A framework to quantify the economic impact of changing the road pavement standard and related municipal bylaws on housing affordability in cold weather regions

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

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ABSTRACT

Jurisdictions in winter regions impose restrictions on asphalt paving of neighbourhood roadways based on severity of cold weather. These limitations are imposed mainly to avoid the inadequate compaction of asphalt that results in poor performance of roads. Paving restrictions during the weather fluctuation of late fall cause delays in work and extend project schedules. As a result, a significant increase in development cost is observed due to long-term project overhead and idle equipment costs, and the increased cost eventually reduces the housing affordability of the residents of this region. In the construction industry, there are few examples of successful paving works at severe low temperature using innovative technologies and materials. Construction professionals, in general, make decisions pertaining to work schedule based on the respective cost-benefit performance of two options, such as: selecting an innovative technology to avoid schedule extension or waiting for suitable weather. This research constitutes a study of the weather limitations on asphalt paving works in greater Edmonton, Alberta, Canada, demonstrating its application to a neighbourhood road construction project. It proposes a framework to quantify the economic impact of these limitations using historical weather data and developing a simulation model of paving work by which to analyze the change of construction progress when weather limitations are relaxed while ensuring the asphalt performance in those conditions. The results of this study can assist decision makers in urban development works, providing them further insight to analyze alternative road development methods in order to search for paving specifications that increase the overall benefit by reducing the development cost and increasing housing affordability.

PREFACE

This thesis is an original work by Monjur Panna. No part of this thesis has been previously published.

ACKNOWLEDGEMENTS

I would like to express my profound gratitude and thanks to my supervisors, Dr. Mohamed Al-Hussein and Dr. Ahmed Bouferguene, for their guidance, instruction, and encouragement during the course of this research.

I am very grateful to all my friends in the Construction Engineering and Management group at the University of Alberta, especially Hamid Zaman, Sadiq Altaf, and Muntaseer Kainat, who have supported me in every stage of this research. All the members at the school were like a second family to me. Special thanks to Jonathan Tomalty for helping me to improve my writing throughout this research.

Special thanks to Andrey Niclevich of Standard General Inc. Edmonton for his support and technical input; without him, the field visits would not have been possible.

I want to express my appreciation to my mother, my wife, my children, and my siblings for their unconditional support and encouragement during my graduate studies. I owe my deepest gratitude to them for fostering in me the motivation to learn and succeed.

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1 CHAPTER 1: INTRODUCTION

1.1 Introduction and Research Motivation

Jurisdictions impose paving restrictions to ensure asphalt performance based on different weather conditions, such as ground temperature, air temperature, precipitation, and wind speed. Many jurisdictions have calendar date restrictions, such as not permitting paving between October 15 and April 15. In terms of climate, greater Edmonton, Alberta, Canada is different from most regions in North America and other colder European cities, given its comparably low annual average temperature and longer duration of snow cover. Based on the severity of weather, city authorities and roadway agencies develop weather limitations for asphalt paving.

Cold weather paving is generally defined as placement and compaction of hot mix asphalt (HMA) when either the base or air temperature is below 10°C (Brakey, 1992). Cold-weather paving is treated with utmost importance in colder regions during late fall, also referred to as the shoulder season. The construction shoulder season may vary depending on the geographical location or climatic region. In greater Edmonton it starts in the late-fall, from September, after a very short summer, when the temperature begins to fall and drives construction managers to complete their scheduled work at a faster pace. However, for construction of neighbourhood roads using HMA, achieving a desirable level of compaction for HMA with a thickness of less than 50 mm (2 in) is a difficult task during shoulder season, and satisfying all the requirements of compaction when the temperature is low reduces the available time for paving (Decker, 2006).

The overall construction industry in Alberta, Canada, accounts for a large share of the province's as well as the nation's economic activity, generating 10.5% of employment in Alberta (Government of Alberta, 2014). In greater Edmonton, the number of housing starts in 2014 was around 10,000, while during the first quarter of 2015, it is already close to 5,000 (City of Edmonton, 2015), indicating the rapid growth of the housing industry in this region. The expected investment in residential construction in Alberta will be around $11 billion in 2015 (Government of Alberta, 2014). Other manufacturing and service industries are also heavily dependent on the housing industry since these industries have opportunities to grow their market share and serve the additional demand generated by the new housing and the new residents it represents.

Pavement construction plays a significant role within the housing industry. The paving limitations sometimes slow down the new residential development sector, given that construction of access roads is very important to maintaining the progress of this industry. HMA regulations sometimes force contractors to discontinue paving operations during late fall, i.e., the shoulder season, when the temperature falls below the minimum limit. As a result, contractors are sometimes forced to reschedule paving work, which narrows the time available for paving. Delays in schedule also generate additional costs for the rental of paving equipment and wages of workforce. This results in higher construction costs, which ultimately drives up the lot price, thereby adversely affecting housing affordability.

This study analyzes the weather limitations on HMA paving works imposed by the jurisdictions in greater Edmonton in order to determine the reasons behind restrictions and the problems associated with HMA paving in low temperatures. It proposes a framework to quantify the impact of these limitations using historical weather data, and develops a simulation model of paving work in order to analyze changes in construction cost and schedule, ensuring strong HMA performance in severe weather. The objective of this study is described in greater detail in the following sub-section.

1.2 Research Objectives

The study focuses on the determination of the available construction time during the shoulder season for the HMA paving industry based on the analysis of historical weather data of greater Edmonton. Further study is carried out to determine the suitability of alternative methods or materials, in terms of cost-benefit analysis, which can perform well under extreme cold weather conditions and can extend the construction season for developing neighbourhoods within this jurisdiction.

Within the context of these considerations, this research is built upon the following **hypothesis**:

"Changing the paving standard and related municipal bylaws in cold regions can improve the housing affordability"

In order to verify this hypothesis, this research includes the following objectives:

1. Determine the amount of additional paving works that can be achieved based on relaxed temperature limitations during late-fall, i.e., from September to November.
2. Compare alternative methods of paving or alternate weather limitations in terms of cost-benefit ratio.

1.3 Thesis Organization

This thesis is organized into five chapters. Chapter 1 introduces the research, its background and objectives.

Chapter 2 (Literature Review) focuses on different types of asphalt mix, such as: hot mix asphalt, marshal and super pave mix design, and their properties. A detailed discussion is then presented on problems associated with HMA when paving is performed in severe cold weather and different precautionary measures to ensure HMA performance during similar situations. It gives a brief overview of the neighbourhood development process within greater Edmonton and its effect on road work. It presents a summary of findings from the existing literature related to cost components of construction processes. Finally, details pertaining to the usage of innovative construction methods or materials practiced in different countries of the world, mainly in winter countries, to ensure the performance in severe conditions of alternative pavements which can replace or reduce the use of HMA.

Chapter 3 (Methodology) discusses the proposed methodology used in this research, including a summary of the data collected from the weather database for Edmonton, existing standards of weather limitations in different jurisdictions, and the cost database from Alberta's road construction industry. It provides brief information on the case study area, based on which the model verification and return on investment or financial analysis are subsequently made. This chapter also introduces the simulation model developed in connection to this case study using the general purpose template of Simphony 4.1 (a simulation software developed by the construction research group at the University of Alberta), which encompasses the paving operation as well as the decision of whether or not to go ahead with construction during late-fall based on the appropriate weather determined using existing weather limitations. It provides a brief summary of financial analysis method for the purpose of choosing the alternative procedure as a replacement of HMA. It also describes the few basic assumptions for making a comparative study on the proposed technology with HMA.

Chapter 4 (Results and discussions) discusses the results and outcomes of the study as to whether the compaction time available at the sites is compatible with the asphalt standard, as well as the cost-benefit analysis of the proposed technology in comparison with the existing HMA technology.

Chapter 5 (Conclusions and recommendations) describes the general conclusions based on the main contributions of the research, and provides recommendations for future research and practical applications.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review on HMA technology used for road development for neighbourhoods in greater Edmonton. It elaborates the problems associated with low temperature and its impact on neighbourhood development processes by investigating the reasons behind these limitations. It briefly describes the activities of neighbourhood development process, and presents a brief literature review on weather modelling and construction processing. The chapter reviews methods for calculating the costs associated with construction, and provides insight into alternative technologies to overcome the limitations involved in asphalt paving related to construction duration, giving a brief review of different paving technologies.

2.2 Asphalt mix design background

Asphalt is a residue bituminous by-product in the refining of crude oil, which is used as the binder used in asphalt concrete materials. HMA or asphalt concrete pavement is a mixture of asphalt binder and mineral aggregate, where asphalt acts as the glue and holds the aggregate particles together and the mineral aggregate provides strength and toughness to the framework forming a dense and waterproof system.

There are three main mix design methods: Hveem, Marshall and Superpave methods. The Hveem and Marshall Design methods are very similar, having the only difference in the strength testing methodology. These two methods do not contain a procedure in their methodology for the selection of aggregates and asphalt binder (Asphalt Institute, 2001). In Canada, the Marshall and Superpave methods are used for hot mix asphalt mix designs. The Superpave mix design method consists of selection of aggregates that meet specified physical property requirements, and determination of the optimum asphalt binder content to meet all the desired volumetric properties.

It is difficult for Marshal Mix design to assure rutting resistance of the design mix. Superpave mix design incorporates performance-based, asphalt materials characterization and ensures controlling of rutting, low temperature cracking and fatigue cracking. Marshal Mix design requires higher field compaction value than the Superpave mix design, which can result in reduced life of HMA for Marshal Mix. In addition to that, for Superpave, more design properties needed to be met, which provide more control of the HMA mixture during production ensuring longer life of the pavement (The Asphalt RAP).

2.3 Weather limitations on HMA in Edmonton and other jurisdictions

Weather limitations in different neighbouring jurisdictions in greater Edmonton are described in greater detail in Chapter 3 while analyzing the weather limitation database. In practice, the early stage of neighbourhood development consists of several steps, e.g., municipal development plan, area and neighbourhood structure plan, road development, and subdivision. Before the road development begins, the underground utility infrastructure needs to be completed and the surface work needs to be preceded by base work and other ground works. It is very common for the asphalt contractors to begin asphalt laying in late-fall after completion of these preceding tasks, as shown in Figure 2-1:

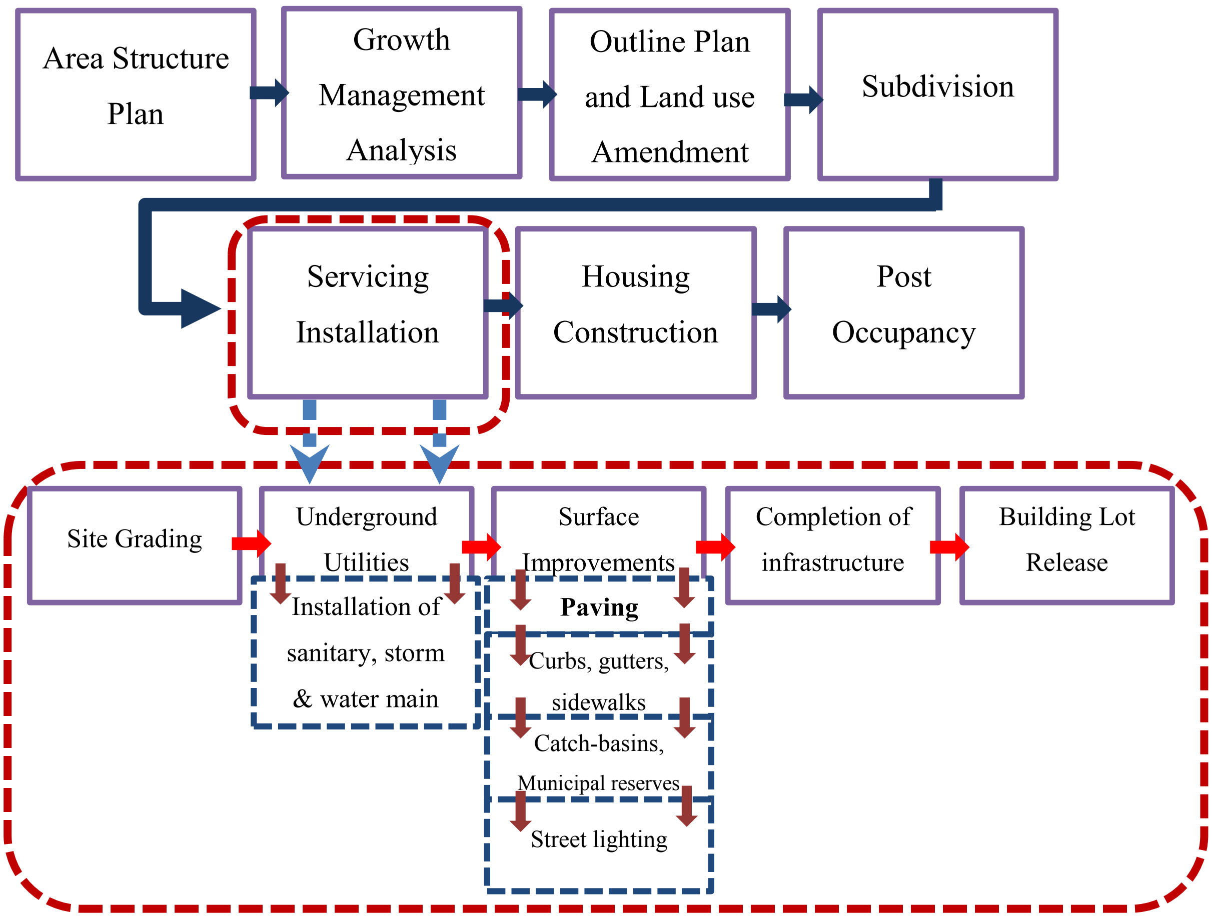


Figure 2-1: Steps of neighbourhood development process (City of Calgary, 2015)

During the colder season, contractors stay updated about the weather forecast before making a paving schedule, given that inspectors from the owner agencies perform weather condition inspections prior to implementation of an asphalt casting schedule and make decisions based on the weather conditions as to whether or not to have asphalt casting carried out.

The consensus among industry practitioners is that late-spring and summer are the ideal times for asphalt casting or repair works. However, many also agree that pavement can be successfully placed at low temperatures, if done properly. Linden et al. (1989), Dore (2002), and Decker (2006) have all discussed the reasons why paving in low temperature is discouraged, while Dickson & Corlew (1970), Brakey (1992), Brock & Milstead (1999), and numerous others have discussed the construction measures to be taken in order to perform asphalt paving in cold weather to ensure better performance of asphalt.

