to remote communities in the Northwest Territories (NWT) and Nunavut, during the summer open water season from mid-June to late September or early October each year (Zheng & Kim, 2017). In more recent years, however, low water levels have caused operational disruptions and early season terminations, resulting in freight delivery delays and cancelations (CBC News, 2014; Bird, 2018). This uncertainty has forced an increased reliance on costly air transport for necessary supplies (Pendakur, 2017; Millerd, 2005). In light of this need for adaptation, the Government of the Northwest Territories has been in support of constructing the all-weather Mackenzie Valley Highway (Government of the Northwest Territories, 2018). However, the enormous cost of this highway has been a major barrier. This is at least in part because the impacts of climate change uncertainty, as well as options for flexibility in infrastructure investment decisions, have not been clearly quantified as assets against this cost.

The purpose of our paper is to explore methods that support flexible infrastructure decision making in accounting for the impacts of growing environmental uncertainties in transportation service provision and infrastructure investment decisions. Targeting the Mackenzie River corridor in Northern Canada–specifically, the decision to continue barging services each year, and when to construct an all-weather highway–we present a methodological framework based on options approaches, to explicitly consider how climate change uncertainties impact transportation operations and infrastructure investment decisions. The question at the heart of this research goes beyond the binary decision to build now or defer; it is, "if we defer, then how long should we defer?"

Decision makers in northern governments (and private companies working in the north) understand the growing criticality of accounting for and adapting to uncertainties arising from climate change in infrastructure planning, but have not yet done so quantitatively. This research applies simple quantitative tools to demonstrate that project valuations can change significantly when uncertainty from climate change impacts are considered, particularly for infrastructure projects in northern and Arctic Canada where climate change impacts are considerable. Such tools can help northern governments and communities clearly communicate the severity of climate change, and need for infrastructure investments that address the rapidly changing northern environment.

2. Background

2.1 Context

There are significant challenges in providing transportation services in Northern Canada due to its highly remote communities, incredibly harsh climates, and rough but fragile terrain (Statistics

Canada, 2015). The impacts of climate change, which are far more severe in the north, add to these already difficult conditions through permafrost degradation, water level fluctuations, and sea ice melt (Northwest Territories, 2008). The Mackenzie River, flowing from Great Slave Lake into the Beaufort Sea, is a historical transportation corridor in the Northwest Territories (NWT) allowing for supplies to be delivered to adjacent communities, as well as those beyond Tuktoyaktuk on the coasts of the Beaufort Sea (Figure 1). The Mackenzie River allows for barge service in the summer months, during a limited navigational window that depends on water levels and ice conditions (Mariport Group Ltd., 2011). Aside from barging, there are few alternative transportation options in this region (GNWT Department of Transportation, 2011a). Some communities are connected by all-weather roads (towards the south and north ends of the river), while more communities connect via seasonal winter roads in winter and marine services in summer (Prolog Canada Inc., 2010). Other communities can only be reached via air.

The all-weather highway network in the NWT is highly limited (Figure 1). Inuvik is connected via the Dempster Highway through the Yukon; Tuktoyaktuk can be reached from Inuvik via the Inuvik-Tuktoyaktuk Highway (opened in November 2017). However, the Mackenzie Highway ends at Wrigley, and there is currently no additional overland access from Wrigley to Inuvik during spring, summer, and fall. The Government of the Northwest Territories (GNWT) annually builds a winter road connecting Wrigley to Fort Good Hope. In summer months, freight flights are the only other transportation option that prevents communities from experiencing shortfalls in essential supplies (such as fuel) if low water levels and other problems hinder barge operations (Bird, 2018). Communities typically have limited to no storage to accommodate extra supply deliveries in good shipping years.

Private companies have provided barging services on the Mackenzie River and Great Slave Lake (Zheng, Kim, Du, & S.A., 2016). However, the largest of these companies – the Northern Transportation Company Limited (NTCL) – filed for bankruptcy in late 2016, and the GNWT purchased NTCL's remaining assets to continue providing essential barging services.

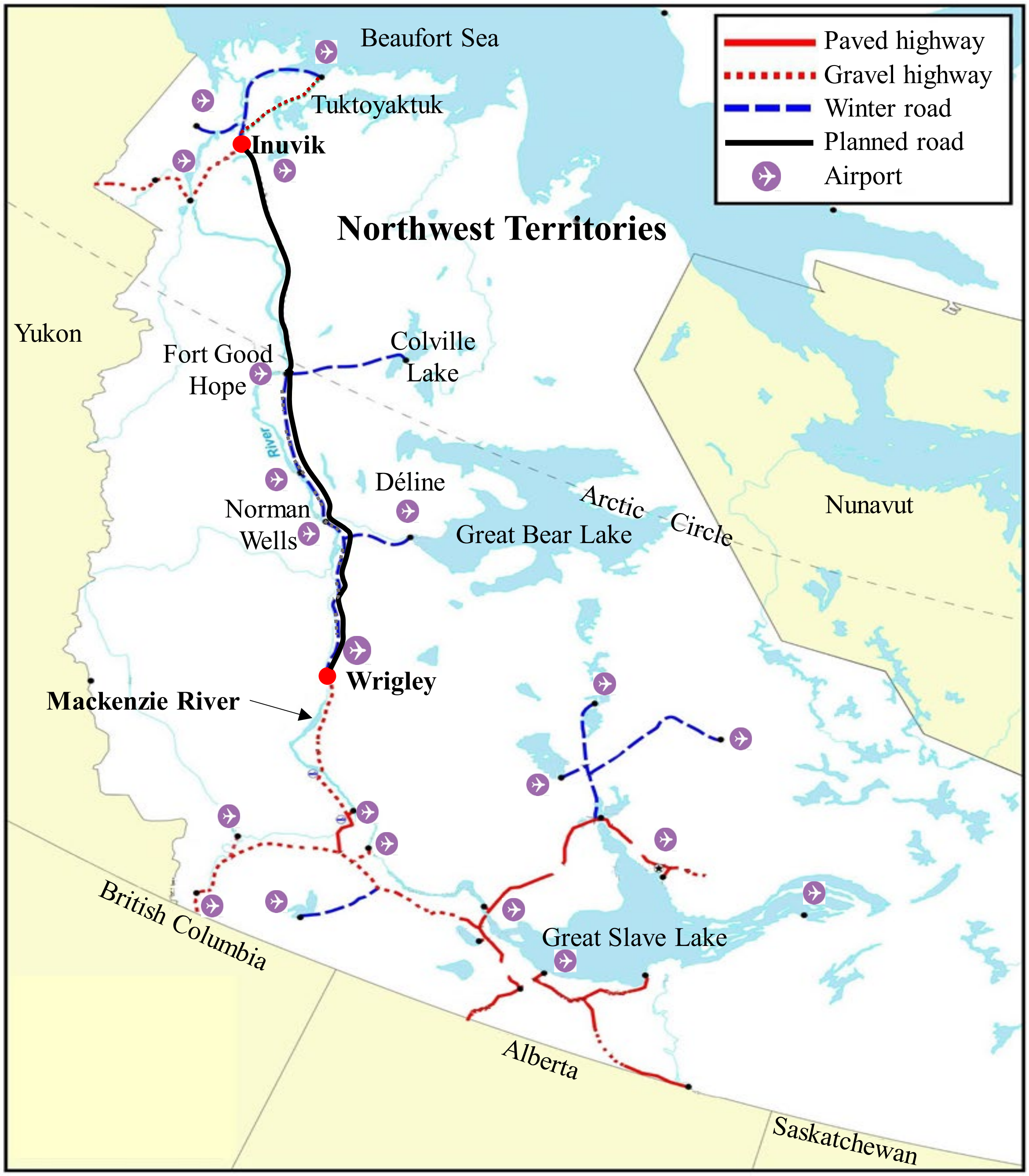

Figure 1. Transportation network of the Northwest Territories, Canada [Adapted from the Government of the Northwest Territories (2018a)].

In recent years, the duration of the Mackenzie River's navigable season has generally grown shorter and more variable, resulting in more delays and costs incurred from the use of alternate delivery modes. Climate change can influence precipitation and temperature, which in turn impact river streamflow (Sung, Burn, & Soulis, 2006; Woo, Thorne, Szeto, & Yang, 2008). Maximum spring flows on the Mackenzie River have generally decreased over the last four decades (Yang, Shi, & Marsh, 2015) due to climate change impacts as well as human-controlled factors upstream of the watershed, contributing to lower water levels. This has, in turn, contributed heavily to the shortening of the once reliable navigational season (Northwest Territories, 2008). Data from the Canadian Coast Guard on navigational buoy placement dates at Rader Island (near Norman Wells) indicates that the number of navigable, open season days decreased from 121 days in 1997 to 110 days in 2017, with a low of 87 days in 2014. Because the unit cost of airlift is reported to be about 10 times higher than barge (GNWT Department of Transportation, 2011b), transport costs in the Mackenzie River corridor have increased (Pendakur, 2017).

To improve transportation reliability and accessibility to remote but important communities, and provide more opportunities for economic development throughout the NWT, the GNWT has considered an all-weather road from Wrigley to Tuktoyaktuk since the 1950s, called the Mackenzie Valley Highway (5658NWT Ltd. & Government of Northwest Territories, 2011). The portion from Inuvik to Tuktoyaktuk opened on November 15, 2017 (Government of the Northwest Territories, 2018b). Although plans to construct the rest of the highway have been stalled due to lack of funding commitments (projected costs are $1.67 billion), in June 2018 it was announced that funding to construct a 15-km portion from Wrigley north to Mount Gaudet had been secured (CBC News, 2018).

Federal and territorial governments have been working to understand the impacts of climate change on existing infrastructure, how to adapt to it (Northwest Territories, 2008), and how to incorporate climate change considerations into infrastructure decisions. However, there are little to no formal tools or processes currently in place to guide the latter (Auditor General of Canada, 2017). There has been no application of quantitative tools that explicitly incorporate environmental variabilities into infrastructure decision-making structures. Northern territorial governments have expressed their need for such tools, given the number of major infrastructure projects currently under consideration.

2.2 Literature review

Infrastructure projects like highway construction are subject to significant uncertainties from multiple sources, including demand, changing weather, and political and social environments (Zhao, Sundararajan, & Tseng, 2004). For transportation infrastructure projects in Northern Canada, climate change impacts are one of the greatest sources of uncertainty. Cost-benefit analysis (CBA) approaches to account for valuations of future uncertainties include sensitivity analysis, and simulating expected cash flow through random sampling of variables (from their probability distributions) (Asplund & Eliasson, 2016; Gaspars-Wieloch, 2019). However, the main shortcoming of CBA, even when accounting for uncertainties, is that it does not produce results that directly support managerial flexibility in the face of uncertainty (Yeo & Qiu, 2003), ignoring growth opportunities or strategic alternatives in project investment (Dixit & Pindyck, 1994; Michailidis & Mattas, 2007). Real options models, based in financial options theory, were developed and applied in response to this shortcoming over the last two decades (Herder, de Joode, Ligtvoet, Schenk, & Taneja, 2011; Galera & Sánchez, 2010). Real options models are distinguished from conventional CBA in that the flexibility of delaying a project under uncertainties can be considered an asset (Michailidis & Mattas, 2007), and thus an additional source of value in a project investment decision (Bodie & Merton, 2000).