2.4 Problems associated with low temperatures

There are several causes of the deterioration in the performance of asphalt pavement cast in low temperatures. Asphalt pavement does not have any contraction joints; hence, during cold weather, when the pavement temperature drops quickly to a low temperature, tensile stresses develop along the entire pavement surface. The resulting tensile stresses can cause cracks in the pavement (Figure 2-2). Low-temperature cracks stretch transversely across part of or the entire pavement, with spacing between cracks ranging from about 3 m to 10 m (10 ft to 40 ft). Low-temperature cracking may not cause a significant problem initially, but cracks tend to become more numerous and wider as time goes by and to cause a significant performance problem after several years (Walker, 2012).

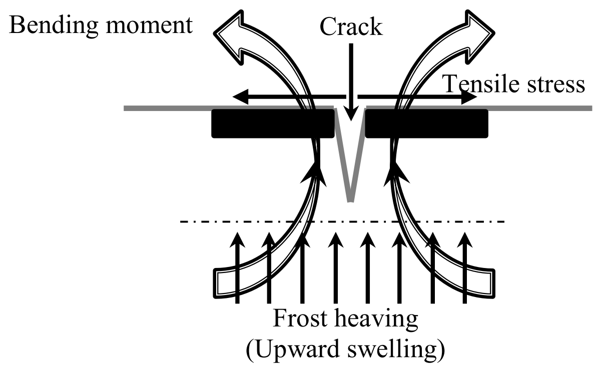


Figure 2-2: Expansion crack (Dore, 2002)

Thermal contraction and volume change occurs along the border layers after the asphalt pouring is completed and the temperature differential between the asphalt layers and the atmosphere is high. However, asphalt pavement loses bearing capacity during spring when higher temperatures soften the asphalt. These factors reduce both the functional and the structural levels of service of pavements (Dore, 2002). This temperature loss from newly paved asphalt is not only related to air temperature and wind speed; it is also dependent on the thickness and temperature of the new asphalt mat, base temperature, and solar radiation flux (Brakey, 1992).

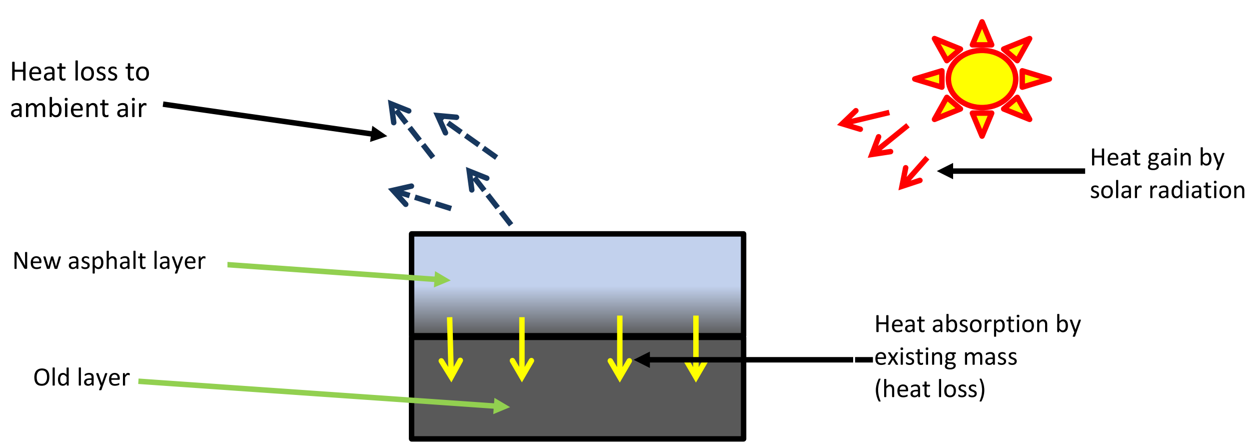


Figure 2-3: Heat transfer process in newly paved asphalt layer

Rapid heat loss of asphalt during the colder season is a major concern for pavement industry professionals. The likelihood of rapid heat loss of asphalt during the late-fall sometimes forces contractors to reschedule paving work, thereby delaying the available schedule and causing increases in construction cost.

2.4.1 Heat loss by asphalt pavement

While describing the thermal behaviour of HMA during compaction, Chadbourn et al. and White et al. described the heat transfer process of an asphalt pavement in the vertical direction by the following equation:

$$\frac{dT}{dt} = \alpha \times \frac{d^2T}{dz^2}$$

Where,

$$\alpha = \frac{k}{\mathrm{Cp}\ \rho}$$

While, α = thermal diffusivity of asphalt, (m^2/s)

ρ = density of asphalt, kg/m^3

C_p = specific heat of asphalt, J/kg·K

k = thermal conductivity of asphalt, W/mK

T = temperature, K

z = vertical distance or pavement lift thickness, m

t = time, seconds

(Chadbourn et al., 1996; White et al., 1987)

2.4.2 Role of compaction of asphalt

Asphalt experts identify compaction as one of the key factors in controlling the performance of asphalt pavements. The optimum level of compaction of asphalt ensures strength, durability, resistance to deformation, resistance to moisture damage, impermeability, and skid resistance. Achieving good density of the newly placed asphalt ensures all these desirable mix properties. Also, bringing the air voids to an acceptable level improves the performance of the pavement, which can be achieved through proper compaction. Lindel et al. have shown that a 1% increase in air voids (above the base air void level of 7%) tends to produce about a 10% loss in pavement life (Linden et al., 1989), while non-uniform compaction causes early pavement failure. Retaining the temperature of the asphalt mat until it is compacted is important due to its kinematic viscosity property. According to the temperature viscosity characteristics of various asphalt grades, it has been observed that at high temperatures (near 150°C) asphalts are liquids with similar consistency to water, whereas at an ambient temperature near 20°C asphalts are semi-solid and at low temperatures (e.g., −15°C) they are brittle (Terrel, 1988). Cut-off temperature is the term used to define the temperature at which the asphalt mix becomes so stiff that further compaction becomes inactive.

Many studies have been conducted to improve asphalt performance during winter construction, focusing on the steps in the pavement construction process, e.g., production, transportation, placement, compaction, and quality assurance. A study conducted in Iowa and Wisconsin in the United States has suggested increasing the temperature of liquid asphalt if the air temperature drops in order to compensate for the cooling effect of the outside temperature. However, it has also suggested that overheating the liquid asphalt can compromise the integrity of pavement by causing the coating on the aggregate to be thinner. Hence, adjusting the temperature of the asphalt mixture is a critical issue and it must be done in a fashion that will not impact the quality of the pavement materials (Benchmark Inc., 2009). Brakey (1992) has suggested minimum pouring temperatures for different pavement thicknesses according to Table 2-1.

Table 2-1: Recommended minimum pouring temperature for various thicknesses (Brakey, 1992)

Base Temp (°C)	**Minimum pouring temperature (°C) according to pavement lift thickness**			
	1 in	**1.5 in**	**2 in**	**≥ 3 in**
−7 to 0	-	-	-	141
1 to 4	-	152	146	138
5 to 10	154	149	141	135
11 to 16	149	146	138	132
17 to 21	143	141	135	129

To avoid rapid temperature drop in asphalt mix during transportation of paving materials to the construction site, studies have suggested covering the asphalt load with tarpaulin during low temperature for longer hauls and also to prevent exposure to precipitation. It should be noted that the temperature differential in the mix, i.e., core and surface temperatures, prevents uniform compaction. According to White et al. the initial paving temperature should be between 120°C and 130°C, while secondary rolling temperature should be between 90°C and 120°C, and final rolling temperature should be between 55°C and 90°C; in their study they argue that this can be achieved using smooth steel rollers during initial rolling, pneumatic tired or vibrating steel rollers during secondary or intermediate compaction, and smooth steel rollers during finishing (White et al., 1987). If the mix is transported in cold weather without a cover the colder mix when placed may become a cold spot in the pavement which cannot be adequately compacted. While for normal haul times the average temperature of the mix is not impacted, for longer hauls a tarpaulin covering ensures a uniform temperature mix, thereby minimizing the effect of temperature segregation. During placement of an HMA course on an aggregate base in low temperature conditions, it is suggested that the base be solidly compacted at or below optimum moisture and not frozen, since freezing or excess moisture saps the heat out of HMA rapidly and may contribute to soft spots in the base (Flexible Pavements of Ohio, 2009). A study by Brock et al. (1999) has shown that a 1% increase in moisture in the pavement material may increase the drying cost by as much as 13%. Drying and heating may be needed as the stockpile may be frozen; furthermore, the moisture content must be reduced to avoid future moisture release.

To improve compaction of HMA, other studies have suggested that the compaction be carried out while the mix is within the compaction temperature range, 135°C to 80°C, which can be ensured by increasing the number, type, and capacity of rollers if necessary. Another study conducted at Auburn University, (Alabama, USA) has suggested that for cold weather casting the most important factors are the temperature of the mix and the thickness of the course being placed. In this study it is suggested that, if the asphalt mix temperature is increased, more time is allowed for compaction. For example, as can be observed in Figure 2-4, for a 30 mm (1.25 in) thick course at 135°C the compaction time available is 7 minutes, which might be too short to achieve proper compaction. However, if the mix temperature is raised to 162°C the time available for compaction is 12 minutes. For increased course thickness, compaction time is higher. However, the additional cost associated with this type of measure and the cost-benefit ratio need to be analyzed, since raising the mix temperature takes extra fuel and lowers the production capacity of the plant; the study mentions that raising the mixing temperature around 40°C can reduce the production capacity of the plant by 15% or more. Similarly, increased aggregate moisture contents also reduce the production capacity, as the aggregates need to be heated longer to remove the moisture. A combination of a higher mix discharge temperature with colder aggregates and higher moisture contents results in a 50% reduction in production capacity during cold weather. Also, the fuel consumption is almost double in this procedure (Flexible Pavement of Ohio, 2009).

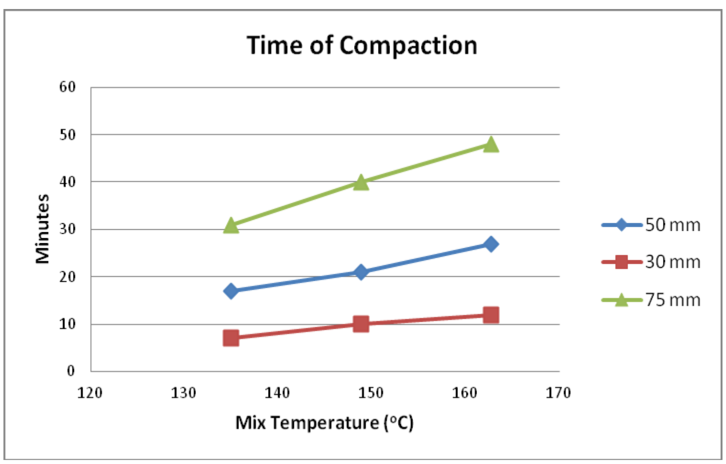


Figure 2-4: Relation between asphalt mix temperature and compaction time for different asphalt thickness (Flexible Pavement of Ohio, 2005)

The US Army Corps of Engineers, in association with AASHTO, NAPA et al. (2000), have suggested available compaction times for different pavement thicknesses in the 'Hot-Mix Asphalt Paving Handbook', considering the time required for cooling to 80°C, which is the minimum required temperature for final compaction of asphalt according to asphalt experts. This information is summarized in Table 2-2, showing the approximate compaction time as was derived from the graphical representation cited in the handbook. The table is subsequently used in Chapter 3 to check the compaction time at the case study site. However, the jurisdictions in Edmonton and the surrounding area do not specifically relate the air temperature to the compaction time of asphalt works.

Table 2-2: Recommended maximum compaction time for various thicknesses
(US Army Corps of Engineers, 2000)

Asphalt temperature during production (°C)	Base temp (°C)	Available compaction time (minutes) according to pavement thickness			
		25 mm	35 mm	50 mm	75 mm
105	-12 to 15	2 - 4	4 - 6	5 - 8	9 – 14
120	-12 to 15	3 - 5	5 - 8	8 - 12	15 – 22
135	-12 to -1	5 - 8	7 - 9	11 - 12	21 – 24
	- 1 to 4			12 - 14	24 – 26
	4 to 10			14 - 16	26 – 27
	10 to 15			16 -17	27 – 29
150	-12 to -1	6 - 8	9 - 12	14 - 15	26 – 29
	-1 to 4			15 - 16	29 – 32
	4 to 10			16 - 17	32 – 34
	10 to 15			17 - 19	34 – 36

A similar study by Decker (2006) considers thickness of the lift, base temperature, initial pavement temperature, air temperature, wind speed, and heat gain from sunlight as the major temperature loss factors during compaction. Dickson et al., in another study, have suggested that in order to achieve adequate compaction of HMA pavement, the temperature of the pavement must be sufficiently high for the period of time necessary to complete rolling and avoid heat loss. Frozen subgrades with high moisture content will significantly decrease time available for compaction compared to placement on an unfrozen subgrade. In addition to rapid cooling, placement of HMA on wet, frozen subgrade also presents the risk of pavement structural failure, due to thawing of the subgrade (Dickson et. al., 1970).

2.4.2.1 Types of compaction equipment

Several types of compaction equipment are used for paving works, including steel wheeled rollers, pneumatic tired rollers, and vibratory steel wheeled rollers. The axle load of a steel wheeled roller determines the compaction capacity. Diameter of wheel and speed influence the compaction performance in terms of surface finish and time of compaction, respectively. Again, for a pneumatic tired roller, the gross weight and speed govern the compaction performance. For a vibratory steel wheeled roller, the vertical movement and the frequency of the movement of the vibratory drum and the rolling speed determine the performance of compaction.

a. Pneumatic Tired Roller
(photo source: www.heavyequipment.com/heavy-equipment/road-highways)

b. Steel Wheeled Roller

Figure 2-5: Different types of construction rollers

Figure 2-5 shows the common types of compaction equipment used in paving construction works in greater Edmonton.

2.5 Asphalt paving examples in low temperature countries

There are many examples of cold weather paving practices in northern European countries. The Dutch Standard Conditions for Contracts in Civil Engineering Works "RAW Standard 2005" specifies the requirements for processing asphalt if the air temperature satisfies Equation (1)

$$T_{air}(^{o}C) \geq W + 5 \tag{1}$$

Where W is the wind speed expressed in m/s.

This equation indicates that, when the air speed is 20 km/h (or 5.6 m/s), the minimum allowable air temperature for asphalt pouring is 10.6°C. Asphalt specialists from other European countries, such as Switzerland, Sweden, and Estonia, specify 5°C as the standard minimum processing air temperature of asphalt pouring, while sharing their experience with the Dutch Highway Authority. However, their report did not specify any wind speed as a maximum limit (Dutch Highway Authority, 2010).

To permit work in severe temperatures, the Dutch Highway Authority in some cases allows contractors to apply novel construction methods to overcome the severe conditions. The contractors apply a technique where existing layers are heated by spreading a layer of hot sand which has been heated in the asphalt mixing plant. They also use Rollpave, which is a pre-fabricated especially composed "rolled up" asphalt product with a thickness of about 30 mm. After the Rollpave is unrolled it is heated up to ensure that it adheres to the existing layer.

Dutch contractors also use a two-layer paving method, where two layers of asphalt concrete are placed "hot on hot" at the same time. A Shuttle Buggy is sometimes used for conditions in which temperatures are below freezing in order to minimize cooling of the asphalt mixture. However, use of a Shuttle Buggy does not increase the work pace of the asphalt paver; rather, the average speed of the asphalt laying is increased due to the fact that the use of the Shuttle Buggy reduces instances of halting. Moreover, it reduces segregation of asphalt and allows good compaction due to reduced temperature loss (Dutch Highway Authority, 2010). In Canada, Nova Scotia’s Ministry of Transportation has encouraged the utilization of the Shuttle Buggy in its specifications for major highway construction projects, offering a subsidy of $1.50 per ton of asphalt laid for its use (Hot-Mix Magazine). The examples from the Dutch Highway Authority, however, do not include any longitudinal study addressing long-term quality performance or additional construction costs of the mentioned road works.

Figure 2-6: Use of Shuttle Buggy for winter paving
(Photo source: http://www.hotmixmag.com/index.php?option=com_content&view =article&id=141:roadtec)

Perveneckas et al. (2013) have focused on finding a durable and economic solution for pavement construction on low volume roads in Lithuania which can resist the winter season. In their paper, low-volume roads are defined as those where annual average daily traffic is 500 or fewer vehicles. As outlined in a study conducted by the American Society of Civil Engineers, the National Association of Home Builders, and the Urban Land Institute of the United States, the Average Daily Traffic (ADT) for access roads is 0-250 ADT, while for Sub-collector roads it is 250-1000 ADT and for collector roads it is 1000-3000 ADT (ASCE , 1990). In comparing the Lithuanian context with Edmonton we note that Edmonton has a different hierarchy of roads, i.e, local, collector, and arterial, where the recent traffic flow map shows more than 500 ADT for all of these types of roads (City of Edmonton, 2014). Hence soft asphalt might not be suitable for Edmonton roads Lithuania had severe winters in 2010-12 which deteriorated the road pavement by reducing the road lift thickness. The Perveneckas et al. study proposed soft asphalt, drawing the experience from Nordic countries, as an alternative to HMA to curtail the deterioration of road pavement during winter. Soft asphalt is a mixture of aggregate and soft bitumen conforming to Lithuanian standards based on the European Norm (LST EN 12591). Soft asphalt is more flexible, able to heal the defects caused by severe winter weather once the cold season is over. It also increases the compactibility during paving. However, it has a limited rut resistance and low skid resistance. The research has also compared the cost of traditional asphalt with soft asphalt for 50 road construction contracts built for low traffic. The study found that soft asphalt reduces the cost of construction by 29%, although it should be noted that the study considered only the initial investment cost. Their study concluded that the maintenance cost would also be decreased in the case of soft asphalt paving since expected service life increases for the case of soft asphalt (Perveneckas et al., 2013). The paper did not elaborate on the weather conditions during paving with soft asphalt; hence, application of this in Edmonton conditions would require further study.

2.6 Construction cost

Many studies have been conducted which seek to document construction productivity and cost variation based on the time of the day during which paving activities are carried out. Some studies have sought to determine the cost variability, specifically for paving cost, for different hours of the day or for different seasons. Minchin et al., in their study, proved statistically in a case study that there is no significant difference in paving cost depending on the time of day. They also found that the delivery of construction items during daytime is not always less expensive, due to the fact that traffic interruptions are more likely to delay delivery of materials during the day (Minchin et al., 2013). However, no studies have been conducted targeting the effect of severe weather conditions on cost.

Akpan defined idle costs for construction resources as the cost of the resources that cannot be released during their non-productive time and need to be kept idle on site until they are needed at a later time (Akpan, 2000). Idle resources are common in any organization's normal course of business, since there may be a gap between committed resources and work progress resulting in partially unutilized resources (Tse et al., 2009). The resource idle time and job waiting time are internally controllable, and can be optimized through proper scheduling, as described in the study by Devi et al. Their study made an attempt to generate a resource-driven scheduling paradigm for housing construction, which is by nature repetitive, and their approach can also be applicable to highway construction (Devi et al., 2007). However, situations such as severe weather, labour accidents, or anything of an uncertain nature can still result in idle time in any construction schedule, and these realities make paving in cold-climate regions in particular inherently unpredictable.

2.7 Cost comparisons with rigid pavement

Smith et al. have studied the performance of different types of concrete roads all over Canada. The types of concrete roads include traditional joined concrete pavement, thin composite pavement, and roller-compacted concrete pavement. These pavements require special attention while placing the concrete where there are extreme low temperatures in order to ensure an acceptable level of performance. Admixtures are used to improve the workability of the concrete. The construction costs are found to be higher for these roads, however, and in general their production and laying rate are also higher; furthermore, they are capable of accommodating traffic earlier, and have lower maintenance costs compared to flexible or asphalt pavements. For interlocking concrete, block pavements have been found to be more cost effective than asphalt pavement over a 40-year life cycle. Again, the conventional concrete pavement in Nova Scotia has been found to have superior indices in terms of riding comfort and friction number compared to asphalt pavement. Most of these pavements have very low maintenance costs for a five-year analysis period. For example, the maintenance costs for a case study road in Nova Scotia have been found to be $167,000 for asphalt pavement, but only $14,000 for concrete pavement. These concrete pavements required curing to initiate the hydration of concrete, where in some cases curing compounds are used additionally. On the other hand, admixtures such as air entraining agents are required in most cases to ensure the concrete can withstand the effects of the freeze-thaw cycle, and admixtures such as water reducers and superplacticizers are used to ensure high early strength (Smith et al., 2001). However, asphalt pavements have low construction cost and very low carbon footprint compared to concrete pavement (Asphalt Pavement Alliance, 2010).

2.8 Warm mix asphalt for low temperature paving

Warm mix asphalt (WMA) is a type of asphalt mix that can be produced and placed at lower temperatures than traditional HMA. Based on the production temperature at the HMA plant, 135°C is roughly the lower limit for HMA and below this temperature the asphalt mix is considered a warm mix, which can be up to the production temperature of 100°C, depending on the specific WMA process been selected. This results in an asphalt mix where production temperatures can be 30°C to 55°C lower than hot mix and having certain added charecteristics from the additives which eventually reduces the viscosity of the asphalt and enables it to pour and compact at lower temperature than the HMA. Early instances of the use of WMA technologies show potential for easier compaction at lower temperatures. These properties may serve to lengthen the time available for compaction and aid with asphalt paving in cold weather (Flexible Pavements of Ohio, 2009).

WMA technologies are being developed in North America to produce paving alternative of HMA. In recent years, the use of WMA in Canada has grown significantly. There are over twenty different WMA additives and coating processes are currently available in the market and this number is expected to increase (Nabhani, 2010). These are categorized as organic additives, foaming processes, and chemical processes and are described here in the following sections.

2.8.1 Organic additives for WMA

Organic additives are of two types, such as: synthetic paraffin waxes and low-molecular-weight ester compounds. Both of these types have their melting temperature below standard HMA production temperature, hence, they can increase the viscosity of the asphalt binder at low temperatures and thus can assist in production of WMA. *Sasobit* is the most common organic additive that is currently being used (Wakefield, 2011).

2.8.2 Foaming process for WMA

Foaming process injects hot water in the form of steam in asphalt binder to increase asphalt's volume and workability and to reduce viscosity. *Aspha-Min*, *Advera*, and *WAM-Foam* are some examples of foaming process (Wakefield, 2011).

2.8.3 Chemical process for WMA

Chemical processes consists of a combination of emulsification agents, polymers, and additives to improve mixture workability and compaction of asphalt. The most commonly used chemical additive Evotherm, which can be of mainly two types, such as Evotherm Dispersed Asphalt Technology (DAT) or Evotherm 3G (Wakefield, 2011).

2.8.4 Examples of winter areas using WMA

D'Angelo et al. (2008) in their study have described applications of WMA in a number of European countries. It highlighted WMA as beneficial due to its ability to obtain required density while paving in cooler temperatures, its longer workability, its ability to use a higher percentage of Reclaimed Asphalt Pavement (RAP), and its shorter construction duration, meaning that traffic can open sooner. Their research outlined case studies in Germany where ambient temperatures were between −3 and 4°C during asphalt paving using WMA treated with Aspha-min. Similar experiences were shared from France and Norway, using WMA with WAM-Foam, Sasobit, Subit, etc. They highlighted in general terms the ability to complete paving in lower temperatures, although actual ambient temperatures were not specified in their contribution. The study highlighted the increased use of RAP at the range of 45 to 50%, in some cases up to 90%, which would eventually reduce the cost of WMA compared to HMA. However, the study does not elaborate on the performance or the cost for such increased use of RAP with WMA. The study addresses the recent developments in terms of health regulations in Europe, which have encouraged the paving industry to reduce production temperature of asphalt in order to mitigate asphalt fumes. This may be another factor that would result in increased use of WMA as an alternative to HMA. However, the study notes that since European contractors are more familiar with WMA technology they are better equipped to implement WMA than are North American contractors (D'Angelo et al., 2008).

According to Croteau and Tessier (2008), regulations related to emissions and energy saving help to promote the use of WMA, since it can be produced at temperatures 20°C to 40°C lower than HMA. They add that WMA reduces the hardening rate and softness during compaction, which helps to extend the paving season. WMA maintains the temperature viscosity relationship in such a manner that mixing and compaction viscosities are achieved at lower temperatures. WMA also allows a greater haul distance compared to HMA since it allows a higher mix temperature compared to compensate for longer transportation time. However, the temperature still remains below the HMA mix temperature, thereby reducing the likelihood of damage to binder pavement materials. Their paper also criticizes the fact that WMA is still not widely used in North America despite having been promoted commercially in recent years, while it is used commonly in many European countries (Croteau and Tessier, 2008).

A study by Kristjansdottir (2008) has advocated WMA over HMA for cold weather paving. Their research involves a case study of paving construction in Reykjavik, Iceland, highlighting the benefits of WMA in terms of reducing energy consumption and carbon emissions. Kristjansdottir has also pointed out that reduced viscosity makes WMA more workable, allowing longer haul distances, and effective compaction due to the lower cooling rate. However, it has lower rut resistance and higher moisture susceptibility, which necessitates application of anti-stripping agents. In this regard, their study makes cost comparisons among three WMA methods: Alpha-min Zeolite, WAM foam, and Sasobit method. It concludes that, for larger paving markets, WAM foam is an economical method with a high initial cost. For smaller markets, Sasobit is a more suitable method, although the production cost increases by 2% compared to HMA. Their study, it should be noted, is mainly based on a survey of industry experts and it does not provide detail of the market size or the cost component related to paving in Iceland (Kristjansdottir, 2008).

Goh et al. in their study have evaluated the performance of WMA treated with a common additive, Sasobit, which is a crystalline long chain aliphatic hydrocarbon also known as paraffin wax, for a project in Michigan, United States. The study advocates WMA due to its benefit in terms of reductions of fuel consumption, carbon footprint, and aging of binder material. For this specific study, the fatigue potential of WMA is found to be higher than that of HMA, while moisture susceptibility is found to be on par with HMA. However, tensile strength is found to be lower than for HMA. For example, for dry samples, average tensile strength was 520 KPa and 609 KPa for WMA and HMA respectively, while, for moist samples average tensile strength was 442 KPa for WMA and 532 KPa for HMA. This indicates again that WMA with Sasobit may tend to crack earlier than HMA. Their study also compares cooling time after pouring between HMA and WMA using the MultiCool program, observing that WMA extends the paving time by 27 minutes. They note that this extension would allow a longer hauling distance for pavement construction in cold weather (Goh et al., 2009).

Manolis et al. have introduced HyperTherm as an additive to be used with WMA in order to extend the paving season by facilitating paving in cold weather. HyperTherm is a non-aqueous liquid warm mix additive introduced by Lafarge, a building material manufacturer, added to liquid asphalt cement for a study on construction work in Ottawa, ON, Canada. According to this study, WMA pre-dosed with HyperTherm offers several benefits, including reduced emissions, lower fuel consumption, segregation of asphalt mix, improved mix workability, potential for longer haul distances, and extension of the paving season. In their study a case project was completed over 6 paving days during the period November 30 to December 14, 2007, during which the temperature ranged between 2°C to −13°C. They note that HyperTherm does not change the viscosity or other properties of asphalt cement, and can be produced without the need for significant changes to the asphalt production plant or the use of specialized paving machinery and rolling patterns on site. Their study, however, does not provide the actual cost data for the test section or the pavement work. Neither does it compare the cost data between conversional WMA or HMA and the mix using HyperTherm, nor include the performance properties related to permanent deformation, fatigue, and low temperature cracking (Manolis et al., 2008). However, the authors of the present study have been in contact with one of the authors of the Manolis et al. study for the purpose of eliciting cost information, and the author has confirmed a $2.5 increase per ton compared to regular HMA. Moreover, the Manolis et al. study reports on the performance of the road after one winter, noting that the road did not require any maintenance after one year of use. However, the standard warranty period for roads following development is typically two years in greater Edmonton, and their study does not address maintenance costs for two years.

Donovan et al. in their study have described the City of Edmonton's implementation of WMA. It encompasses the comparison of field and laboratory performance of WMA with HMA and evaluates three types of mixes, one with HMA, while the second and third are with WMA treated with water foaming process and chemical additives, respectively. The trial roads are located in the Westridge neighbourhood in Edmonton, where approximately 1,500 to 3,000 tons of each of the mentioned mix types were used. All three types contained 20% Recycled Asphalt Pavement (RAP), and the properties tested were moisture resistance, rutting resistance, fatigue resistance and dynamic modulus. Moisture susceptibility is an indicator for the strength of the aggregate structure of the asphalt mix, stiffness of its binder material or its performance against moisture. For this trial, the obtained results indicated that performance of WMA is similar to HMA in terms of moisture susceptibility. Rutting susceptibility and fatigue properties indicate the performance of pavement against stress and repeated load, respectively. For this trial, the obtained results indicated that HMA performs better in both of these tests; however, the City of Edmonton does not have any minimum or maximum requirements for these two criteria in its specification for HMA. In addition, the Dynamic Modulus test indicates the stress-strain relationship of an asphalt mix. It was observed that WMA chemical additive significantly lowers the modulus of the mix at high temperatures. While making their field observations, Donovan et al. observed the WMA roads to be performing well even after two winters. Their study concludes that WMA does not adversely affect the pavement performance; however, they recommend that future studies evaluate the consistency of WMA performance. Their study does not provide any insight in terms of a cost comparison between WMA and HMA (Donovan et al., 2012).