Financial options valuation models were first proposed by Black and Scholes (1973) and Merton (1973). Pindyck (1979) studied the impact of two sources of uncertainty on non-renewable resource markets. Tourinho (1979) looked at the valuation of a natural resource when the price of the resource followed a stochastic process. Since the 1970s, real options models have been applied to many different types of infrastructure decisions, including manufacturing site location choice (Kogut & Kulatilaka, 1994), IT network expansion (Benaroch & Kauffman, 2000), oilfield development in Alaska (Conrad & Kotani, 2005), power plant construction timelines (Kato & Zhou, 2011), and parking garage sizing decisions (Zhao & Tseng, 2003). Uncertainties (sometimes from multiple sources) often end up being the key decision drivers in these models (Bräutigam, Esche, & Mehler, 2003). Kim et al. (2017) applied a real options framework to assess renewable energy investments in developing countries, accounting for uncertainties due to rapidly changing technologies and host government conditions. A real options model was used to evaluate NASA technology investments based on development and programmatic risks (Shishko, Ebbeler, & Fox, 2004). The feasibility of privatized infrastructure projects was assessed using an option pricing-based model, with uncertainties, such as bankruptcy risk, accounted for (Ho & Liu, 2002).

There have been relatively few applications of real options models specific to transportation infrastructure decision problems. However, it has been identified as an appropriate approach for handling issues of climate change when evaluating transportation projects, particularly when the uncertainties arising from climate impacts are too significant to be ignored (Dewar & Wachs, 2006). Applications include the aforementioned parking garage with future parking demand uncertainty (Zhao & Tseng, 2003) and highway expansion accounting for uncertainties in travel demand, land prices, and pavement deterioration (Zhao, Sundararajan, & Tseng, 2004). These two papers applied dynamic programming to generate solutions. The analysis of a tolled highway extension project used a binomial tree model (Garvin & Cheah, 2004), a popular and easy-to-implement class of approaches that include the binomial lattice method (Kato & Zhou, 2011; Brandão, Dyer, & Hahn, 2005; Smith, 2005; Michailidis & Mattas, 2007). Considering the uncertainty of minimum revenue guarantee, Huang and Chou (2006) evaluated the Taiwan High-Speed Rail Project using a compound option pricing approach. Real options has also been applied to network design and expansion decisions considering the uncertainty of demand (Chow & Regan, 2011a; Chow & Regan, 2011b). Stochastic variables have been represented as a Geometric Brownian Motion (GBM) process in real options models applied to transportation. Chow and Regan (2011a) modeled traffic demand as a GBM process, while Couto et al. (2015) modeled high speed rail demand as a GBM process. Zhao et al. (2004) represented both traffic demand and land price as GBM processes in their highway infrastructure decision model.

Only more recently has climate change uncertainty been accounted for using an option-type model. Sturm et al. (2016) presented a modified Black-Scholes model application to the annual decision of whether to construct an ice road in the Northwest Territories of Canada, given varying temperature conditions. They used the ice road season length as their climate input, as it is dependent on ice thickness and quality, which in turn is impacted by climate change. The annual decision of constructing the ice road for another winter season or not is analogous to a European-style option (represented by the Black-Scholes model) where the decision to buy/sell is made at a single pre-defined time (i.e., in the winter before barging season begins). Sturm, Goldstein, and Parr (2017) assessed the impacts of snowfall on various facilities using the same model. These are the only works that apply options theory to evaluate infrastructure investments considering climate change uncertainty. However, the Black-Scholes model alone is limited in its capability to model these decisions, because it can only represent the decision to continue barging or not for a given season, taking into account the number of open season days (the length of the summer shipping season, or OSD) projected for that year alone. The decision to build a road does not only include expected transport costs for one year but rather, many future years, as future uncertainties also impact that decision of if and when to build.

Thus, we expand on the existing literature by building a comprehensive methodological framework that better represents and supports the transportation infrastructure investment decision process under climate uncertainty. We then apply this framework to the Mackenzie River corridor. The first stage of this framework involves modeling open season days (OSD) for barge sailing – our proxy for climate change impacts – as a stochastic process. The second stage involves applying the modified Black-Scholes model to one OSD forecast, in the same manner as Sturm et al. (2016), to determine the expected costs associated with the annual decision to reconvene summer barging operations (and airlifting supplies when low OSD causes barging capacity shortfalls). In the third stage, these expected costs are used to calculate deterministic costs and benefits of barging and road building. In the final (and most critical) stage, we apply the binomial lattice method, a real options modeling approach, that supports managerially flexible decisions of *if* and *to when* to defer all-weather highway construction in the Mackenzie River corridor. Specifically, we determine whether construction is financially justified in the face of future years of OSD uncertainty, and if so, when this decision should be deferred to, given a 20-year highway life before major rehabilitation is needed. This research demonstrates how much project valuations change when climate change uncertainty is accounted for, specifically in the north where these impacts are among the most severe in the world.

3. Analysis framework and data

3.1 Methodological framework for flexible decision-making under uncertainty

Our framework for incorporating environmental uncertainties to generate flexible transportation investment decisions and thus, support investment decision-making and policies, consists of three major stages that center around the options approach. Although the framework can be used for any transportation infrastructure decision process, we feel its application is particularly well-suited for northern geographies where significant climate change and demand uncertainties render the decision-making process particularly challenging. **Stage 1** involves understanding the uncertain (and possibly volatile) factors that are important to operations and thus, the investment decision. These factors may include a variety of climate measures, passenger or freight demands, and possibly others. Historical data for these factors (if available) can be used to parameterize stochastic process models that in turn are used to generate forecasts. **Stage 2** involves using forecasts to find expected project values (of the planned transportation infrastructure) in a cost-benefit analysis. **Stage 3** involves choosing and implementing a real options approach, which depends on the number of stochastic inputs and the processes they are represented by, as well as complexity of the decision problem at hand.

The modeling framework for the specific decision problem at hand – whether barging operations should continue, and when it should be replaced entirely with truck delivery via a new all-weather Mackenzie Valley Highway – is shown below in Figure 2. The impacts of climate change uncertainty on this infrastructure investment decision are represented in the variability of marine open season days (OSD) on the Mackenzie River.

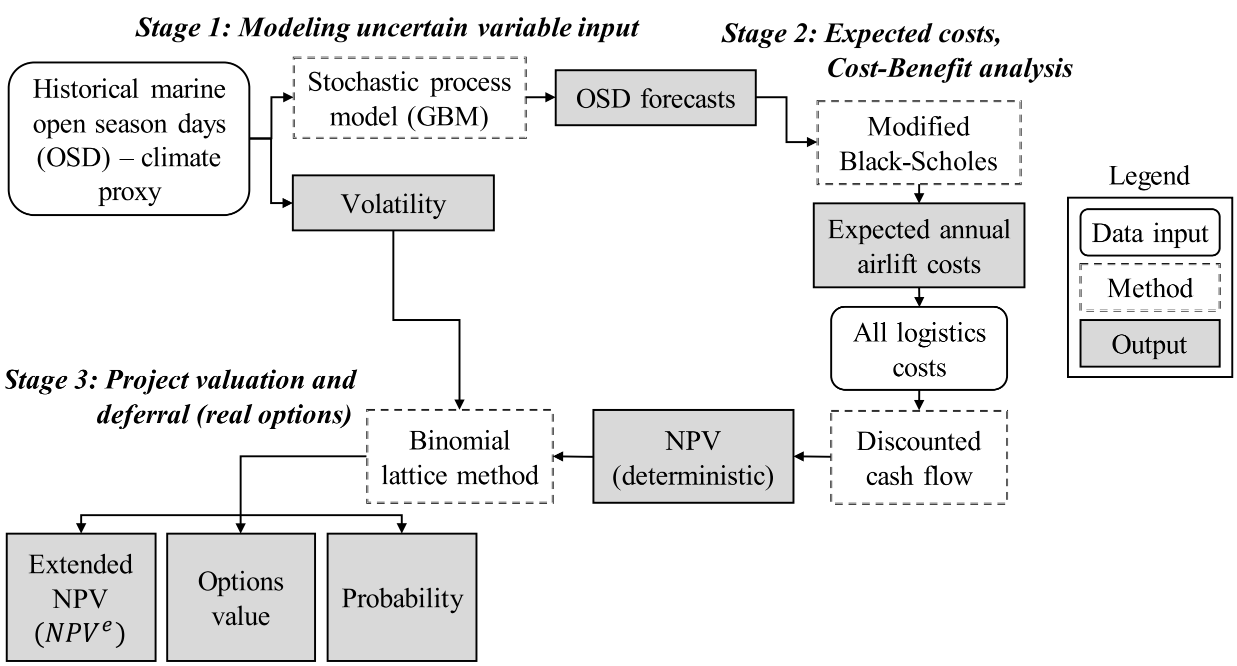

Figure 2. Modeling framework.

First, we use historical environmental conditions data that serves as a proxy for climate change (impacting the transportation service and infrastructure investment problem in question), and model it as a stochastic process (Section 4.1). Specifically, we model river open season days (OSD) as a geometric Brownian motion (GBM), and obtain OSD forecasts for a 20-year horizon. In Stage 2a (Section 4.2), we use historical and forecast OSDs in a modified Black-Scholes model (Sturm, Goldstein, Huntington, & Douglas, 2016), which outputs the expected airlift costs for each year barging operations are continued. These expected costs are meant to represent the risk, as observed by the barge operator, in the choice of continuing barging operations for another summer season instead of diverting those operational costs towards other means of delivery (and possibly, delays). In Stage 2b (Section 4.3), we then use these expected costs to calculate the highway construction project NPV, which, with OSD volatility, are input to the model in Stage 3 (Section 4.4). We determine whether Mackenzie Valley Highway construction between Wrigley and Inuvik (and therefore, replacement of barge shipping with trucks) is justified when we incorporate OSD uncertainty into the project NPV using the binomial lattice method. This results in project valuations (extended NPV, or NPV^e) that can help planners determine if and how long the construction project should be deferred. The most notable outcome is how much transportation project valuations change when climate change impacts are accounted for, specifically in the north where these impacts are among the most severe in the world.

3.2 Data and modeling inputs

Data and information used for this research was gathered from Statistics Canada (2019), the Canadian Coast Guard (CCG), NTCL, BBE Expediting (a northern logistics company based in Edmonton, Canada), and various reports and other literature both provided by the GNWT and found online. The key inputs required for our models, including the data and assumptions required to populate those inputs and build our model application, are listed in Table 1 and further discussed in this section.

Table 1 Model Data Sources

Input		Unit	Source	Application
Freight volumes		Tonne	NTCL	Cost-benefit analysis
Historical open season days (OSD)		Days/year	CCG	Climate uncertainty
Minimum open season days (OSD)		Days/year	NTCL	Cost-benefit analysis
Freight transport costs	Barge	$/tonne	BBE Expediting	
	Truck	$/tonne	BBE Expediting	
	Air	$/tonne	BBE Expediting	
Construction timeline		Years	GNWT	
Life of all-weather road		Years	GNWT	
	Discount rate	%	Bank of Canada	

Input		Unit	Source	Application
Other parameters	Investment cost	$	GNWT report (Tetra Tech EBA, 2011)	
	Other logistics and maintenance cost components	$/tonne	Assumption	

3.2.1 Freight volumes

Estimates of future barge freight volumes to communities between Wrigley and Inuvik are required for the cost-benefit analysis (4.2). In the absence of an all-weather highway, these volumes consist entirely of freight that is ideally delivered by summer barging when possible. In barge capacity shortfalls (due to shortened seasons), the remaining freight is assumed to be delivered by airlift. If the all-weather highway were constructed, barge services would be discontinued and all freight would be delivered by trucks.