2.8.5 Economic and environmental benefit

Wakefield in his study cited several examples from the paving industries where WMA was evaluated to contribute in energy savings and reduction in carbon emission during production. For example, Lafarge Canada, in a trial in Vancouver, British Columbia, found that 10% reduction was possible in carbon monoxide, carbon dioxide and nitrogen oxide level while producing and 24% reduction in energy consumption was made as well. Other examples, as the paper mentioned, provided 24% reduction on the air pollution and 18% reduction on fossil fuel consumption compared to HMA (Wakefield, 2011).

2.8.6 WMA standard in different jurisdictions

The City of Calgary considers WMA on a case by case basis, where the contractors needs to make a proposal specifying the WMA process or the additive to be used, while the resulting mix design must meet the design and quality requirements (City of Calgary, 2012). However, none of the jurisdictions in greater Edmonton have developed any standard specifications for WMA, although they have experimented with constructing trial road sections with WMA.

2.9 Summary

This chapter has presented a literature review encompassing different aspects of the development process for neighbourhood roads. This has included a review of efforts to overcome the problems associated with low-temperature paving. It is determined that, although a considerable volume of research has been conducted, the economic and environmental information available in the literature pertaining to HMA and WMA production does not provide a complete evaluation of the financial aspects of implementing WMA.

3 CHAPTER 3: METHODOLOGY

3.1 Introduction

The study follows several steps to explore the possible relaxation of weather limitations or adoption of alternative paving options for greater Edmonton. However, with minor adaptations in the methodology, this research can be applicable for other jurisdictions in the colder region having similar weather limitations in asphalt paving.

The methodology uses different steps which include studying the limitations in different jurisdictions and analyzing weather data to evaluate the possible increase in construction hours if the weather limitations are relaxed. The next step determines the possible increase in paving work and whether it is capable of ensuring an acceptable level of asphalt performance during the increased available paving season. A simulation model is used to determine the degree of change in paving work for the increased range of time for the shoulder season. A case study area is then chosen as a means of verifying the model. At the final step, a cost comparison is made in order to determine the changes or increases in cost for a suitable alternative method relative to existing HMA practice.

3.2 Methodology

The methodological framework used for this study starts with the analysis of the weather standards for asphalt paving in different jurisdictions. Next, the outcome is analyzed in terms of increased construction hours considering a hypothetical situation where the weather limitation is relaxed to a certain logical extent for the shoulder season. Based on this relaxed weather limitation the rate of return or the opportunity cost as a result of achieving the increased construction hours is determined in the financial analysis section. The detailed methodological flowchart used for the study is illustrated in Figure 3-1.

Methodological Flowchart

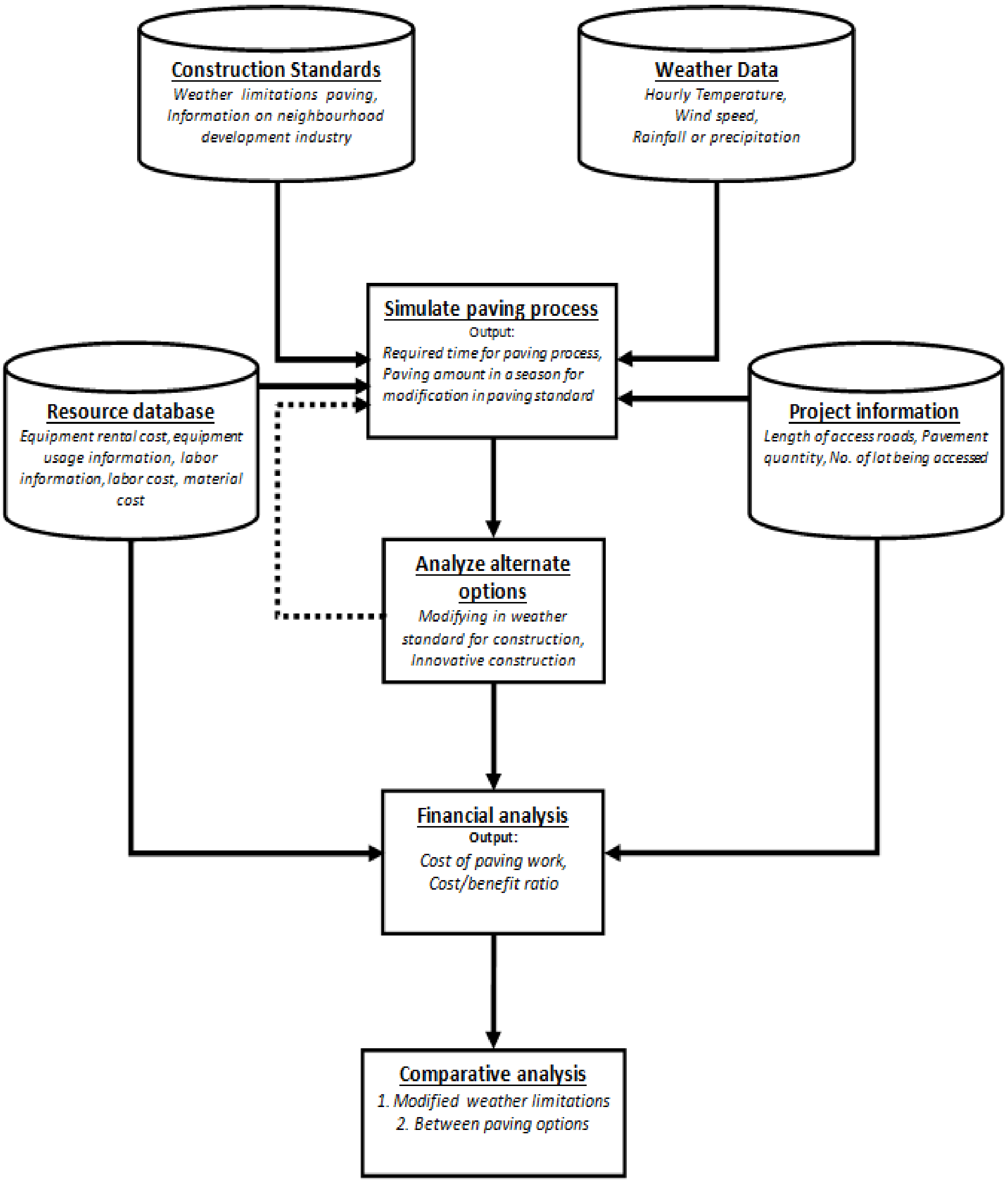


Figure 3-1: Methodological flowchart of the research

3.2.1 Asphalt standards in Edmonton and neighbouring cities and counties

Jurisdictions impose paving restrictions to ensure asphalt performance based on weather conditions such as ground temperature, air temperature, precipitation, and wind speed. Many jurisdictions have calendar date restrictions, such as not permitting paving between October 15 and April 15. The roadway design standards and construction specifications by the City of Edmonton and its neighbouring cities and counties specify the weather conditions for asphalt casting. According to these specifications, HMA is allowed to be placed only when both the air temperature and wind speed conditions are within a pre-defined limit. The applicable limits for asphalt paving in Edmonton are expressed in Figure 3-2 below. For example, the City of Edmonton imposes restrictions on paving work for a pavement thickness of 50 mm when the air temperature is below 4°C and the wind speed is higher than 10 km/hr. For wind speeds higher than 10 km/hr, there is a linear correlation between wind speed and temperature as specified in the weather limitation shown below in Equation (3.2). Accordingly, pavement with a thickness of 75 mm is to be placed only when the air temperature is above 2°C; however, when the wind speed is higher than 10 km/hr, the air temperature has to be more than 2°C according to Equation (3.4).

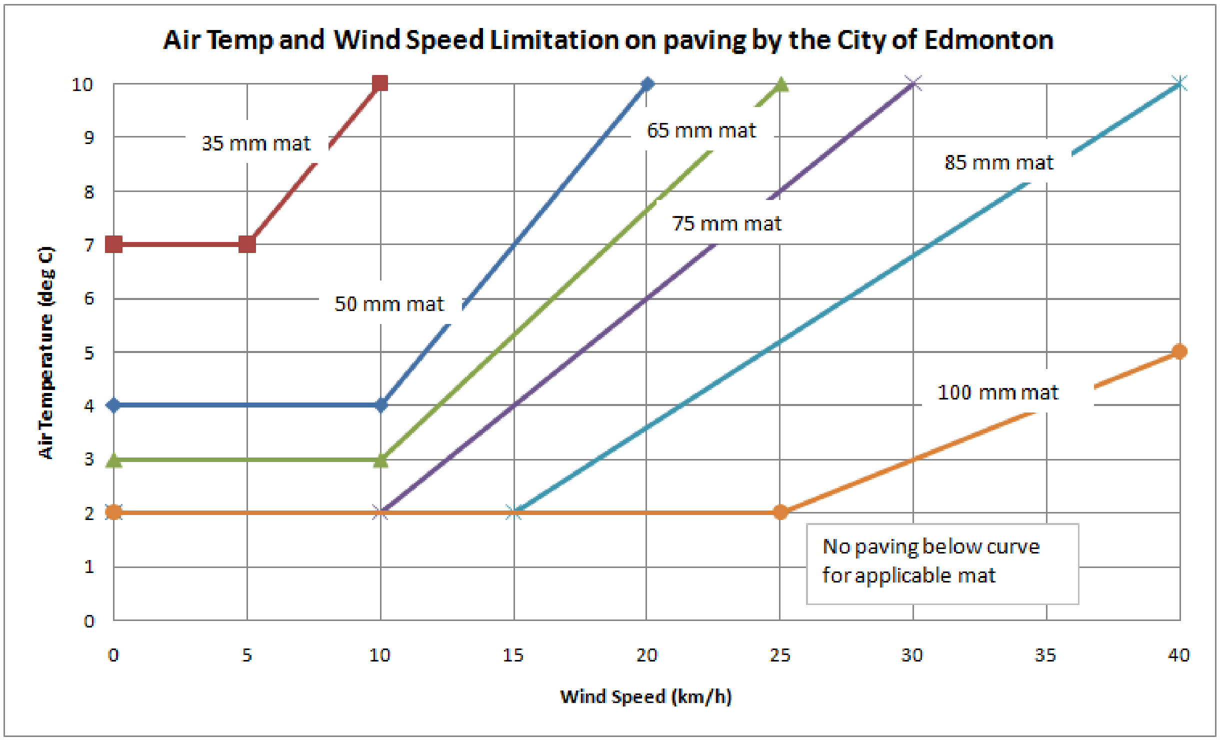


Figure 3-2: Air temperature and wind limitations on paving by the City of Edmonton (Source: Chart 0274.1, Roadways Design Standards Construction Specifications 2012, City of Edmonton)

Using the above chart, allowable air temperatures relative to different wind speeds for different thicknesses of asphalt paving are summarized as below, where W is wind speed in km/hr and T_{air} is the air temperature in degrees Celsius (°C).

1. For pavement thickness of 35 mm:

$$T_{air} = 7 + \frac{3}{5}\max(0, W - 5) \qquad 3.1$$

2. For pavement thickness of 50 mm:

$$T_{air} = 4 + \frac{3}{5}\max(0, W - 10) \qquad 3.2$$

3. For pavement thickness of 65 mm:

$$T_{air} = 3 + \frac{7}{15}\max(0, W - 10) \qquad 3.3$$

4. For pavement thickness of 75 mm:

$$T_{air} = 2 + \frac{2}{5}\max(0, W - 10) \qquad 3.4$$

5. For pavement thickness of 85 mm:

$$T_{air} = 2 + \frac{8}{25}\max(0, W - 15) \qquad 3.5$$

6. For pavement thickness of 100 mm:

$$T_{air} = 2 + \frac{1}{5}\max(0, W - 25) \qquad 3.6$$

Neighbouring cities or counties within greater Edmonton have similar limitations. The City of St. Albert, for instance, prohibit asphalt paving when the weather is foggy, rainy, windy, or when the air temperature is 2°C or lower. The City of Spruce Grove requires having sufficient daylight hours to complete compaction of asphalt pavement and a temperature of at least 2°C, as well as a dry road surface. Neither of these cities specifies pavement thickness or wind speed in their limitations. The City of Leduc and Strathcona County both follow an air temperature and wind limitation curve for different pavement thicknesses, as illustrated in Figure 3-3.

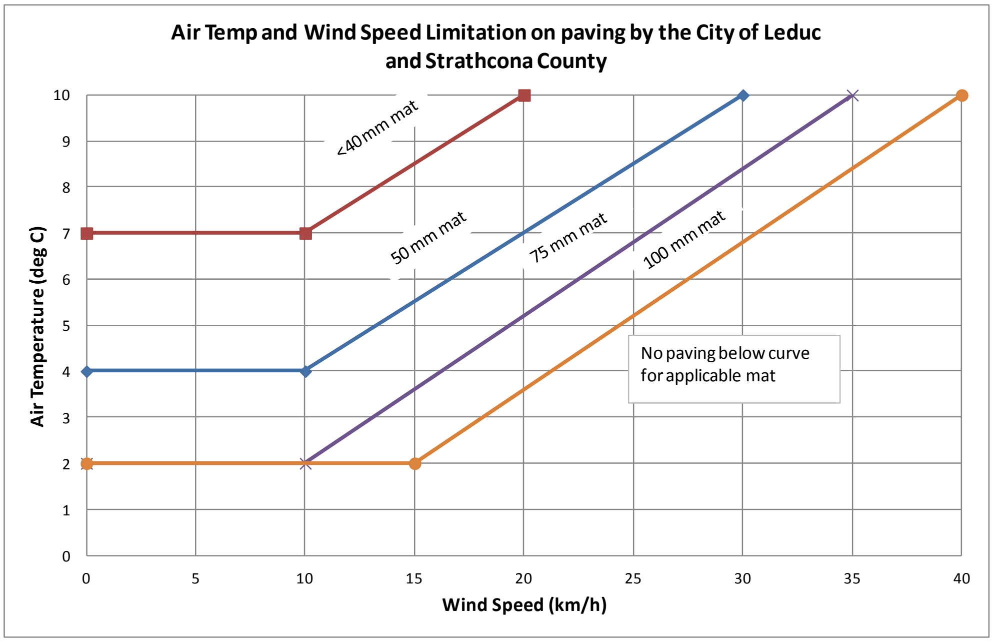


Figure 3-3: Air temperature and wind Limitations on Paving by the City of Leduc and Strathcona County
(Source: Drawing No. 3.16, Minimum Engineering Design Standards 2006, City of Leduc; Hot-Mix Asphalt Concrete Appendix F, Design and Construction Standards Vol. 1, December, 2011, Strathcona County)

The limitations for Leduc and for Strathcona County specify smaller ranges of pavement thicknesses; however, in each case the maximum wind speed limit is higher than that of the City of Edmonton. Using the above chart, allowable air temperatures during different wind speeds for different thicknesses of asphalt paving can be interpreted as below. Here, W is wind speed in km/hr and T_{air} is the air temperature in degrees Celsius (°C).