Barge freight volumes from 2002-2014 were obtained from NTCL, the largest and oldest barging company on the Mackenzie River (Zheng, Kim, Du, & S.A., 2016). We make two assumptions to generate future freight volume estimates. First, NTCL provided, by far, the most barging service on the Mackenzie, carrying the greatest volumes and providing the largest geographic coverage (in fact, the only company to provide service to the Mackenzie River Delta at Tuktoyaktuk, and into the Beaufort Sea), we assumed that NTCL's freight volumes accounted for 80% of the total freight volumes carried on the Mackenzie. Second, we assume that future freight volumes will increase at the rate of GDP growth in the Northwest Territories from 2013-2017 (Statistics Canada, 2019). To obtain a forecast for 2015, we simply took the average barge freight volumes from 2002-2014 and applied the GDP growth rate, and assumed growth continues at that rate until 2037. This is one approach, but freight volume forecasts can be obtained from any number of methods including time series analysis, and this may be updated as better data becomes available.

3.2.2 Open season days (OSD)

The Mackenzie River is only navigable between the dates that the Canadian Coast Guard (CCG) installs and removes navigational buoys for the summer season. Open season days (OSD) indicate the length of this shipping season; in this work we use it as our climate proxy, modeled as a stochastic process in Section 4.1, for the following reasons. Mackenzie River OSD are determined by a complex combination of factors. Environmental factors include air and water temperature (and thus, ice breakup, freeze-up, and floating ice), precipitation, water levels, and water volumes. These are all impacted by climate change. Human factors include watershed management upstream in British Columbia throughout the season (thereby impacting volumes) as well as buoy placement by the Canadian Coast Guard (which is impacted not only by river conditions but also, labor availability). Because modeling the impacts of each factor that influences shipping capabilities on this 1700 km river is out of the scope of this work, we use the OSD, the final manifestation of these stochastic factors that directly impacts shipping.

Based on data (provided by the CCG) from 1997-2017 regarding dates of placement and removal of three buoys near Rader Island, we calculate the average historical OSD as the average number of days between buoys placement and removal each season.

We define minimum OSD as the minimum days in a shipping season required to transport all freight (the volumes that are forecasted as per 3.2.1) by barge. We first calculate the average freight volumes shipped by NTCL per day during open season, from 2002-2014. If we divide average total annual freight volume by the average daily freight volume, we calculate a minimum OSD of 107 days.

3.2.3 Freight transport costs by mode

We obtained estimates of unit freight transport cost by barge, truck, and air from BBE Expediting Ltd., a provider of expediting, supply chain logistics, and cargo handling services in the Canadian Arctic. They suggested that shipping costs from Edmonton to Inuvik were, in 2018, in the order of CAD $680-730/tonne by barge, and CAD $580-610/tonne by truck (note that all monetary units in this paper are in Canadian dollars). In the absence of further information, we assumed that shipping costs between Wrigley and Inuvik are proportional by distance and are the average of the resulting range, such that barging cost is $260/tonne and trucking cost is $225/tonne. As mentioned in Section 2.1, delivering heavy freight (ideally delivered by barge or truck) by air is estimated to cost, roughly and conservatively, about 10 times that of barge delivery (GNWT Department of Transportation, 2011b), such that the benefits of faster delivery times by air are entirely outweighed by the costs. Thus, we assume that the unit cost of air freight delivery is $2600/tonne. Note that 1) we also assumed that these transportation costs hold over the entire study period, and 2) we considered average shipping costs from Wrigley to Inuvik, rather than considering each individual community in the corridor.

3.2.4 All-weather highway construction time and life

The time and cost of construction for an all-weather highway in Northern Canada, and the highway life, depends on many factors including: planning, data collection, and design; subsurface conditions (particularly considering permafrost); labor, supply, and equipment costs (including costs for transporting all the above); weather conditions, and many others. The construction of a new highway can take anywhere from five to ten years, from the time the project is designed to the time it is built (Government of Nova Scotia, 2018). Political consideration, concept planning, and design of this all-weather highway has been ongoing since the late 1950s (5658NWT Ltd. & Government of Northwest Territories, 2011). Given that the (gravel) Inuvik-Tuktoyaktuk Highway (ITH) construction project lasted four years, we will assume the same timeframe for construction of this gravel highway. Also, in the north, gravel roads and runways are less costly to maintain than paved surfaces, which can be subject to significant cracking and sinking. According to discussions with GNWT Infrastructure, the ITH was built with a planned lifespan of 75 years; with new gravel application required every five years, and major bridge rehabilitation (i.e., replacing bridge decks) required in 20 years. As a result, we will assume the lifespan to be 20 years for this stretch of the Mackenzie Valley Highway between Wrigley and Inuvik.

3.2.5 Other parameters

We require assumptions for several other modeling parameters:

- The annual discount rate converts future monetary values to a present value (García-Gusano, Espegren, Lind, & Kirkengen, 2016), and is required for a multi-year cost-benefit analysis. The discount rate is estimated as the mean of the average inflation for Canada during 2009 and 2018 (Bank of Canada, 2019), which is 1.59%.
- The total construction cost of the all-weather road from Wrigley to Inuvik is reported to be $1.67 billion, according to a project description report prepared for the GNWT (Tetra Tech EBA, 2011; CBC News, 2013).
- Maintenance costs for both the barging-airlift system and the planned all-weather highway are assumed to be 5% of total freight costs.

4. Model and results

We introduce the models we use to assess the Wrigley-Inuvik all-weather highway decision.

4.1 Representing climate uncertainty (Stage 1)

The volatility parameter is a commonly used expression of uncertainty in the real options literature (Dixit & Pindyck, 1994). We assume that climate change uncertainty – open season days (OSD) being our proxy for climate change impacts on this barging system – is a stochastic process, and may have a trend and certainly some level of volatility. OSD forecasts may be obtained by modeling OSD as a stochastic process (as done by Sturm et al. (2016) for winter road open season days) or using time series analysis methods. Our rationale for using Geometric Brownian Motion (GBM), a continuous-time stochastic process in which the logarithm of the variable follows a Brownian motion with drift (Ross, 2014), to represent OSD is that OSD looks much like a random walk with drift and is always positive. Also, GBM has been used to model other variables related to climate uncertainty; notably, Gersonius et al. (2013) modeled rainfall intensity as a GBM, while Truong et al. (2018) modeled the count of climate-related catastrophic events as a GBM. We obtain simulated forecasts and descriptive parameters for use in the models of Sections 4.2 and 4.4.

In the options literature, GBM has often been used to model stock prices (Ozorio, Bastian-Pinto, & Brandão, 2018). A stochastic process S_t following a GBM is represented as follows (Dixit & Pindyck, 1994):

$$dS_t = \eta S_t d_t + \theta S_t dW_t \tag{1}$$

where W_t is a Wiener process, also called Brownian motion, which is a continuous-time stochastic process; η is the drift, or the change rate of the mean of a stochastic process; and θ is the volatility of the stochastic process. The solution for S_t is found by applying Ito's Lemma; the derivation is widely available (Dixit & Pindyck, 1994; Ross, 2014):

$$S_t = S_0 e^{\left(\eta - \frac{1}{2}\theta^2\right)t + \theta dW} \tag{2}$$

In this paper, S_t represents OSD in year t; S_0 is the initial value at $t = 0$; η is the average growth rate of S_t; and θ is the average annual volatility of OSD. We can calculate η and θ using historical data (Yang & Blyth, 2007; Dmouj, 2006):

$$\eta = \frac{1}{n}\sum_{t=1}^{n} ln\left(\frac{S_t}{S_{t-1}}\right) \tag{3}$$

$$\theta = \sqrt{\frac{1}{n-1}\sum\nolimits_{t=1}^{n}\left[ln\left(\frac{S_t}{S_{t-1}}\right) - \overline{ln\left(\frac{S_t}{S_{t-1}}\right)}\right]^2} \tag{4}$$

We use Monte Carlo simulation to generate 1,000 numerical solutions for S_t. Specifically, we generate random numbers in a Wiener process that follows a standard normal distribution:

$$dW_t = \varepsilon\, dt \tag{5}$$

where ε is distributed standard normal $N{\sim}(0,1)$. Figure 3 shows historical OSDs (1997-2017) and 1,000 simulated forecasts for 2018-2041 based on Eqs. (2)-(5).

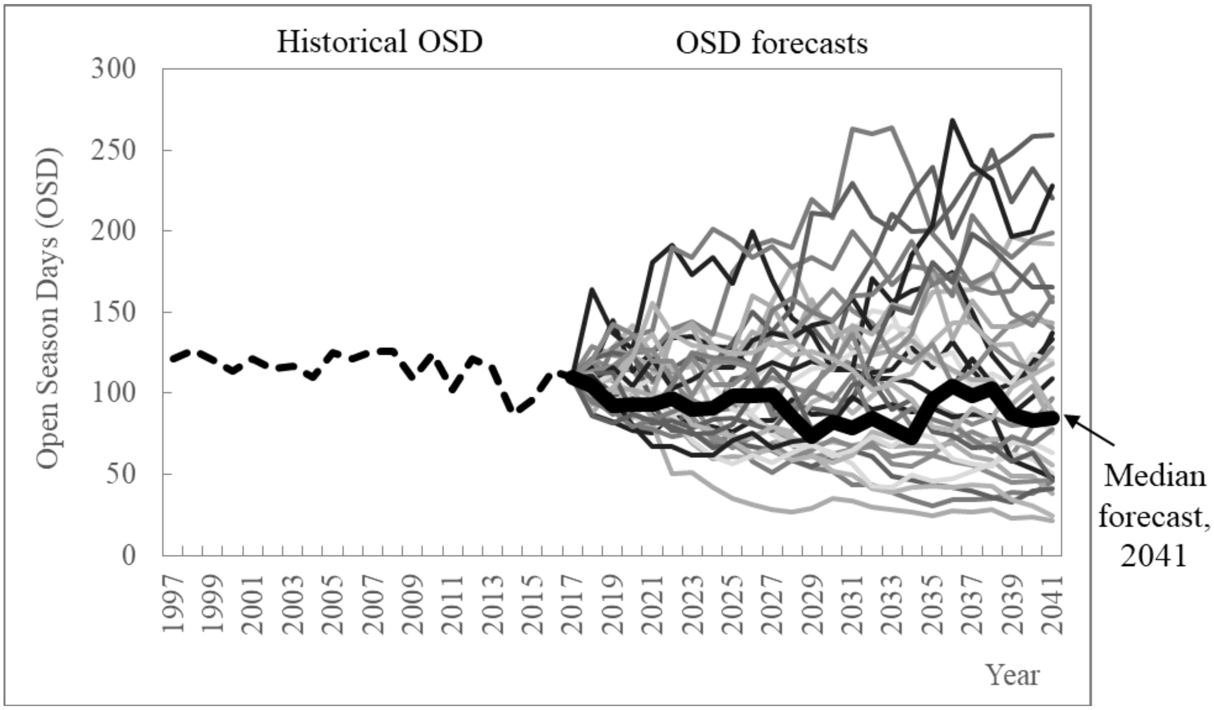

Figure 3. Forecasted OSD and its volatility.

The 24-year OSD forecast (2018-2041) considers a construction time of three years and highway life of 20 years starting in 2019. The thick red line represents one OSD forecast whose 2041 OSD is the median of all forecasts. We chose this forecast to calculate deterministic future airlift costs and expected future airlift costs using the modified Black-Scholes model, and our NPV from the cost-benefit analysis, because it exhibits the same trend as the historical data and the Black-Scholes expected cost results end up being very close to deterministic values. In the end, any of the other forecasts could be chosen. Also, we use the historical OSD volatility (which is a representation of future OSD uncertainty) for input to our real options model (Section 4.4).

4.2 Expected annual barge/airlift costs (Stage 2a)

We want to determine the costs of airlifting cargo in years with barging capacity shortfalls. Capacity shortfalls occur when the number of open season days (OSD) on the Mackenzie River is not sufficient to transport all expected cargo (in addition to other logistics and operational problems, which we do not consider in this paper). As mentioned in 3.2.2, OSD is a result of both climate change impacts and human-driven decisions. Our socio-climatic problem is similar to options in a financial market that are assessed by an options approach, used for reducing investment risk (the corollary here is that we want to reduce airlift cost risks). An option is the right to buy or sell an asset at an agreed price at a specific time (Hull, 2005), and the option value is the price paid or received for purchasing or selling the options. We adopt Sturm et al.'s (2016) modified Black-Scholes option pricing formula to determine the annual expected costs of continuing barging, prior to the barging season when the decision to continue or plan other logistics must be made. In Black-Scholes, if a buyer or seller believes the real price of the underlying asset will be lower or higher, respectively, than the agreed price before the specific date, they may not "exercise" the option. This is analogous to the situation where the GNWT barging operations team decides, at a certain time between winter and the start of the barge season, to abandon barge operations altogether that summer in favor of other transport options (we also discussed this in 2.2). In this case, the calculated expected airlift costs due to barging shortfalls that summer, caused by uncertain OSD, is too high to tolerate.

The "additional" cost of shipping undelivered cargo by airlift is determined using the modified Black-Scholes model (Sturm, Goldstein, Huntington, & Douglas, 2016):

$$P(S_t,t) = N(-d_2)Ke^{-r_f(T-t)} - N(-d_1)S_t$$
$$d_1 = \frac{1}{\sigma\sqrt{T-t}}\left[ln\left(\frac{S_t}{K}\right) + \left(r_f + \frac{\sigma^2}{2}\right)(T-t)\right], d_2 = d_1 - \sigma\sqrt{T-t} \tag{6}$$

where:

$P(S_t,t)$ is the expected airlift cost at time t;
$N(\cdot)$ is the standard normal cumulative distribution function;
T represents the time at which a decision must be made about whether to barge that year or forego it and build a road instead, t is current time, and $T-t$ is the time remaining to make the decision;
S_t is the actual OSD at t;
K is the minimum required OSD to ship all freight demand by barge;
r_f is the annual discount rate; and
σ is the adjusted standard deviation of the OSD.

When $S_t < K$, airlift costs are incurred. We view this problem as one where the operational team at GNWT faces the choice to barge or not barge each year, at some time before the barging season is expected to begin, such that $T-t = 6$ months. If the OSD was distributed lognormal, its standard deviation would be σ. The Mackenzie River OSD does not follow a lognormal distribution, much like the ice road OSD in Sturm et al. (2016) does not. Thus, we also adopt an adjusted value as per Sturm et al. (2016), which they found to work with reasonable accuracy. We randomly generate 10,000 numbers whose logarithm follows a normal distribution $N(\mu,\sigma)$, and using Eq. (9), vary f such that the mean value of OSD is equal to that of the randomly generated numbers (Sturm, Goldstein, Huntington, & Douglas, 2016):

$$\mu = l\,n\left(\frac{S_t}{\sqrt{1+\frac{v}{S_t^2}}}\right) \tag{7}$$

$$\sigma = \sqrt{ln\left(1 + \frac{v}{S_t^2}\right)} \tag{8}$$

$$v = (f \cdot \sigma')^2 \tag{9}$$

where σ' is the standard deviation of OSD. Using the above, we obtain the additional barging days $P(S_t, t)$ required to fully serve freight demand in the season. If N is the average volume of freight transported per day under optimal barging conditions, and P_p is the unit cost of airlifting freight, then the airlift cost incurred due to insufficient OSD $\left(C_{B,P,t}\right)$ can be determined using Eq. (10).

$$C_{B,P,t} = P(S_t, t) \cdot N \cdot P_P \tag{10}$$

Figure 4 shows the expected airlift costs (due to insufficient OSD) versus OSD for historical (1997-2017) and forecast (2018-2041) years. The forecast airlift costs are based on the one OSD forecast chosen from the results in 4.1 – the forecast expected costs are from the Black-Scholes formula, while the deterministic forecast costs are calculated directly from the OSD forecast process.

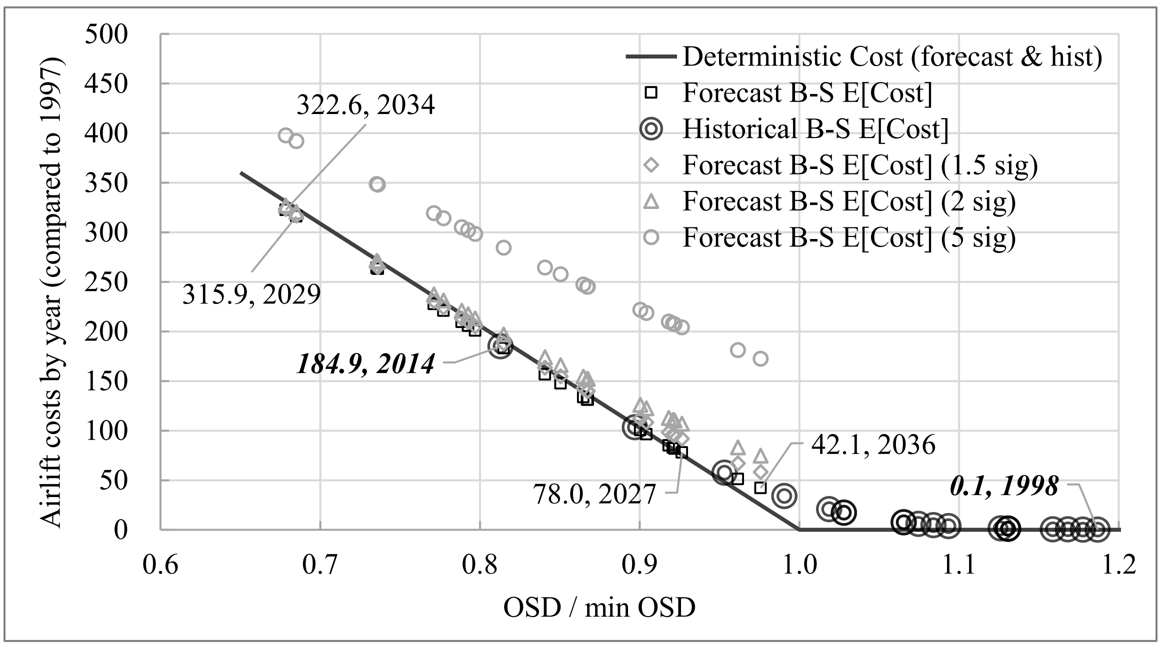

Figure 4. Airlift costs in different years (normalized to 1997) versus OSD ratios for one forecast OSD time series. Labels are (airlift cost, year).

The x-axis is the ratio of OSD and the minimum OSD (107 days) for each year; (OSD/min OSD)>1 indicates that there is enough OSD in the season to transport everything by barge; the opposite is true when (OSD/minOSD)<1. The y-axis is the annual airlift cost normalized to that of 1997 (the first year of study).

The above figure can be used to understand the risk of barging as observed by the GNWT barge operations planner six months before barging season begins (December). Even in historical years when it came to pass that OSD/minOSD>1 and no airlift costs were incurred, the operator would have gone into the season expecting some airlift costs. According to the results of Figure 4, expected airlift costs increased between 1997 and 2017 at an average annual growth rate of 15.3%, peaking in 2014[1]. In fact, the largest difference in historical airlift cost ratios is 184.8, with the minimum occurring in 1998 and maximum in 2014. The risks of continuing barging increase significantly with the OSD forecast used; forecast airlift costs are significantly higher than in historic years, with a greater spread (the maximum difference in forecast airlift cost ratios is 280.5, with the minimum expected in 2036 and maximum in 2034). When OSD/minOSD)<1, the B-S forecast expected costs are close to the forecasted deterministic costs due to the forecast having a relatively low standard deviation. If the standard deviation should grow larger in the future, barge operations planners would also observe higher expected costs.

These results suggest that we could expect significantly larger freight airlift costs to the Mackenzie River communities into the future, due to growing climate uncertainty (represented as OSD volatility) causing barging capacity issues. However, the results do not suggest that the barge operator will discontinue barging operations in a given year. As long as the costs involved in setting up another barging season (barge and tug preparation, hiring of personnel, etc.) are lower than the cost difference between delivering some amount of freight by barge and air (which is likely to be true), the GNWT will continue barging, albeit under more financially risky circumstances. However, the situation could encourage the GNWT to invest in all-weather highway construction.

We plot expected airlift costs for the entire set of 1,000 OSD forecasts from 4.1 in Figure 5. The variations in results are due to both the yearly forecasted OSD time series values as well as each time series' standard deviation.

[1] 2014 was one of the worst barging seasons in recent history, due to water levels deteriorating rapidly through July and August. In fact, NTCL suspended their services in mid-August (they typically expect to run into late September or early October), leaving much cargo undelivered.

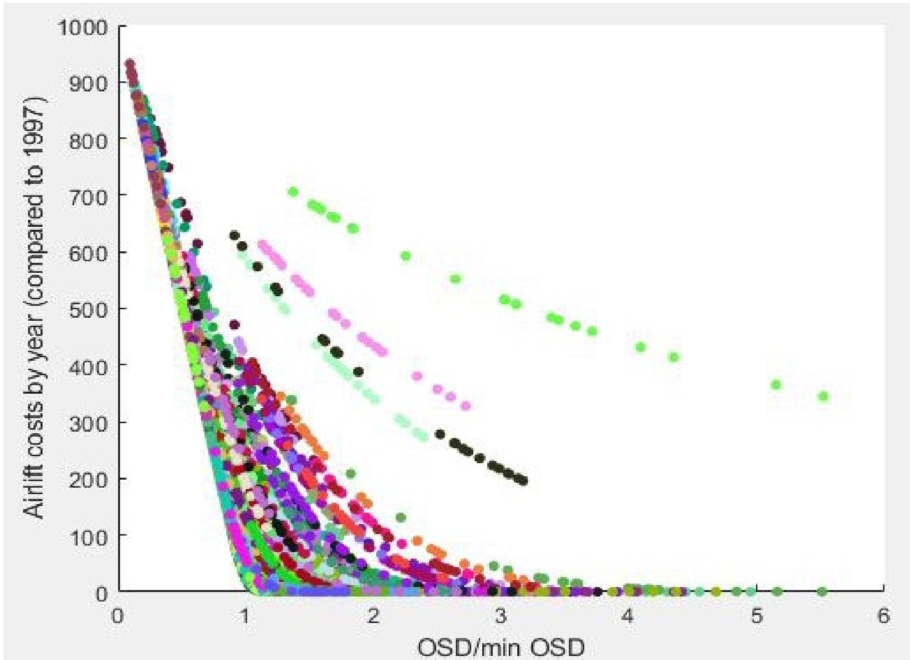

Figure 5. Airlift costs (normalized to 1997) versus OSD ratios for all forecast OSD time series

4.3 Cost-benefit analysis (Stage 2b)

Let us say that the highway project's net present value (NPV) is the difference between the present total project benefits (C) and project investment costs (I).

$$NPV = C - I \tag{11}$$

It does not include valuations of uncertainty for the elements considered. A real options value (the extended NPV, or NPV^e) is composed of the project's NPV and the value of the embedded options due to uncertainty (Andoseh, Bahn, & Gu, 2014).