1. For pavement thickness of 40 mm:

$$T_{air} = 7 + \frac{3}{10}\max\left(0, W - 10\right) \qquad 3.7$$

2. For pavement thickness of 50 mm:

$$T_{air} = 4 + \frac{3}{10}\max\left(0, W - 10\right) \tag{3.8}$$

3. For pavement thickness of 75 mm:

$$T_{air} = 2 + \frac{8}{25}\max\left(0, W - 10\right) \tag{3.9}$$

4. For pavement thickness of 100 mm:

$$T_{air} = 2 + \frac{8}{25}\max\left(0, W - 15\right) \tag{3.10}$$

Furthermore, the provincial standard for Alberta does not have a weather limitation for HMA castings (Alberta Transportation, 2012). While Ontario limits asphalt pouring for surface course mentioning the air temperature at the road surface has to be at least 7°C, except for Stone Mastic Asphalt (SMA), which is HMA consisting of a stone on stone coarse aggregate with asphalt and also for Superpave mix design of HMA. The temperature requirement for these two is at least 12°C (Ontario Ministry of Transportation, 2012).

Other neighbouring major cities, such as Calgary, do not have a wind speed limitation for asphalt paving; however, the City of Calgary permits asphalt pouring only when the construction site has sufficient natural or artificial light and when the temperature is rising and meeting the following minimum requirements:

1. Minimum 7°C for pavement thickness less than 50 mm
2. Minimum 4°C for pavement thickness less than 70 mm and greater than 50 mm
3. Minimum 2°C for pavement thickness greater than 70 mm, or
4. Surface temperature higher than 5°C (City of Calgary, 2012).

In Regina, SK, Canada, the minimum air temperature during asphalt pouring is 2°C (City of Regina, 2010). However, the City of Saskatoon, SK, Canada, just recently withdrew their minimum temperature restriction, where the temperature limitation had been set at a minimum of 2°C during pouring of asphalt of any thickness (City of Saskatoon, 2015). There are, however, additional limitations in weather conditions for most of these jurisdictions, such as requirements of dry surface and zero precipitation during pouring.

An extended at-a-glance summary of the weather limitations of asphalt in different jurisdictions in Canada is included in Appendix 1.

3.2.2 Analyzing weather data of greater Edmonton for construction hours

For this study, a sensitivity analysis is performed on the air temperature and wind speed data for Edmonton, Alberta. Seven years-worth of hourly data spanning the years 2008 to 2014 with respect to air temperature, wind speed, and rainfall for Edmonton City Centre from the Government of Canada's Climate webpage is studied to determine the number of additional construction hours to be achieved in one year if the temperature limitation is relaxed by 1°C or more. Daylight hours are taken from the webpage timeanddate.com for the year 2013 and the same sunrise and sunset times are used for the remaining years studied for weather data, i.e., from 2008 to 2014.

Initially, it is determined that, throughout a given year, the average permissible paving time for 50 mm paving thickness according to the City of Edmonton standard would be 2,391 hours since the minimum temperature requirement is 4°C. The calculation of total construction hours is made based on the following assumptions:

1. Construction hours are considered only when daylight is available.
2. Paving is not permitted if any form of precipitation (rain, snow, hail, etc.) is occurring or imminent.
3. Any number of consecutive hours (one hour or greater) during daylight is considered to be construction hours.
4. The wind speed limitation is based on the City of Edmonton's weather limitation specifications for respective thicknesses.

While analyzing the weather database, the weather limitation is considered according to the City of Edmonton's standard; the checklists used are as follows:

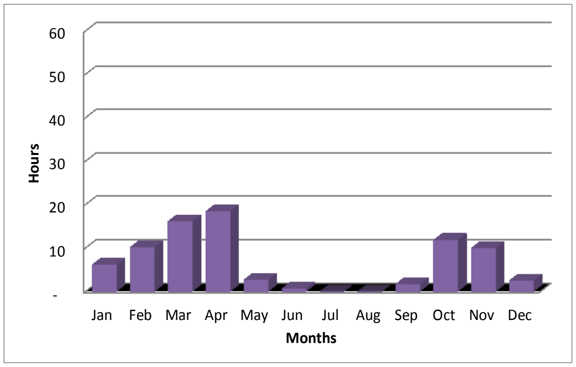
1. Since paving is not permitted while there is any form of precipitation, any hours with rain (heavy, moderate, light/regular), drizzle (heavy, moderate, light/regular) or snow (heavy, moderate, light/regular) are excluded from available construction hours.

2. In Edmonton, paving after sunset is permitted; however, in some jurisdictions within the greater Edmonton area it is not authorized; accordingly, to arrive at a generalized idea of the sunlight hours available for paving activities, any hours before sunrise and after sunset are excluded from construction hours.
3. The wind speed is considered according to the linear equation provided in the City of Edmonton standard described above when it exceeds the minimum value for certain pavement thicknesses.

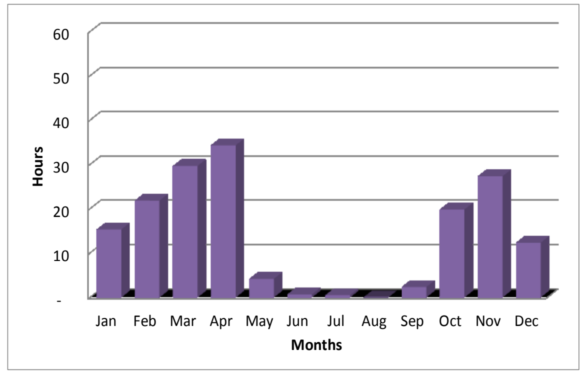
Analysis of the weather data is performed in two steps: by observation using Microsoft Excel and by validation of the data using a data fit option for statistical distribution in Simphony.NET 4.0. This is achieved using the paving thickness range of 50 mm to 75 mm, since this range accounts for the majority of local roads.

3.2.2.1 Analyzing weather data for 50 mm thick HMA pavements

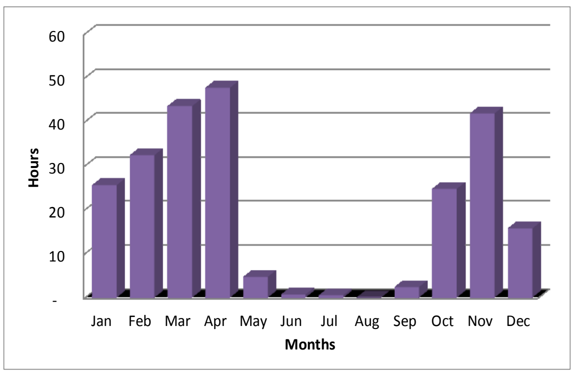
For 50 mm asphalt thickness, the minimum allowable air temperature for paving is 4°C; lowering the allowable temperature for asphalt pouring, as described in different examples in the literature review section, from 4°C up to −4°C will increase the available paving construction hours for Edmonton. The achievable additional hours are shown in Figure 3-4:



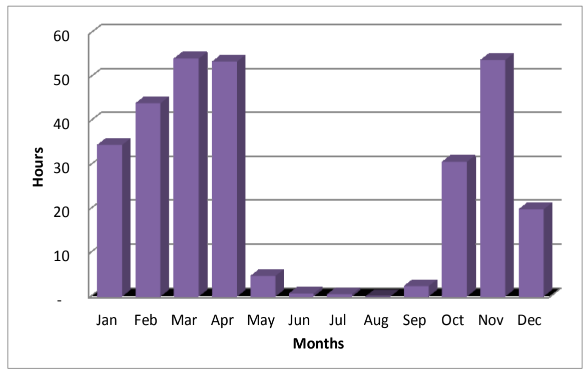
a) Additional hours for lowering the standard to 2°C



b) Additional hours for lowering the standard to 0°C



c) Additional hours for lowering the standard to −2°C



d) Additional hours for lowering the standard to −4°C

Figure 3-4: Additional construction hours for lowering the temperature standard during asphalt pouring (50 mm)

However, for further analysis, we consider September to November to be the period during which there are more fluctuations in weather, which is the main concern of our study. The average annual precipitation in Edmonton is 47.7 cm, comprising 36.6 cm of rain and 11.1 cm of melted snow, where snowfall is around 123.5 cm per annum (Climate Canada, 2015). The heaviest precipitation occurs from late spring to early autumn. During these months of heavier precipitation, occasional instances of a number of successive rainy days occur, which can create significant disruption to roadwork, limiting the number of available paving days per year. Study shows that, for the period 2008 to 2014, on average the number of days in a year with at least some form of precipitation (more than 0 mm of precipitation) is 347 days and days with more than 1 mm of precipitation is 92 days (Figure 3-5). However, this number represents the average data from all the weather stations in Edmonton. According to this data, for the shoulder season, the number of days with some form of precipitation is 88 days, and the number of days with more than 1 mm of precipitation is 11.

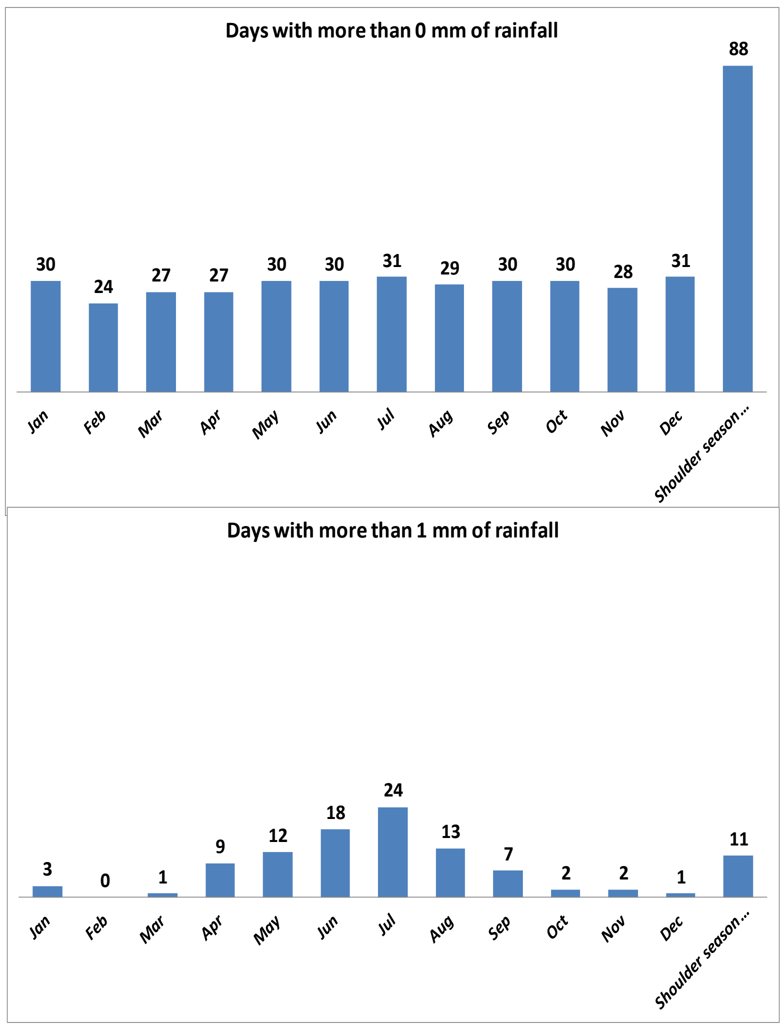


Figure 3-5: Number of days with precipitation in Edmonton (> 0 mm and > 1 mm)

In addition, in greater Edmonton the ground usually remains covered with thick snow during the period from December to April, thereby preventing any paving work for the mentioned period. At 4°C, the average number of available paving hours during the period September to November is 497. The additional construction time achieved by lowering the existing standard from 4°C to −4°C is shown in Figure 3-6:

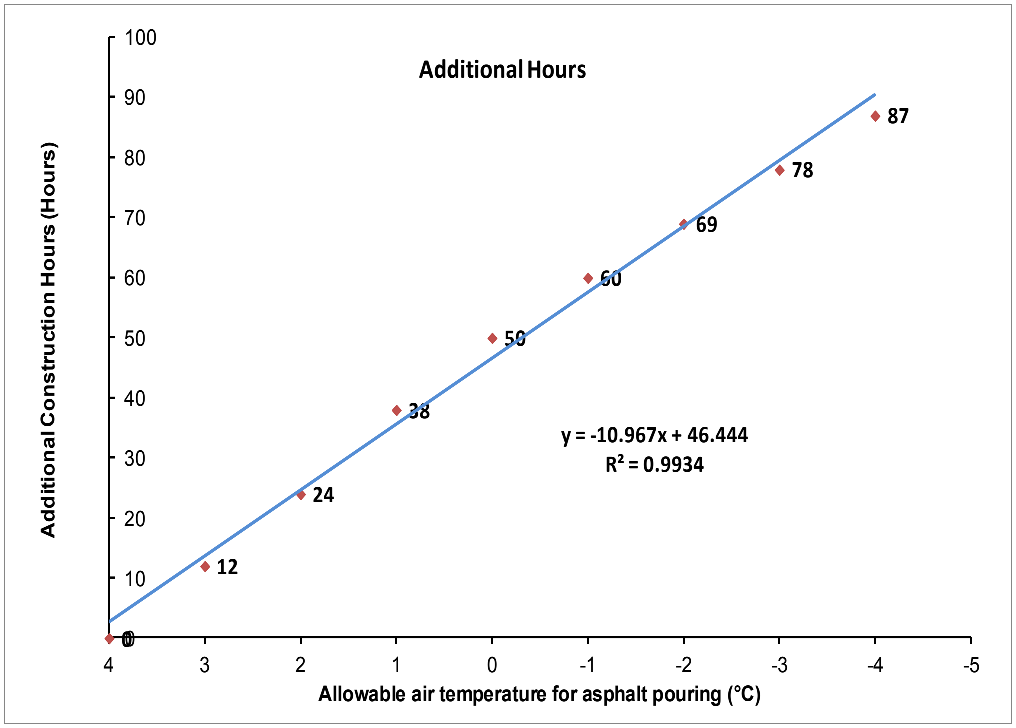


Figure 3-6: Sensitivity analysis of changing allowable air temperature for 50 mm thick asphalt during shoulder season

Using regression analysis for the additional construction hours to be achieved by lowering the air temperature limitation, a linear relationship is defined between additional construction hours and new allowable air temperature limitations for asphalt pouring, as follows:

$$Hr = 46.444 - 10.967 * T_{air} \qquad 3.4$$

Where *Hr* is the additional construction hours (in hours) and T_{air} is the changed air temperature in degrees Celsius (°C). The regression equation has a R^2 value of 0.9933 and a p-value of $6.92 * 10^{-9}$ (i.e., less than 0.05).