Let us define present project benefits C as the cost savings of building the highway (thus, using truck transport after the highway is constructed, also called the *construct* scenario) versus not building the highway (continuing use of barge and airlift, called the *do nothing* scenario):

$$C = C^D - C^C \tag{12}$$

Where C^D and C^C are the total present (i.e., discounted) costs of the *do nothing* and *construct* scenarios, respectively, and consist of the following:

$$C^D = \sum_{t=1}^{T_1+T_2} \left(X_{b,t}P_b + X_{a,t}P_a\right)(1 + b_{ob})\, e^{-rt} \tag{13}$$

$$C^C = \sum_{t=1}^{T_1} \left(X_{b,t}P_b + X_{a,t}P_a\right)(1 + b_{ob})\, e^{-rt} + \sum_{t=T_1+1}^{T_1+T_2} X_t P_h (1 + b_{oh}) e^{-rt} \tag{14}$$

where:

T_1, T_2 are project construction and operation periods, respectively, in years; $T_2 > T_1 > 0$;

$X_{b,t}, X_{a,t}$ are total cargo delivered by barge and airlift, respectively, in year t (tonnes), where $X_{b,t} + X_{a,t} = X_t$;

P_b, P_a, P_h are prices for transporting a unit of cargo by barge, airlift, and highway (truck) via all-weather highway, respectively ($/tonne);

b_{ob}, b_{oh} represent the other logistics and maintenance cost components for barging and highway trucking, respectively, and are calculated as a proportion of total costs, and

r is the annual discount rate.

In the *construct* scenario, freight is transported by barge (and airlift, when necessary) until T_1, when the all-weather highway is built. After it is built, all freight is transported via trucks. In the *do nothing* scenario, all freight continues to be delivered by barge and airlift only. The amount of freight transported by barge and airlift are taken from the results of 4.2. Given how similar the deterministic and expected forecast annual airlift costs are, we can use either for our NPV calculations. Note here that the costs and benefits included in this NPV only include those directly related to freight transport cost. There are many other cost and benefit elements that should be included in an analysis by the GNWT.

If the highway were to be constructed immediately, the NPV of the project, calculated with parameter values introduced in 3.2, is -$1.08B. The enormous cost of building this highway ($1.67B) far exceeds the costs saved in freight delivery by truck compared to the barge/airlift system ($0.59B). This all-weather highway construction project would never be justified using such a cost-benefit analysis. In the following section, we show how the project NPV changes when we consider the option of project deferral due to environmental uncertainty.

4.4 Real options analysis (Stage 3)

Our results suggest that climate change impacts on the Mackenzie River may result in increased future freight delivery costs to communities, due to greater use of airlifts to make up barge capacity shortfalls. Here we build on the previous sections to present a real options model that determines *if* and *when* an all-weather highway should be constructed.

4.4.1 Binomial lattice method

A project's value, when subject to an uncertain input, can be determined using a binomial lattice model developed by Cox et al. (1979), a simple and widely-used method for options valuation. We divide the time period between the current and options exercise time into n intervals, assuming that the project's value S can either increase or decrease within each time interval (Brandão, Dyer, & Hahn, 2005). Given its initial value at the beginning of a time interval t (where $t = 0 \ldots n$), S may increase by multiplicative factor u with probability p to uS, or decrease by multiplicative factor d with probability $(1 - p)$ to dS over time step size Δt. These values are calculated as follows (Michailidis & Mattas, 2007):

$$u = e^{\theta\sqrt{\Delta t}} \tag{15}$$

$$d = e^{-\theta\sqrt{\Delta t}} \tag{16}$$

$$p = \frac{e^{r\Delta t} - d}{u - d} \tag{17}$$

where r is the annual discount rate (4.2), and θ is the OSD volatility (4.1).

As the number of time steps approaches infinity, it is a necessary condition that $ud = 1$, as proposed by Cox, Ross, and Rubinstein (1979). Figure 6 illustrates the real options calculation process using the binomial lattice method. The method requires a forward calculation, starting at $t = 0$, of all possible paths that the underlying project value S could take over time intervals $t = 0 \ldots n$. Project value S either increases by factor u or decreases by factor d for each time step as per Eqs. (15)-(17). Then, it requires a backwards calculation to determine options values.

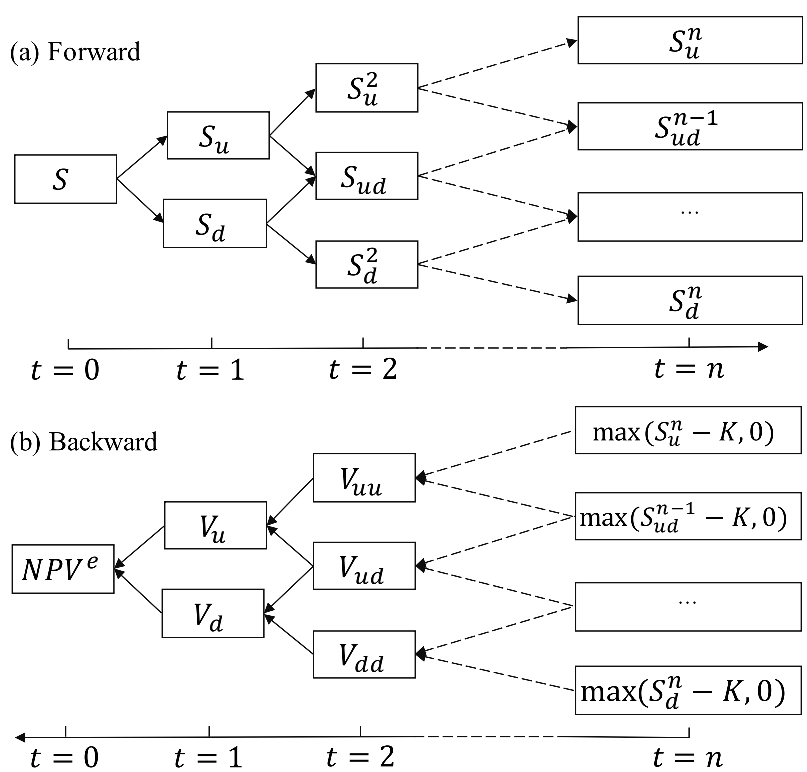

Figure 6. Calculating options values using the binomial lattice method

For the backward calculation, starting at final time step $t = n$, options values are calculated backwards in t for each node using Eq. (18), until at $t = 0$ we obtain the final option value (the NPV^e of the project).

$$V_{ud} = e^{-rt}(pV_{uud} + (1-p)V_{udd}) \tag{18}$$

The option value is calculated as the difference between NPV^e and NPV. The above process is done for each year we are interested in obtaining NPV^e.

Decision-makers may defer construction of the all-weather road when there is no positive net benefit from investment, accounting for the likelihood that continued reliance on barging will result in growing airlift costs. To this end, the optimal year for highway investment can be selected. In the literature, this decision to invest or not invest has been based on two criteria: the NPV^e (i.e., considering the benefits of deferral) of the project is positive (profitable), and the probability of benefit exceeding some predetermined threshold β (Yang & Blyth, 2007; Kato & Zhou, 2011). We will investigate the results of the first criteria below.

4.4.2 Results: Project value and investment year

Figure 7 shows the highway project's extended NPV (NPV^e) and options value by construction deferral year.

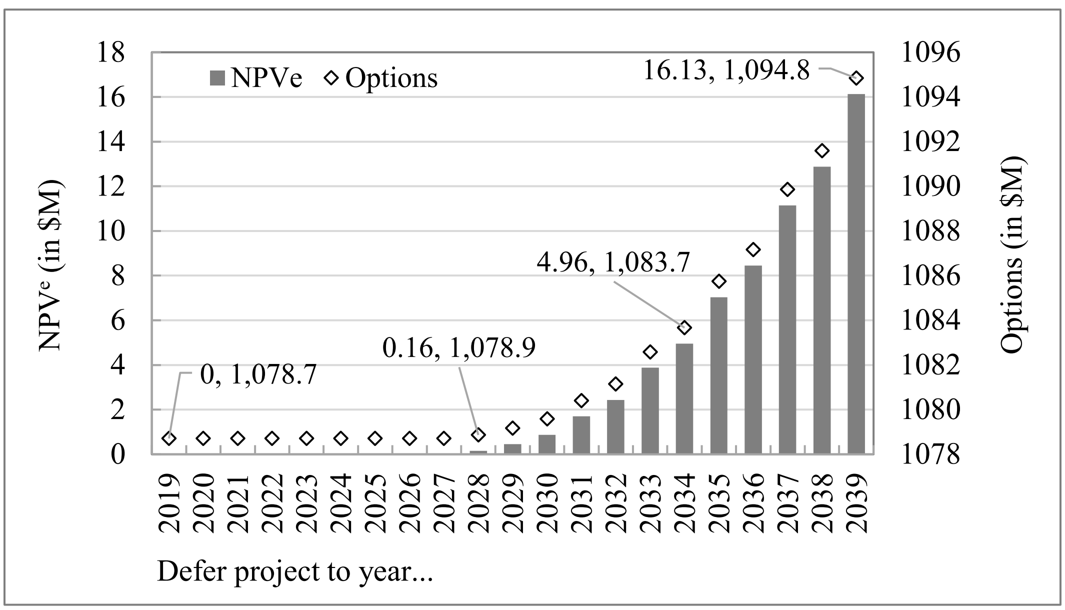

Figure 7. Project NPV^e and options values ($M) by construction year

The NPV^e is determined from application of the binomial lattice method in 4.4.1. The options value is calculated directly from the NPV^e and the project NPV from 4.3; as the NPV is constant, the options value simply follows the NPV^e. A positive NPV^e indicates an overall project benefit [with respect to the elements we included in the cost-benefit analysis (4.3) and OSD uncertainty (4.1)].

We do not observe a positive net benefit (NPV^e) from constructing this highway immediately (i.e., in 2019), which we already know from the negative project NPV reported in 4.3. Construction in 2019 does not allow us to account for OSD uncertainty through a project delay strategy. By considering the project for a future year, we are allowing the possibility of gaining benefit from the additional time we are not obligated to build the project, captured in the options value. However, even with the option to defer, we must do so by at least nine years (to 2028) to observe a positive NPV^e (\$0.16M), which grows significantly to the last deferral year considered (2039, or 20 years deferral). Continued reductions in OSD from year to year result in increasing airlift costs; by delaying construction at least nine years, we increase the probability of obtaining benefits from the all-weather highway through its 20-year lifespan. By exercising the deferral option, planners can take a "wait and see" approach, allowing for the possibility of good years to occur.

Decision makers and planners may choose any criteria for triggering an investment decision. They may decide that construction should begin the first year a positive NPV^e is observed [they may also combine this with threshold probabilities as per 4.4.4 (Kato & Zhou, 2011)]. In addition, although the NPV^e will continue to grow past 2039, we only consider deferral to that year as it is grows increasingly difficult to do investment planning beyond a 20-year timeframe. Because political and economic situations can change quickly, infrastructure investment plans should be made as soon possible. Overall, it is clear that OSD uncertainty, combined with the option of deferring construction, significantly increases the project's value.

Finally, we emphasize that our case study results in a 9-year deferral because the enormous costs of road building outweigh the cost effects of OSD uncertainty. If road building costs were lower or uncertainty effects were greater, our results would support a decision towards shorter deferral, or even immediate construction. As we anticipate future changes to the features of climate change uncertainty itself, the managerially flexible results offered by the real options methods becomes increasingly valuable against the binary results (defer or build) of CBA methods. With results indicating that investment should be deferred for nine years (instead of, for instance, 5, or 15, or 0), decision makers should not entirely abandon the idea of the project, as results support future feasibility.

4.4.3 Sensitivity analysis

Considering the susceptibility of a highway project's valuation to the inputs, we conducted a sensitivity analysis of the key parameters and inputs on the NPV^e results – future freight volumes, total all-weather highway investment cost, OSD volatility, air-to-barge and truck-to-barge cost ratios, and highway lifespan. All results are based on the previous section's finding that the optimal investment strategy is to defer highway construction for nine years (to 2028).

Freight volumes, project investment cost, and OSD volatility

Figure 8 shows how the NPV^e of the decision to defer to 2028 is impacted by future freight volumes, project investment cost, and OSD volatility.

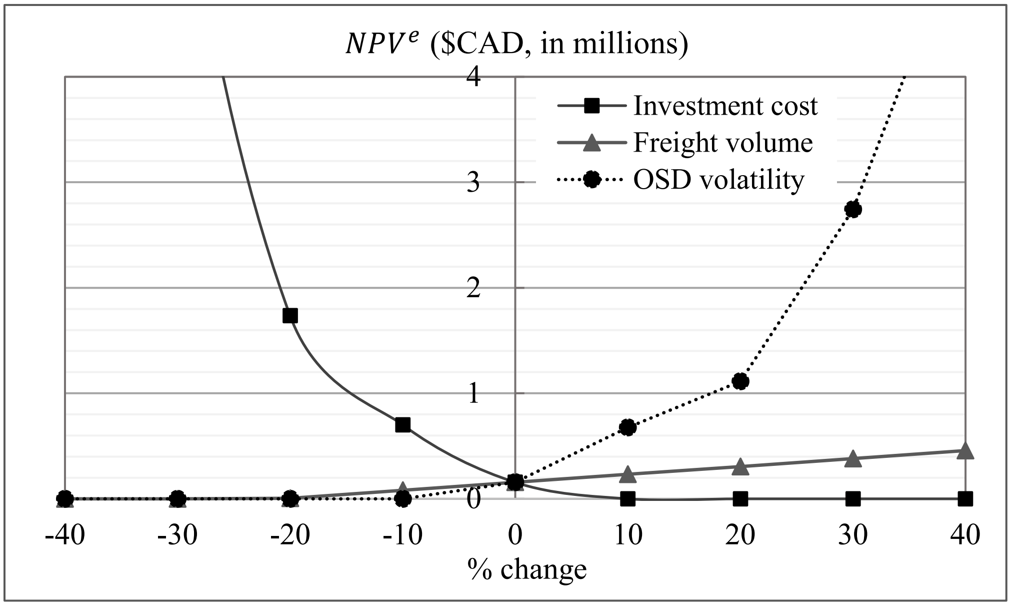

Figure 8. Sensitivity of freight volumes, investment cost, and OSD volatility on 9-year project deferral (2028) NPV^e

In Figure 8, the x-axis represents the percentage change in total freight volume, investment cost, and OSD volatility from the (benchmark) values used to generate the results in 4.4.2. The y-axis shows the percentage change in the NPV^e. Increases in freight volumes and OSD volatility result in higher 2028 NPV^e values; larger freight volumes and OSD volatility increase the probability of incurring airlift costs each year. The NPV^e appears to be more sensitive to OSD volatility than freight volumes, suggesting that with a higher OSD volatility, it is highly likely that the project deferral recommendation would be less than nine years.

The results show that the NPV^e is highly sensitive to changes in project investment costs, but this is not surprising given its enormous value ($1.67B). The NPV^e increases with decreases in investment cost, which will result in a recommendation to build earlier. For instance, a 10% lower investment cost results in a recommendation to build in 2027 (eight years deferral). When the investment cost increases more than 3%, the NPV^e falls below zero in 2028 such that deferral may be pushed to a year beyond 2028. On-going research indicates that consideration of staged road-building can yield different results.

Unit freight delivery costs

Given that this work considers a $1.67B all-weather highway investment to avoid the high costs of freight airlift, we also look at how the NPV^e of the decision to defer to 2028 is impacted by barge, airlift, and trucking unit cost parameters (Figure 9). Benchmark cost ratios as introduced in 3.2.3 and used in the NPV and NPV^e calculations are represented by the vertical lines.

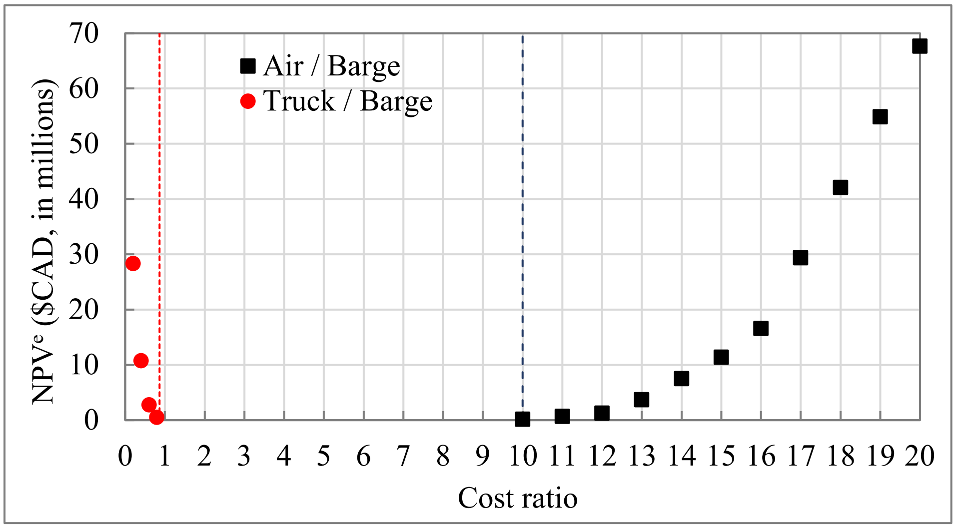

Figure 9. Sensitivity of cost parameters on 9-year project deferral (2028) NPV^e

Figure 9 shows that the NPV^e grows with the unit airlift/barge cost ratio, such that project deferral could be significantly less than the benchmark nine years. Figure 9 also shows that the NPV^e grows with a decreasing truck/barge cost ratio, meaning that as trucking costs decrease, the total cost of building and delivering freight via an all-weather highway also decrease, making it a more attractive option.

Project lifespan

We also investigate how the all-weather highway lifespan impacts project valuation (Table 2). When the lifespan is shorter than the previously assumed 20 years, the NPV^e at nine years project deferral decreases significantly, such that a positive NPV^e will not be observed unless the project is deferred even longer.

Table 2 Project Values at Nine Years Deferral, by Lifespan

Lifespan (years)	NPV (% change)	NPV^e ($M)
5	-44	0
10	-26	0
15	-11	0
20	-	0.16

These results also indicate that longer highway lifespans will result in deferral recommendations shorter than the nine years recommended for a highway with a 20-year lifespan, suggesting that the GNWT should extend the all-weather highway's lifespan through major rehabilitation work.

4.4.4 Probability of net benefit

We can also calculate the probability of a net benefit ($NPV^e > 0$) from the investment, using a binomial decision tree calculation for the option valuation. At each node of the decision tree one can either choose to invest or defer, moving forward from the current year. The probability of the increase s is shown in Eq. (19), while the probability of gaining a net benefit from all-weather road investment is given by Eqs. (20) and (21).

$$s = \frac{1}{2}\left(1 - \frac{\eta}{\theta} - \frac{\theta}{2}\right)\sqrt{\Delta y} \tag{19}$$

$$p_{i,j} = \begin{cases} sp_{i,j-1} + (1-s)p_{i-1,j-1}, p_{1,1} = 1, if\ when(i,j) \neq investment \\ p_{i,j} = 0, if\ (i,j) = investment \end{cases} \tag{20}$$

$$P_j = 1 - \sum_{i=0}^{j} p_{i,j} \tag{21}$$

Where

s is the probability of increase to the next node (and $1 - s$ is probability of decrease);
η is the drift of OSD (4.1);
θ is the historical OSD volatility (as per 4.1);
$p_{i,j}$ is the probability of deferring the investment at node i, when considering year j;
P_j is the probability of a net benefit by making the investment in year j, and
Δy is the time interval (one year).

Figure 10 shows the probabilities of obtaining a net benefit (i.e., $NPV^e > 0$) with different project investment costs.

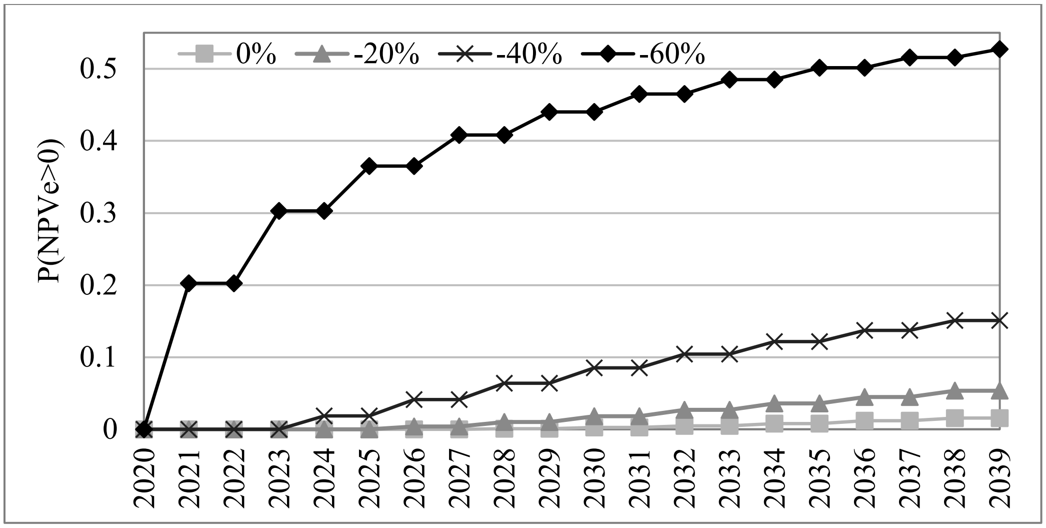

Figure 10. Probabilities of net benefits with reduction in investment costs

It can be observed that the probability of obtaining a net benefit under the benchmark investment costs (\$1.67B, represented by the 0% curve) is very low, remaining under 2% even with project deferral to 2039. These low values are due to the relatively low project NPV^e values calculated; probabilities are highly sensitive to NPV^e and therefore, inputs. In the literature, recommendations to construct are given despite that these probabilities are often quite low (Yang & Blyth, 2007). The probability of a positive NPV^e (and the NPV^e value itself, as shown previously) increases with decreasing investment costs. There is a significant difference between a 40% and 60% reduction.

Figure 11 shows the probabilities of obtaining a positive NPV^e with different OSD volatility values and freight volumes, expressed as a percentage of the benchmark values used in 4.4.2.

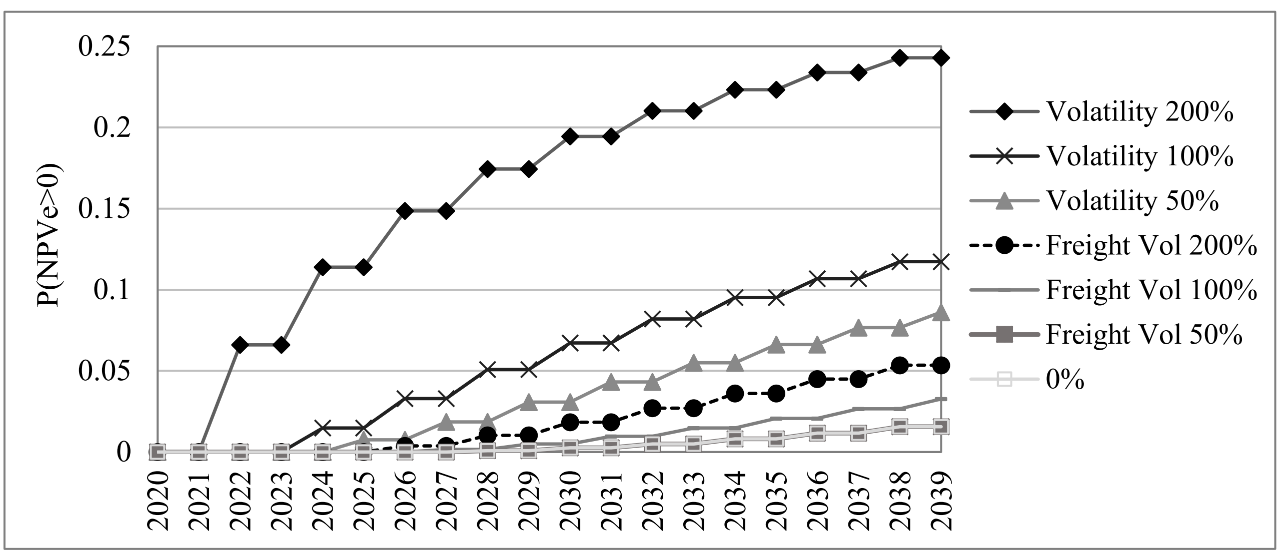

Figure 11. Probability of net benefit with different volatilities and freight volumes

Again, Figure 11 is consistent with previous results showing that greater OSD volatility and future freight volumes will increase the probability of a positive NPV^e (with corresponding increases in NPV^e and options values). Although a 200% increase in freight volumes does lead to a significant change in NPV^e, also consistent is that percent increases in OSD volatility have a much greater impact than equivalent percent increases in freight volumes. It can also be observed that a 50% increase in freight volumes has a very small effect on the probability of net benefit (consistent with Figure 8), and thus, a small impact on NPV^e. We also note that a 200% increase in freight volumes along this corridor, although it appears extreme, is not entirely unreasonable; the Northwest Territories holds potential for significant economic growth due to vast mineral resources and oil & gas deposits (the latter particularly along the river and in the Beaufort Sea) and tourism, all of which will put pressure on the transportation system in terms of passenger and freight transport (Department of Infrastructure, GNWT, 2019; CBC News, 2018).