In addition, hourly data during daylight hours and with zero precipitation for this period (2008 to 2014) for the shoulder season (September to November) is analyzed using wind speed limitations for 50 mm thick pavement in order to obtain the probability distribution data for temperatures lower than 4°C. The data set follows a logistic distribution considering least square, moment matching, and maximum likelihood method, as illustrated in Figure 3-7 according to the parameters outlined below:

Table 3-1: Distribution parameters for weather data

Distribution Parameters	**Input Data**	**Theoretical Distribution**
Location: 12.3889 Scale: 4.9963 (total of 3,165 observations over 7 years, i.e., 452 hours per year on average that meet the daylight, wind speed, and precipitation requirements)	Maximum: 33.5 Mean: 11.7497 Minimum: −26.6 Std Deviation: 9.1841	Maximum: ∞ Mean: 12.3889 Minimum: −∞ Std Deviation: 9.0623

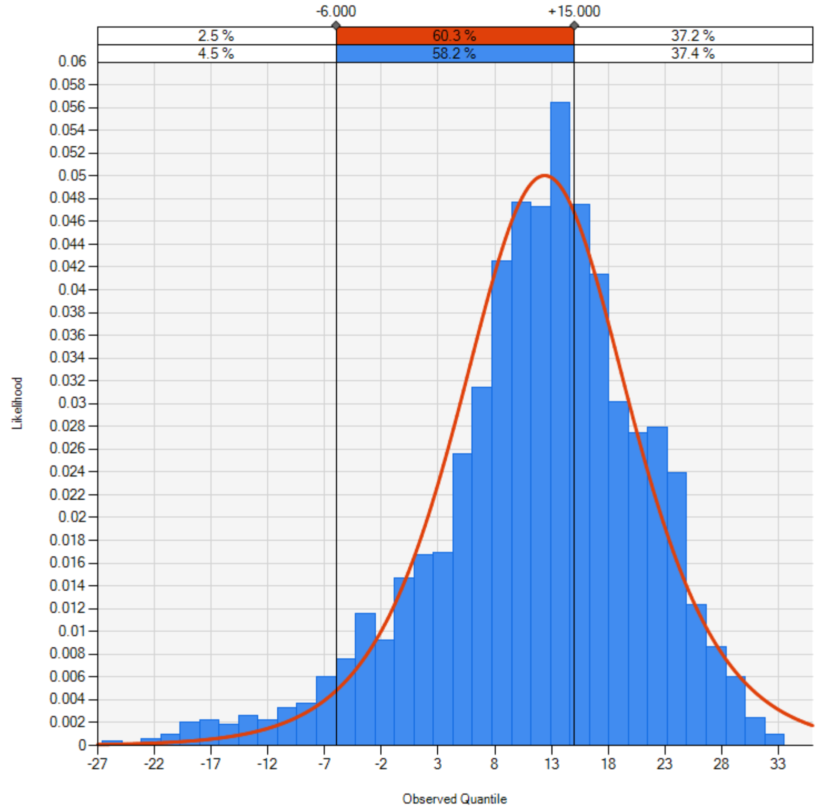


Figure 3-7: Logistic distribution of air temperature data qualifying for sunlight hour, precipitation and wind speed limitation for 50 mm thick pavement

Using the cumulative distribution function for this distribution we find that approximately 84.50% of the air temperature readings for this range remain over 4°C. Considering a change in allowable temperature for paving, i.e., if it is lowered from 4°C to 2°C, there is 1.8% increase in paving hours.

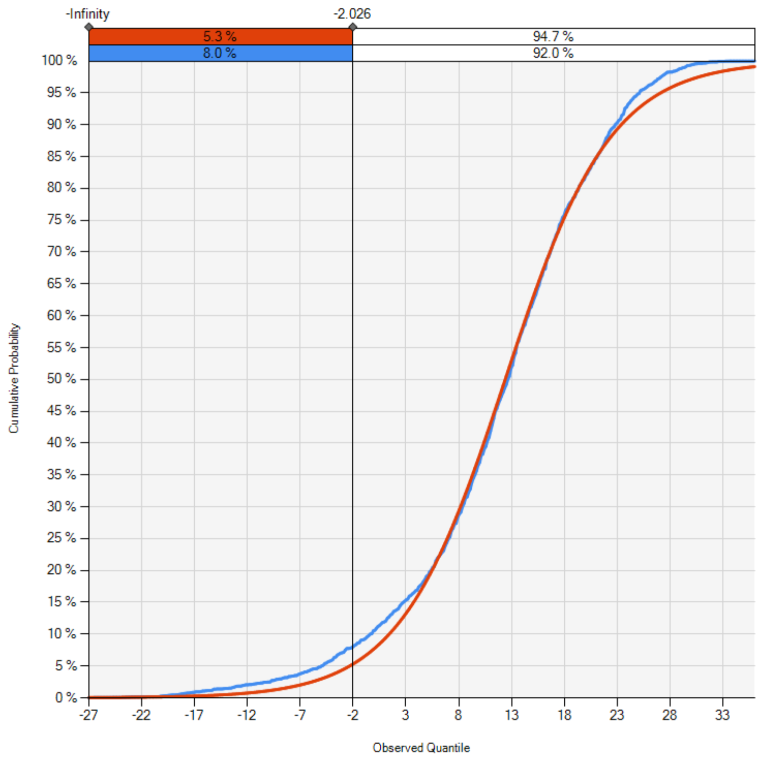


Figure 3-8: Cumulative density function of air temperature for 50 mm thick pavement

Similarly, lowering the minimum allowable temperature from 4°C to −4°C increases the construction hours, based on the 452 construction hours available for a temperature threshold of 4°C, as shown in the following table (Table 3-2):

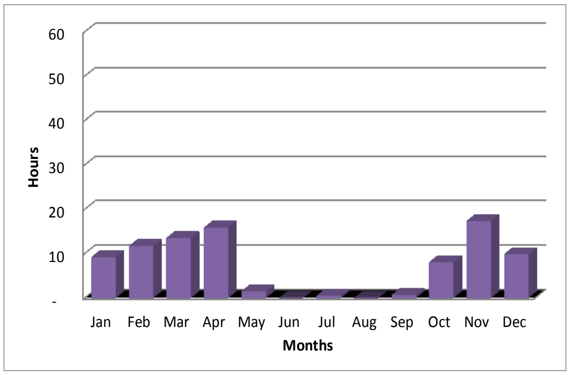
Table 3-2: Additional construction hours according to data distribution

Temperature (°C)	Percentage of data above the temperature	Additional construction hours in the shoulder season
4	84.5	0
2	86.1	7
0	89.3	22
−2	92.0	34
−4	94.2	44

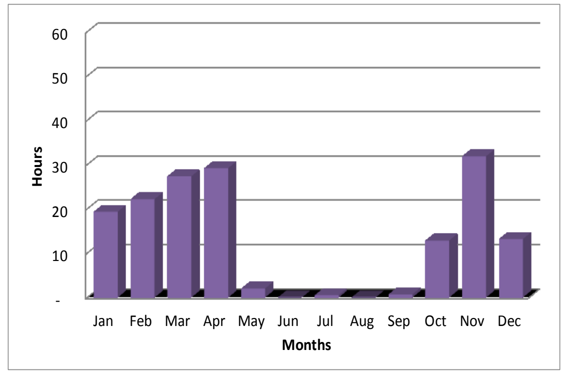
The outcomes in terms of construction hours from these analyses show significant variation. However, for further analysis in the cost-benefit section the targeted temperatures are considered to be 0°C and −4°C, which is expected to increase the construction season by totals of 22 hours and 44 hours, respectively.

3.2.2.2 Analyzing weather data for 75 mm thick HMA pavements

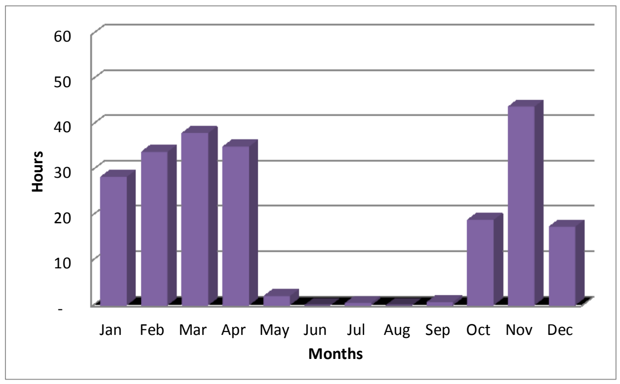
Again, for a 75 mm asphalt thickness, the minimum allowable air temperature for paving is 2°C; lowering the minimum allowable temperature for asphalt pouring from 2°C to −4°C increases the available paving construction hours for Edmonton as shown in Figure 3-9:



a) Additional hours for lowering the standard to 0°C



b) Additional hours for lowering the standard to -2°C



c) Additional hours for lowering the standard to −4°C

Figure 3-9: Additional construction hours for lowering the temperature standard during asphalt pouring (75 mm)

The summary of the additional construction time achieved by lowering the existing standard from 2°C to −4°C for 75 mm thick pavement between September and November is shown in Figure 3-10; this is based on average annual construction hours for 75 mm paving at 2°C of 609 hours for the years 2008 to 2014:

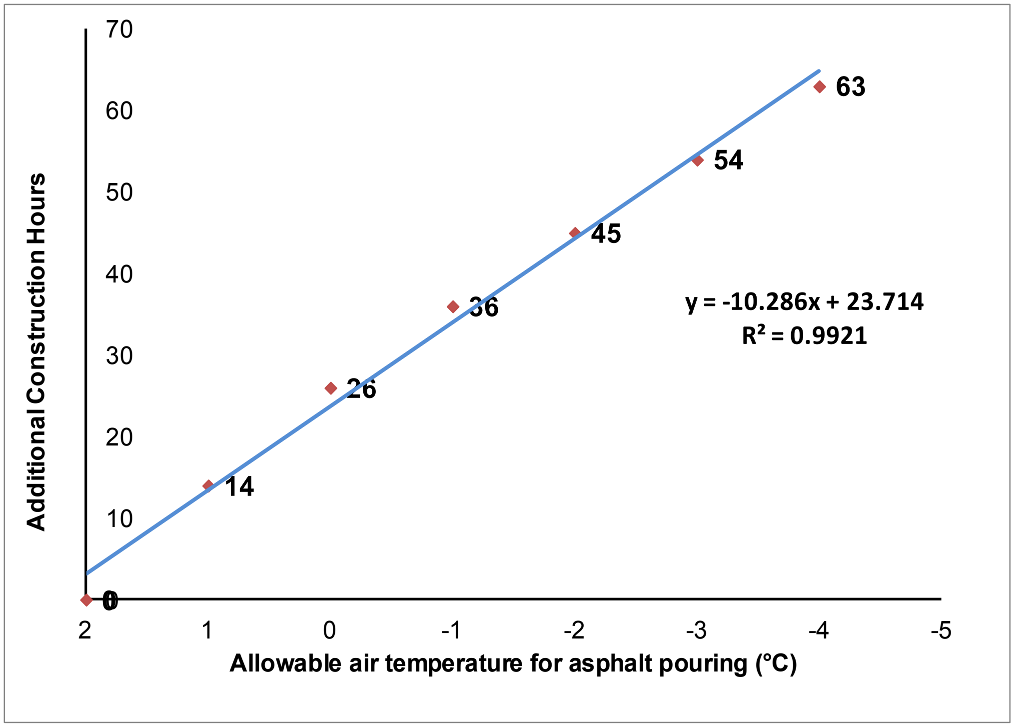


Figure 3-10: Sensitivity analysis of changing allowable air temperature for 50 mm thick asphalt during shoulder season

Using regression analysis for the additional construction hours to be achieved by lowering the air temperature limitation gives a linear relationship between additional construction hours and new allowable air temperature limitations for asphalt pouring, as follows:

$$Hr = 23.714 - 10.286 * T_{air} \qquad 3.4$$

Where, Hr is the additional construction hours (in hours) and T_{air} is the changed air temperature in degrees Celsius (°C). The regression equation has a R^2 value of 0.9921 and a p-value of $1.91 * 10^{-6}$ (i.e., less than 0.05).