We have observed that probabilities increase with longer deferral and higher OSD volatilities, similar to NPV^e values. This is because we prefer to invest later (i.e., hold the option) to wait for a greater chance of having a higher return on investment when OSDs grow more uncertain.

5. Implications for Infrastructure Planning

Decision-makers have recognized the growing need for decision-support (often, benefit-cost analysis) models that account for climate change impacts to guide large-scale infrastructure decisions. Climate adaptation is a major concern throughout Canada but particularly in the north where impacts are severe. Federal and territorial governments, as well as private companies operating in the north, have been working to understand the impacts of, and how to adapt to, climate change on existing and future infrastructure (Northwest Territories, 2008). However, at the systems planning level, due to the complexity and scale of problems, adaptation planning and consideration of climate change impacts has been largely subjective.

In light of the above, the federal government has recognized there is a lack of formal, empirically-based tools and processes for guiding large-scale infrastructure investments (Auditor General of Canada, 2017) in a changing and uncertain environment. This deficiency has been identified at the territorial level as well. For instance, the GNWT has a number of major transportation infrastructure projects in various planning stages, and the need to account for the impacts of climate change on current and future systems (and business cases for expansion) is not formalized in decision support and modelling tools. At the Roundtable on Connectivity for Small Populations in Remote Communities (International Transport Forum, 2019), an international group of policy-makers and researchers identified that current benefit-cost analyses do not include critical but complex social and environmental adaptation considerations that counter the enormous costs of providing remote connectivity. The Treasury Board of Canada mandated the use of benefit-cost analysis to justify federal regulations (Treasury Board of Canada Secretariat, 2018);

however, benefit-cost analyses can be improved on (as identified in the ITF meeting), and these requirements do not extend to infrastructure projects.

Furthermore, Indigenous community consultation is foundational to the process of infrastructure planning in the territorial north. Climate change, its impacts, and adaptation needs are central in the two-way information exchange. Indigenous communities have long communicated the need for adaptation and economic opportunities, and governments need tools to effectively communicate that climate change impacts are explicitly being considered in decision-support.

This modelling framework supports flexible decisions for large-scale infrastructure, particularly in an environment where climate change impacts are severe and infrastructure costs are extraordinarily high, and can address two key needs within the planning process. First, it is a first step towards developing a quantitative and empirically-based tool that can be formalized in federal, territorial, and provincial government infrastructure investment decision-support processes. Such a tool as the decision-support framework of this paper currently does not currently exist within the large-scale infrastructure investment planning process. Second, such a tool can be employed in the community outreach and consultation process. They are a means to communicate how community-observed climate change impacts are being systematically considered, in supporting projects aiming to reduce the uncertainties (and thus, the social costs) introduced by climate change.

6. Conclusions

The results of this paper demonstrate that when we explicitly incorporate environmental uncertainty into cost-benefit analyses through simple real options model applications, project valuations can change significantly. Such tools can help governments – particularly northern governments and communities facing the acute impacts of climate change – clearly communicate the severity of climate change impacts, and the need for infrastructure investments that address the rapidly changing northern environment. We have proposed a framework to support flexible infrastructure decision making in accounting for uncertain climate impacts in Northern Canada. We applied it to the decisions to barge on the Mackenzie River each year, as well as to construct the all-weather Mackenzie Valley Highway, considering ever-increasing uncertainty in river barge freight delivery conditions (and thus, growing freight airlift costs) resulting from climate change impacts.

The key results of this work include the following. The Black-Scholes model application of Part 2 indicated that the decision to continue barging grew riskier (i.e., expected airlift costs increased) from 1997-2017, and that this trend will continue for the next two decades based on the simulated future open season days (OSD) time series. Application of the binomial lattice method (Part 4) showed that the project should be deferred nine years (to 2028) to achieve a positive extended NPV (NPV^e, which accounts for future uncertainties in the decision to defer investment).

When climate uncertainty is considered, a road project's benefit-cost ratio increases significantly towards feasibility, and the option to delay allows for this future feasibility to be considered. Sensitivity analyses show that the project's NPV^e results, and therefore, project deferral time, are most heavily dependent on the all-weather highway construction costs and comparative airlift costs.

This analysis framework can be applied to other types of transportation investment projects impacted by climate change uncertainty, and offers opportunities for improvements and extensions. Although the simplicity of the binomial lattice approach has facilitated applications in research and practice, it requires that the uncertain variable (OSD) follows a lognormal distribution and be modeled as GBM. Furthermore, although the OSD is a simplified, final manifestation of both climate change impacts (e.g., air and water temperatures, water volumes) and human-driven conditions (water volumes, navigational buoy placement) that influence shipping capacities, this representation was required in order to apply this particular approach. Accounting for more than one source of uncertainty (i.e., replacing OSD with several factors as identified above, and incorporating future freight volumes as a stochastic process (Zheng & Kim, 2017)), or considering the ordering of project stages requires other modeling approaches. A next step in this research is to apply dynamic stochastic methods, such as the multi-option Least Squares Monte Carlo (LSM) simulation method. This method can incorporate multiple stochastic variables with different distributions (GBM, jump diffusions, or other processes), and simulate these to determine real options values.

We further note that the analysis of this paper did not consider winter roads construction and delivery costs in the cost benefit analysis, winter road open season days as a stochastic environmental input variable, nor other indirect benefits and external costs. In Northern Canada, there are other significant considerations in road-building decisions, including: more opportunities for employment and tourism, and medical transport, for historic Indigenous communities; more opportunities and cost-sharing for natural resource exploration and development (Mackenzie Aboriginal Corporation, 2007); and Arctic sovereignty. Some of these benefits, if tangible, are highly debated. Thus, for this research we chose to demonstrate our model focusing on transportation infrastructure and operations costs, and climate change impacts to them. Future interdisciplinary extensions should consider these elements. However, we also reiterate that this analysis method should be considered one tool of many tools and considerations that inform complex transportation infrastructure investment decisions.

Acknowledgement

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References

5658NWT Ltd., & Government of Northwest Territories. (2011). *Project Description Report for Construction of the Mackenzie Valley Highway.* Retrieved from http://reviewboard.ca/upload/project_document/EA1213-02_Project_Description_Report_for_the_Tulita_district_of_the_Sahtu_Settlement_Area.PDF

Andoseh, S., Bahn, R., & Gu, J. (2014). The case for a real options approach to ex-ante cost-benefit analyses of agricultural research projects. *Food Policy, 44*, 218-226.

Asplund, D., & Eliasson, J. (2016). Does uncertainty make cost-benefit analyses pointless? *Transportation Research Part A, 92*, pp. 195-205.

Auditor General of Canada. (2017, 10). *October 2017 Report of the Auditor General of Canada to the Northwest Territories Legislative Assembly: Climate Change in the Northwest Territories.* Retrieved from Office of the Auditor General of Canada: http://www.oag-bvg.gc.ca/internet/English/nwt_201710_e_42609.html

Bank of Canada. (2019). *Inflation (year-over-year percentage change)*. Retrieved from Bank of Canada: https://www.bankofcanada.ca/rates/indicators/capacity-and-inflation-pressures/inflation/historical-data/

Benaroch, M., & Kauffman, R. (2000). Justifying electronic banking network expansion using real options analysis. *MIS Quarterly, 24*, 197-225.

Benth, F., & Šaltytė-Benth, J. (2005). Stochastic Modelling of Temperature Variations with a View Towards Weather Derivatives. *Applied Mathematical Finance, 12*(1), 53-85.

Bird, H. (2018, 10 22). *'It's devastating': Barge cancellation taking a toll on Kugluktuk business, residents*. Retrieved from CBC: https://www.cbc.ca/news/canada/north/kugluktuk-supply-barge-cancellation-1.4872661

Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *Journal of Political Economy, 81*(3), 637-654.

Bodie, Z., & Merton, R. (2000). *Finance.* Upper Saddle River, NJ: Prentice Hall.

Brandão, L., Dyer, J., & Hahn, W. (2005). Using Binomial Decision Trees to Solve Real-Option Valuation Problems. *Decision Analysis, 2*(2), 69-88.

Bräutigam, J., Esche, C., & Mehler, B. A. (2003). Uncertainty as a key value driver of real options. *in Proceedings of the Seventh Conference on Real Options: Theory Meets Practice.* Washington, DC.

Calle Fernández, A., & Tamayo Bustamante, V. (2009). Investment decisions through real options (Article published in Spanish). *Estudios Gerenciales, 25*(111), 107-126.

CBC News. (2013, 10 9). *Mackenzie Hwy. extension to Dempster could cost $1.7B*. Retrieved from CBC: https://www.cbc.ca/news/canada/north/mackenzie-hwy-extension-to-dempster-could-cost-1-7b-1.1928488

CBC News. (2014, 09 04). *Low water levels cause delays for Mackenzie River barges*. Retrieved 01 30, 2019, from CBC: https://www.cbc.ca/news/canada/north/low-water-levels-cause-delays-for-mackenzie-river-barges-1.2754792

CBC News. (2018, 11 1). *CBC*. Retrieved from Record number of tourists spent $200M in N.W.T. last fiscal year: https://www.cbc.ca/news/canada/north/tourists-nwt-spending-record-1.4888497

CBC News. (2018, 06 27). *Mackenzie Valley Highway project to get $102M boost from federal gov't*. Retrieved 12 05, 2018, from CBC: https://www.cbc.ca/news/canada/north/federal-announcement-mackenzie-valley-highway-project-nwt-1.4724467

Chang, S., Wang, J., & Wang, X. (2015). A fitted finite volume method for real option valuation of risks in climate change. *Computers & Mathematics with Applications, 70*(5), 1198-1219.

Chow, J. Y., & Regan, A. C. (2011a). Real Option Pricing of Network Design Investments. *Transportation Science, 45*(1), 50-63.

Chow, J. Y., & Regan, A. C. (2011b). Network-based real option models. *Transportation Research Part B: Methodological, 45*, 682-695.

Conrad, J. M., & Kotani, K. (2005). When to drill? Trigger prices for the Arctic National Wildlife Refuge. *Resources and Energy Economics, 25*, 273-286.