Similar analysis on the air temperature data between September and November during sunlight hours with no precipitation for 75 mm thick pavement again follows the logistic distribution shown in Figure 3-11, with the parameters as outlined below:

Table 3-3: Distribution parameters for weather data (75 mm)

Distribution Parameters	**Input Data**	**Theoretical Distribution**
Location: 10.6789	Maximum: 33.5	Maximum: ∞
Scale: 4.73	Mean: 10.6789	Mean: 10.6789
(total of 4,943 observations over 7 years, i.e., 706 hours per year on average that meet the daylight, wind speed, and precipitation requirements)	Minimum: −26.6	Minimum: −∞
	Std Deviation: 8.5793	Std Deviation: 8.5793

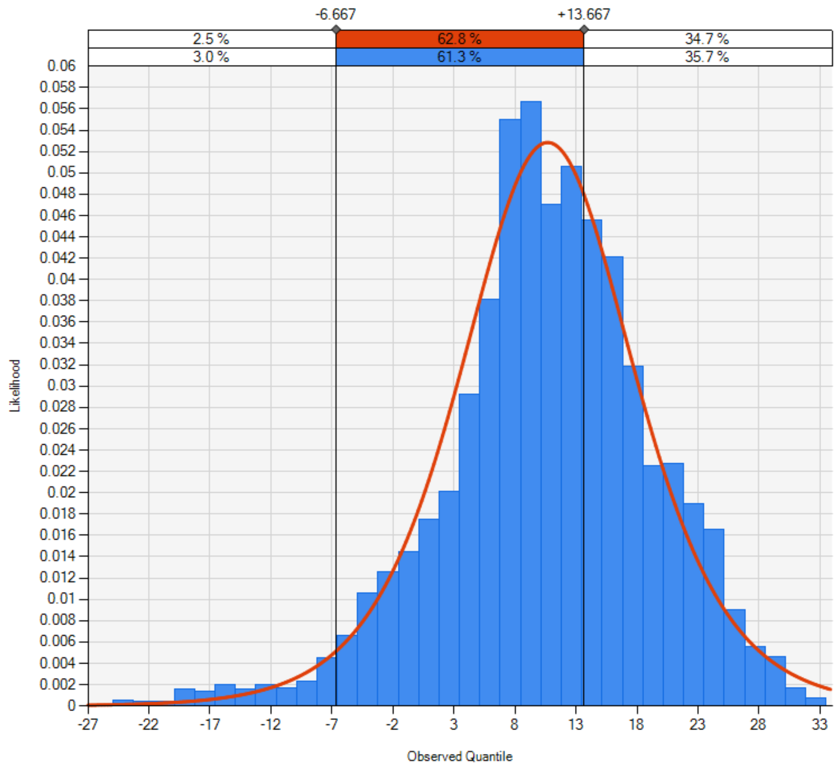


Figure 3-11: Logistic distribution of air temperature for 75 mm thick pavement

Using the cumulative distribution function from this distribution, we find that 86% of the air temperature readings for this range remain above 2°C. Considering a change in allowable temperature for paving, i.e., if it is lowered from 2°C to 0°C, there is 3.6% increase in paving hours.

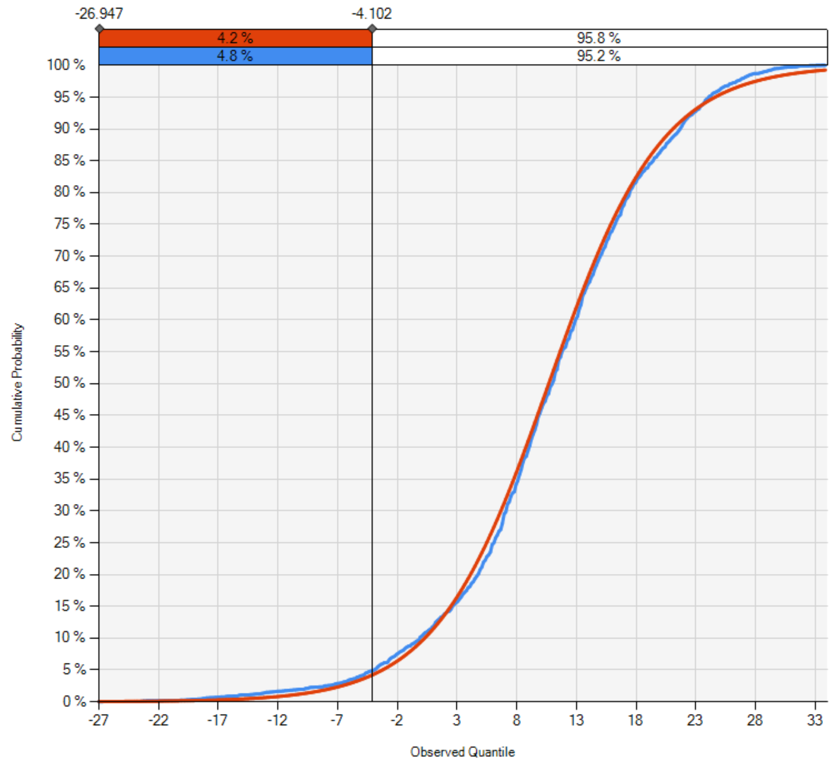


Figure 3-12: Cumulative density function of air temperature for 75 mm thick pavement

Based on the average 706 hours of construction as observed, the increase in construction hours associated with lowering the minimum allowable temperature from 2°C to −4°C is provided in the following table (Table 3-4):

Table 3-4: Additional construction hours according to data distribution

Temperature (°C)	**Percentage of data above the temperature**	**Additional construction hours in shoulder season**
2	86.0	0
0	89.6	30
−2	92.3	52
−4	95.0	74

For further analysis in the cost-benefit section the targeted temperatures are considered to be 0°C and −4°C, which is expected to increase the construction season by totals of 30 hours and 74 hours, respectively.

This study is carried out considering the additional investment required to extend the construction time according to the achievable number of paving hours available which result in a finished product that maintains the targeted level of roadway performance and the expected outcome of the investment.

3.3 Case study neighbourhood

The case study uses the developing neighbourhood of Rosenthal, Edmonton for the purpose of verifying the simulation model developed to analyze paving based on weather limitations. Rosenthal is a primarily residential neighbourhood in west Edmonton, Alberta, Canada, that has been under development since 2009 under the Rosenthal Neighbourhood Structural Plan (NSP), which had been initially under the Lewis Farms area plan. It is bound on the west by 231 Street (Hillview Road), on the north by the future extension of Webber Greens Drive (87 Avenue), on the east by Winterburn Road (215 Street), and on the south by Whitemud Drive. The neighbourhood has been under development with a gross developable are of 232.82 hectares, where total circulation area, i.e., road network within the neighbourhood, covers 15% of the total area, which is around 336,000 m^2. The residential units have been planned as follows:

Table 3-5: Summary of Rosenthal Neighbourhood

Land use	Area (ha)	Units	Population
Single/Semi-Detached Low Density	119.6	2,990	8,371
Row Housing Medium Density Residential	20.2	909	2,544
Low-Rise Apts/Medium Density	8.5	766	1,379
Total	**148.3**	**4,664**	**12,294**

(City of Edmonton, 2015)

The developer, Melcor Developments Ltd., started development of this neighbourhood initially focusing on the low density areas in 2012, dividing it into 13 (thirteen) stages; while the contractor, Standard General Inc. (SGI), involved in developing the road network of this neighbourhood, started their construction in the same year.

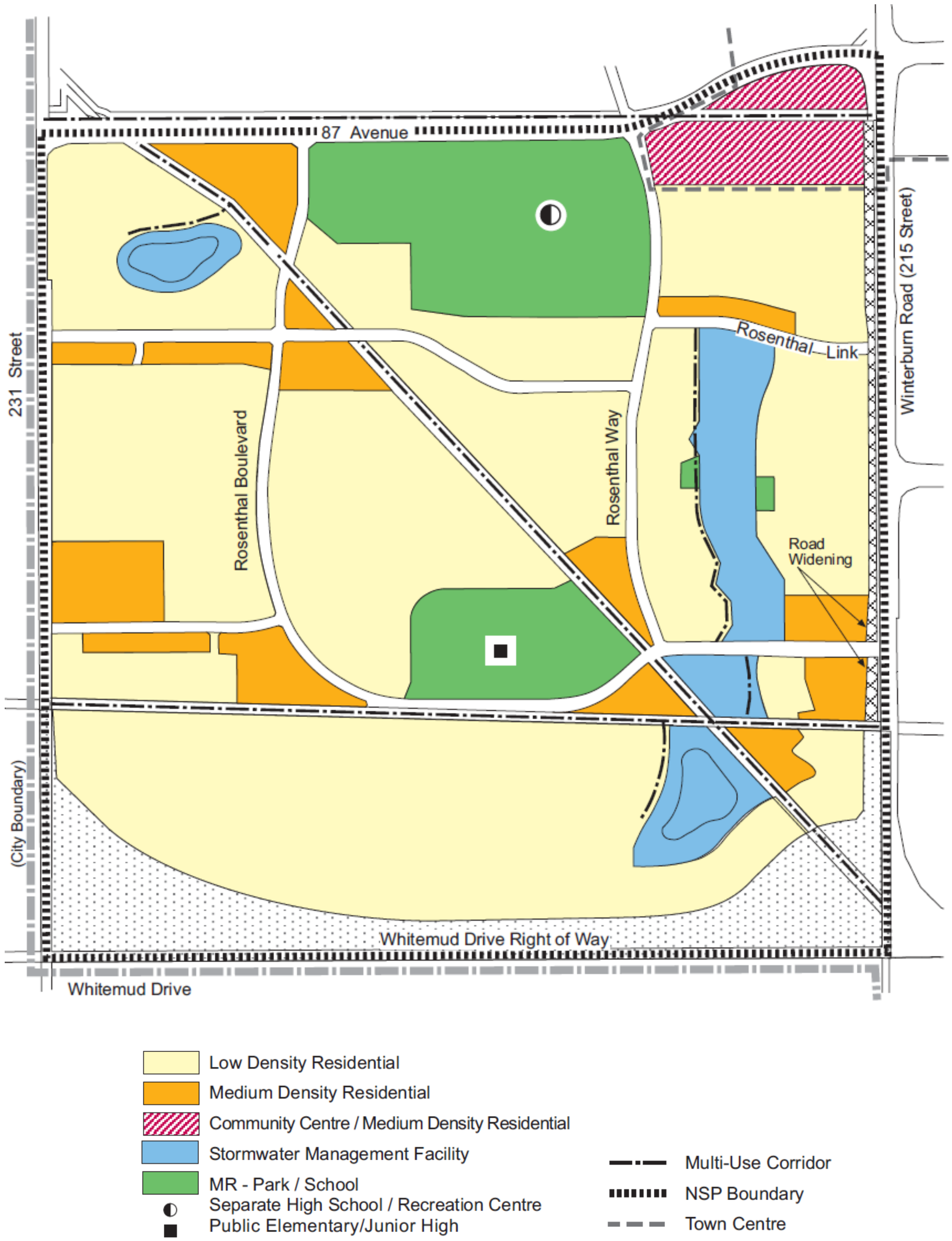


Figure 3-13: Rosenthal neighbourhood structural plan (City of Edmonton, 2014)

Figure 3-14: Rosenthal neighbourhood from Google Maps

This thesis proposes a basic framework for paving work based on observation of the paving work at Rosenthal, and uses the neighbourhood road development data of Rosenthal for the verification of the model.

Table 3-6: Summary of work at Rosenthal

Stage No.	HMA volume (T)	Working Hour (hr)	Developed Road Length (m) (Approx)	No. of Developed Lots	Accessible Lot Area (m^2) (Approx)
1	2,350.00	22.5	1,150.00	96	35,037.00
4	3,363.00	29	1,579.00	119	35,207.00
5	2,972.00	36	1,902.00	177	51,960.00
7	419.00	5	210.00	26	10,334.00
10	939.00	6	389.00	52	12,726.00
12	655.00	7	295.00	66	13,640.00

3.3.1 Resource data for cost

The resource data is studied mainly in terms of the construction cost incurred and the crew used by the contractor in the study area related to the pavement construction during neighbourhood development.

Neighbourhood development involves cost at every stages of its process starting from planning and approval stages till the release of lots. Paving is done after the subdivision of lots while installation of all the services is done. Asphalt paving process consists of preparing sub grade, sub base, base and surface courses.

The weather limitation on asphalt paving has its influence mainly over surface works, the study only includes the direct cost components related to surface works, such as:

1. Cost of workforce
2. Cost of equipment
3. Cost of material

There are a few other direct costs related to paving construction, such as site preparation, material testing, form work etc. and finally, maintenance costs, which have not been considered in this study. Similarly, there are a few indirect costs, such as office overhead, marketing costs, general sales tax (GST) on material, and contingency costs. However, contingency costs generated from weather risk may differ and become lower if the weather limitation has been relaxed; still, this cost is not taken into consideration in this study.

These costs are excluded from the present study due to the fact that changes to these costs based on the adoption of an alternative construction method such as WMA or alternate weather limitation would be insignificant.

The cost components considered in this analysis, as mentioned above, are analyzed using other databases such as:

1. Alberta Roadbuilders & Heavy Construction Association (2014)
2. RSMeans (2014)

This is elaborated on in the following sub-sections:

3.3.1.1 Cost of workforce

According to RSMeans data, the workforce used in the paving work includes 1 foreman, 7 general workers, and 3 equipment operators as included in the crew type B-25B. The cost of this workforce including operational cost and profit is as follows:

Table 3-7: Cost of paving workers (RSMeans)

Type	No.	Including O&P	
		Hourly (CAD)	Daily (CAD)
Labour Foremen	1	60.95	487.60
Labourers	7	57.85	3,239.6
Equipment Operators	3	76.75	1842.0

This table (Table 3-7) considers average 8 hours of work in a day with a daily output of 5,305 m^2 of paving when thickness is approximately 50 mm. This is the standard cost of different types of paving workers; however, in practice the cost of equipment includes the cost of operators.

From the Albertan industry point of view, the volume of work during neighbourhood development encourages the contractors to use increased number of workforce and equipment. For example, the crew size generally includes, 1 foreman, 9 general workers and 6 equipment operators as observed while visiting the case study neighbourhood at Rosenthal, Edmonton. This is mainly because there are many manual activities, such as, raking, screeding or grading and manual work is additionally required where the road width varies close to the intersection to complete the width adjustment after pouring and also to maintain the slope of the pavement. The operators cost are included in the equipment cost and charged in daily basis; however, the other workforce are paid on hourly basis which includes the work interruption time during a construction day. The rate for weekend or holiday is approximately 1.5 times on Saturdays and twice on Sundays and other statutory holidays. Other than the foreman there are several roles for the general workers, involved in finishing, screeding, raking, and grading. The standard rate for workers, taking the average for general workers and the foreman on a weekday as used in further calculation is included in the following table (Table 3-8).

Table 3-8: Hourly rate of paving workers

Type of worker	Total hourly cost (CAD)
Foreman	83.00
General worker (including but not limited to Finisher, Raker, Screed person, Grade person)	54.00

3.3.1.2 Cost of equipment

The equipment directly involved in the paving process are trucks, pavers and compactors. Generally, asphalt paving work uses a fleet of asphalt trucks, which is provided by a separate asphalt mix supplier or the contractor itself and the cost is included as freight cost for material. Asphalt paver (Figure 3-15) is used for paving and in addition to that, there are usually two types of compactors used, i.e., steel roller and pneumatic roller (Figure 2-5). The compactors operate behind the paver to provide the final finishing of asphalt. The number of the equipment to be used is decided depending on the volume of paving work.