Copeland, T., Koller, T., & Murrin, J. (2000). *Valuation: measuring and managing the value of companies. 3rd ed.* New York: Ed.: Wiley.

Couto, G., Nunes, C., & Pimentel, P. (2015). High-speed rail transport valuation and conjecture shocks. *The European Journal of Finance, 21*(10-11), 791-805.

Cox, J. C., Ross, S. A., & Rubenstein, M. (1979, September). Option pricing: A simplified approach. *Journal of Financial Economics, 7*(3), 229-263.

Cox, J., Ross, S., & Rubinstein, M. (1979). Option pricing: A simplified approach. *J. Financial Econom, 7*, 229–263.

Damaraju, N., Barney, J., & Makhija, A. (2015). Real options in divestment alternatives. *Strategic Management Journal, 36*(5), 728-744.

Department of Infrastructure, GNWT. (2019). *Mackenzie Valley Highway Project*. Retrieved from https://www.inf.gov.nt.ca/en/MVH

Dewar, J., & Wachs, M. (2006). Transportation Planning, Climate Change, and Decisionmaking Under Uncertainty. *Proceedings of the Workshop Conference on Climate Change and US Transportation* (p. 26). Washington, DC: National Academies of Sciences.

Dixit, A., & Pindyck, R. (1994). *Investment under Uncertainty.* Princeton: Princeton University Press.

Dmouj, A. (2006). *Stock price modelling: Theory and Practice.* Retrieved from https://beta.vu.nl/nl/Images/werkstuk-dmouj_tcm235-91341.pdf

Fisher, A., & Rubio, S. (1997). Adjusting to climate change: Implications of increased variability and asymmetric adjustment costs for investment in water reserves. *Journal of Environmental Economics and Management, 34*(3), 207–227.

Galera, A. L., & Sánchez, A. S. (2010). A Real Options Approach for the Valuation of Highway Concessions. *Transportation Science, 44*(3), 416-427.

García-Gusano, D., Espegren, K., Lind, A., & Kirkengen, M. (2016). The role of the discount rates in energy systems optimisation models. *Renewable and Sustainable Energy Reviews, 59*, pp. 56-72.

Garvin , M., & Cheah, C. (2004). Valuation techniques for infrastructure investment decisions. *Construction Management and Economics, 22*(4), 373-383.

Gaspars-Wieloch, H. (2019). Project Net Present Value estimation under uncertainty. *Central European Journal of Operations Research, 27*, 179-197.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2013). Climate change uncertainty: Building flexibility into water and flood risk infrastructure. *Climatic Change, 116*(2), 411–423.

GNWT Department of Transportation. (2011a). *On Track – Status, Challenges, and Initiatives of the Department of Transportation.* Retrieved from https://www.inf.gov.nt.ca/sites/inf/files/resources/on_track_final_document.pdf

GNWT Department of Transportation. (2011b). *Community Re-Supply Options and Costs. Department of Transportation.*

Government of Nova Scotia. (2018). *Highway Construction*. Retrieved from https://novascotia.ca/tran/highways/faq.asp.

Government of the Northwest Territories. (2018). *Mackenzie Valley Highway*. Retrieved from Inuvik & Tuktoyaktuk Mackenzie Valley Highway: http://ith.inf.gov.nt.ca/

Government of the Northwest Territories. (2018a). *Northwest Territories Highway, Ferry and Ice Crossing Information*. Retrieved from https://www.inf.gov.nt.ca/en/highways

Government of the Northwest Territories. (2018b). *Mackenzie Valley Highway (MVH)*. Retrieved from Transportation: https://www.inf.gov.nt.ca/en/mackenzie-valley-highway-project

Graham, D. (1981). Cost-Benefit Analysis Under Uncertainty. *The American Economic Review, 71*(4), pp. 715-725.

Grayburn, J. (2012, 03 19). *Real Options and Investment Decision Making.* Retrieved 01 30, 2019, from ofgem: https://www.ofgem.gov.uk/sites/default/files/docs/2012/03/real_options_investment_decision_making.pdf

Herder, P. M., de Joode, J., Ligtvoet, A., Schenk, S., & Taneja, P. (2011). Buying real options – Valuing uncertainty in infrastructure planning. *Futures, 43*, 961-969.

Ho, S., & Liu, L. (2002). An Option Pricing-Based Model for Evaluating the Financial Viability of Privatized Infrastructure Projects. *Construction Management and Economics, 20*, 143-156.

Huang, Y., & Chou, S. (2006). Valuation of the MRG And the Option to Abandon in BOT Infrastructure Projects. *Construction Management and Economics, 24*(4), 379-389.

Hull, J. (2005). *Options, Futures and Other Derivatives (6th ed.).* Prentice-Hall.

International Transport Forum. (2019, September 23-24). *Connecting Remote Communities Roundtable*. Retrieved from ITF-OECD: https://www.itf-oecd.org/connecting-remote-communities-roundtable

Kato, M., & Zhou, Y. (2011). A basic study of optimal investment of power sources considering environmental measures: economic evaluation of CCS through a real options approach. *Electrical Engineering in Japan, 174*, 9-17.

Kensinger, J. (1987). Adding the value of active management into the capital budgeting equation. *Midland corpart finance journal, 5*(1), 31-42.

Kim, K., Park, H., & Kim, H. (2017). Real options analysis for renewable energy investment decisions in developing countries. *Renewable and Sustainable Energy Reviews, 75*, 918–926.

Kogut, B., & Kulatilaka, N. (1994). Operating Flexibility, Global Manufacturing, and the Option Value of a Multinational Network. *Management Science, 1*, 123-139.

Kulatilaka, N. (1993). The Value of Flexibility: The Case of a Dual-Fuel Industrial Steam Boiler. *Financial Management, 22*(3), 271-280.

Mackenzie Aboriginal Corporation. (2007). *Mackenzie Valley All-Weather Road Opportunity Assessment.* Retrieved from http://www.internationalfrontier.com/i/pdf/Mackenzie-Valley-All-Weather-Road.pdf

Mariport Group Ltd. (2011). *Western Arctic access routes.*

Merton, R. (1973). Theory of rational option pricing. *The Bell Journal of Economics and Management Science, 4*(1), 141-183.

Michailidis, A., & Mattas, K. (2007). Using Real Options Theory to Irrigation Dam Investment Analysis: An Application of Binomial Option Pricing Model. *Water Resources Management, 21*(10), 1717-1733.

Millerd, F. (2005). The Economic Impact of Climate Change on Canadian Commercial Navigation on the Great Lakes. *Canadian Water Resources Journal, 30*(4), 269-280.

Northwest Territories. (2008). *NWT climate change impacts and adaption report.* Environment & Natural Resources. Retrieved from https://www.enr.gov.nt.ca/sites/enr/files/reports/nwt_climate_change_impacts_and_adaptation_report.pdf

Ozorio, L. d., Bastian-Pinto, C. d., & Brandão, L. E. (2018). *The Choice of Stochastic Process in Real Option Valuation.* Retrieved from http://realoptions.org/openconf2012/data/papers/49.pdf.

Pendakur, K. (2017). *Northern Territories.* Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/assess/2016/Chapter-3e.pdf

Pindyck, R. (1979). *Uncertainty and the pricing of exhaustible resources.* MIT Energy Laboratory. Retrieved from http://hdl.handle.net/1721.1/35223

Prolog Canada Inc. (2010). *The northern transportation systems assessment.* Retrieved from https://buyandsell.gc.ca/cds/public/2018/04/11/786956da5aabf5eb7d35d624b80ad57a/ntsa_phase_1-_final-_word_version.pdf

Rambaud, S. C., & Pérez, A. M. (2016). Assessing the Option to Abandon an Investment Project by the Binomial Options Pricing Model. *Advances in Decision Sciences*, Article ID 7605909,12 pages. Retrieved from http://dx.doi.org/10.1155/2016/7605909

Ross, S. (2014). *Introduction to Probability Models.* Amsterdam: Elsevier.

Shishko, R., Ebbeler, D. H., & Fox, G. (2004). NASA technology assessment using real options valuation. *System Engineering, 7*(1), 1-13.

Smith, J. E. (2005). Alternative Approaches for Solving Real-Options Problems (Comment on Brandao et al. 2005). *Decision Analysis, 2*(2), 89-102.

Statistics Canada. (2015). *Transportation in the North*. Retrieved from Statistics Canada: https://www150.statcan.gc.ca/n1/pub/16-002-x/2009001/article/10820-eng.htm

Statistics Canada. (2019). *Gross domestic product (GDP) at basic prices, by industry, provinces and territories.* Retrieved from Statistics Canada: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610040201

Sturm, M., Goldstein, M. A., & Parr, C. (2017). Water and life from snow: A trillion dollar science question. *Water Resources Research, 53*, 3534-3544.

Sturm, M., Goldstein, M. A., Huntington, H., & Douglas, T. A. (2016). Using an option pricing approach to evaluate strategic decisions in a rapidly changing climate: Black–Scholes and climate change. *Climate Change, 140*(3-4), 437-449.

Sung, R.-J., Burn, D., & Soulis, E. (2006). A Case Study of Climate Change Impacts on Navigation on the Mackenzie River. *Canadian Water Resources Journal, 31*(1), 57-68.

Tetra Tech EBA. (2011). *Project Description Report for Construction of the Mackenzie Valley Highway.* 5658 NWT Ltd., Government of the Northwest Territories. Retrieved from http://reviewboard.ca/upload/project_document/EA1213-02_Project_Description_Report_for_the_Tulita_district_of_the_Sahtu_Settlement_Area.PDF

Tourinho, O. (1979). *The valuation of reserves of natural resources: An option pricing approach.* Berkeley: University of California.

Treasury Board of Canada Secretariat. (2018, September 10). *Policy on Cost-Benefit Analysis*. Retrieved from Government of Canada: https://www.canada.ca/en/treasury-board-secretariat/services/federal-regulatory-management/guidelines-tools/policy-cost-benefit-analysis.html#toc3

Trigeorgis, L. (1999). *Real options: A primer.* Boston, MA: Springer.

Truong, C., Stefan, T., & Mathew, S. (2018). Managing risks from climate impacted hazards –The value of investment flexibility under uncertainty. *European Journal of Operational Research, 269*, 132–145.

Woo, M., Thorne, R., Szeto, K., & Yang, D. (2008). Streamflow hydrology in the boreal region under the influences of climate and human interference. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1501), 2251–2260.

Yang, D., Shi, X., & Marsh, P. (2015). Variability and extreme of Mackenzie River daily discharge during 1973–2011. *Quaternary International, 380-381*, 159-168.

Yang, M., & Blyth, W. (2007). *Modeling Investment Risks and Uncertainties with Real Options Approach.* IEA. Retrieved from https://www.iea.org/publications/freepublications/publication/ROA_Model.pdf

Yeo, K., & Qiu, F. (2003). The value of management flexibility—a real option approach to investment evaluation. *International Journal of Project Management, 21*(4), 243-250.

Zhao, T., & Tseng, C.-L. (2003). Valuing Flexibility in Infrastructure Expansion. *ASCE Journal of Infrastructure Systems, 9*(3), 89-97.

Zhao, T., Sundararajan, S. K., & Tseng, C.-L. (2004). Highway Development Decision-Making under Uncertainty: A Real Options Approach. *ASCE Journal of Infrastructure Systems, 10*(1), 23-32.

Zheng, Y., & Kim, A. M. (2017). Rethinking Business-As-Usual: Mackenzie River Freight Transport in the Context of Climate Change Impacts in Northern Canada. *Transportation Research Part D: Transport & Environment, 53*, 276-289.

Zheng, Y., Kim, A. M., Du, Q., & S.A., R. (2016). *The Potential Impacts of a Northern Shipping Route into Canada via the Arctic.* Transport Canada Project Report, University of Alberta, Edmonton.