At Rosenthal, the contractor Standard General Inc used 2 sets of equipment of the following specifications:

Table 3-9: Hourly rate of paving workers

Equipment	Brand	Max Speed (m/min)
Crawler Paver	Vogele 5200-2	76
Pneumatic Tire Rollers	CAT PS300B	100
Steel Rollers	HAMM HW90B	169

Figure 3-15: Asphalt paver

From the rate information booklet of Alberta Roadbuilders & Heavy Construction Association (2014), the standard hourly rate collected for these equipment and would be used for further calculation is as follows:

Table 3-10: Hourly rate of paving equipment

Sl. No.	Equipment	Quantity	Hourly rate (CAD/hour)
1	Crawler paver	1	340.0
2	Pneumatic tire rollers	1	130.0
3	Steel rollers	1	118.0

3.3.1.3 Cost of material

Cost of asphalt differs based on the strength requirement according to expected traffic load during its lifespan. Based on the price information provided by Standard General Incorporation's Acheson Asphalt Plant's data for last three years and considering a 5% inflation in price, we use an average value of **87.0 CAD/T** as the unit rate of HMA used while doing further calculation, which includes the cost of material, loading at plant, unloading at and freight up to the delivery site.

3.3.2 WMA as alternative material

From the literature review, examples from different countries and jurisdictions showed WMA would be a suitable alternative to continue paving during the colder season. And for the cost benefit analysis, the cost of WMA has been considered as a chosen alternative of HMA for construction during the shoulder season. According to the cost information from Standard General, the cost difference of WMA with HMA is very marginal. However, for any adding any additives with WMA, as discussed in the literature review section, the cost would increase, ranging from 2 to 7 CAD/T. Similar feedback regarding price was received from Lafarge Inc. through private communication. For further analysis, in this chapter we use a total cost of 95.0 CAD/T for using WMA with chemical additives.

For further analysis, the cost components derived in this section are for the purpose of determining the financial benefits of different paving options, i.e., if any financial benefits can be obtained if weather condition requirements are relaxed or alternative material is used.

3.3.3 Volume in Tons for unit length of Road

The basic calculation for volume (tons per 1,000 m) of paved length is shown in this section; the calculation is made here for a road with 9 m road width and 50 mm of thickness after compaction, which will be used to obtain results following simulation.

Calculation of Volume in Tons for unit length of Road:

Road Length, L: 1,000 m

Road Width, W: 9 m

Pavement thickness (after compaction), T_1: 50 mm

Pouring thickness, T_2: 60 mm

(20% reduction after compaction)

Wastage: 5%

Specific Gravity of HMA, SG_{HMA} : 2.37 T/m^3

Specific Gravity of WMA, SG_{WMA} : 2.28 T/m^3 (Nabhani et al. 2010)

Total HMA Quantity (for 1km), $Q_{HMA} = L * W * T_2 * SG_{HMA}$ + add wastage @ 5%

$= 1000 * 9 * (60/1000) * 2.37 * 1.05$

$= 1343.79$ T

Total WMA Quantity (for 1km), $Q_{WMA} = L * W * T_2 * SG_{HMA}$ + add wastage @ 5%

$= 1000 * 9 * (60/1000) * 2.28 * 1.05$

$= 1292.76$ T

3.4 Simulation Model

A simulation model is built to include two key components of the typical paving process in greater Edmonton: (1) the main operational process of paving and (2) the decision making process based on weather conditions. The model replicates equipment utilization as well as specific timing for each task, such as paving by the paver, compaction by the two types of compactors, travel time by the truck, as well as idle time when the weather does not permit paving.

3.4.1 Model Development

The model is developed using Simphony 4.1, as mentioned above, using discrete-continuous events, where continuous components are used for the paving process and the discrete components are used to make decisions based on weather conditions. Both these components are connected in the general scenario of the model.

The model gives a generalized picture of the paving process using the model, where the paving and compaction speeds are taken into account as observed in Rosenthal neighbourhood development during road construction work. After the model development, the required data from this neighbourhood road construction work are used for model verification.

The model begins by creating a number of trucks to transport the asphalt, assuming a capacity of approximately 9 tons. After the arrival of the first truck element, the paving process begins with an initial weather check to determine whether or not to continue with paving. Once the paving is permitted to continue, depending on the weather conditions, two compactors are used for compaction—initially by the steel roller and then by the pneumatic roller.

The initial truckloads of material (in tons) is converted into corresponding length of cast pavement using a formula to calculate the paving length at the execute button, which is used in the latter stages for further calculation during simulation. When the total simulation time elapses, the comment section on the general scenario gives an output on the screen regarding total pavement progress and total paving hours utilized.

To achieve more accurate results from the distribution, the model is simulated for 100 runs and, in order to achieve more accurate output, statistics collection elements are used to obtain the mean value of paving length and paving time for a season. In addition, a statistics element is also used to check the compaction required time for each lay—to determine whether it meets the required paving criteria.

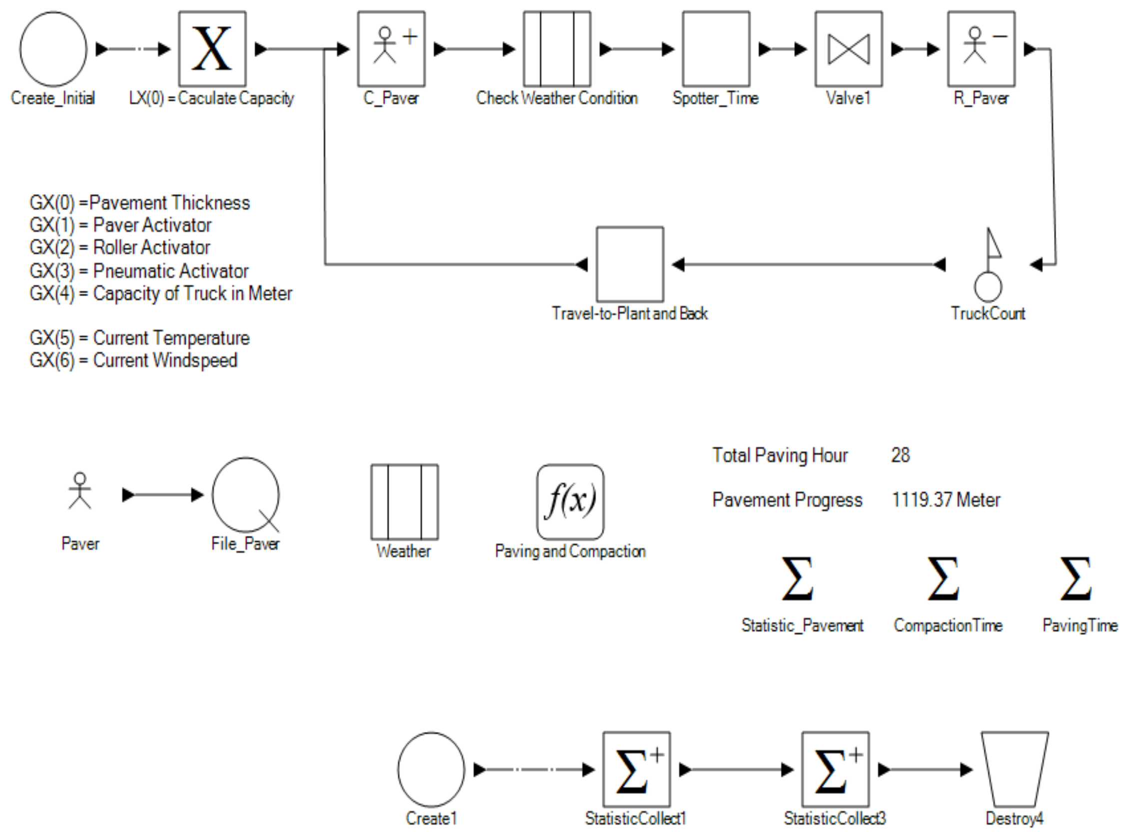


Figure 3-16: Paving process simulation

3.4.2 Paving process model

The paving process is included in the continuous portion of the model, which is activated from the general scenario through the valve; after paving a segment according to the capacity of the truck, the two compactors start working simultaneously. The speed of the compacters as observed at the construction site is included in the flow element as the rate. The compaction time per lay is calculated in compaction time statistics to determine if it satisfies the timing required.

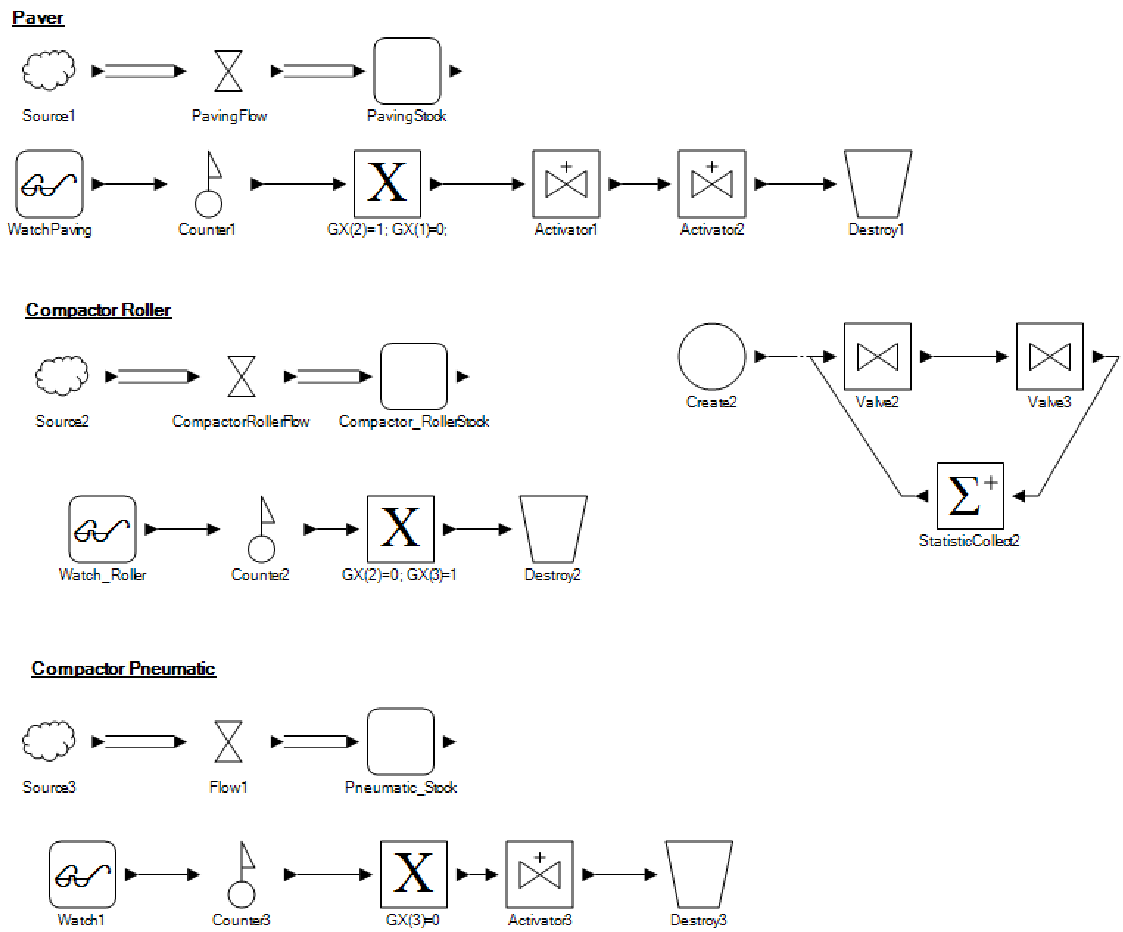


Figure 3-17: Paving detail

The paving rate and the compaction rate are calculated using the site observation. Paving equipment covers the length according to the length converted from truck capacity, while each compactor covers this length using four passes, back and forth, to complete proper compaction. Limited data is obtained during the site visit, which is summarized as follows:

Table 3-11: Data for calculating speed of equipment

Equipment Type	Distance Covered	Required time (Minutes) (distribution)
Paver	1 * Converted truck capacity (m)	Normal, mean 5.0034, Std Dev 1.4521
Steel Roller Compactor	4 * Converted truck capacity in (m)	Normal, mean 3, Std Dev 0.7071
Pneumatic Roller Compactor	4 * Converted truck capacity in (m)	Normal, mean 2.9167, Std Dev 0.7592

3.4.3 Weather condition

To match the weather limitation for paving, two composite elements are used in this model. Distributions for air temperature and wind speed each represent the distribution for temperature and wind speed data during daylight hours when no precipitation occurs (during the period between Septembers and November). The distributions are as follows:

1. Logistic distribution for air temperature with the following parameter:

Table 3-12: Distribution parameters for temperature

Distribution Parameters	Input Data	Theoretical Distribution
Location: 8.4113	Maximum: 33.5	Maximum: ∞
Scale: 5.1373	Mean: 8.4113	Mean: 8.4113
(temperature during daytime with no precipitation between September and November)	Minimum: −26.6	Minimum: −∞
	Std Deviation: 9.3180	Std Deviation: 9.3180

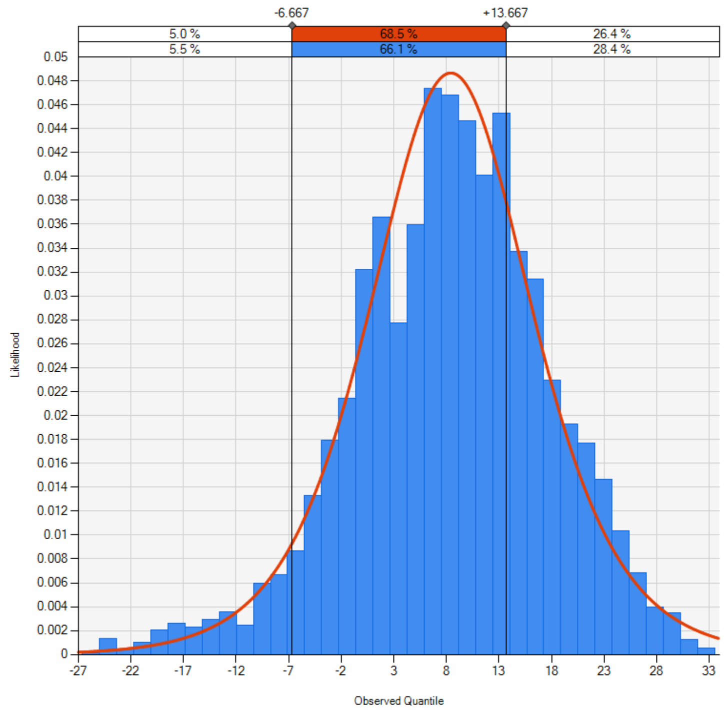


Figure 3-18: Distribution of air temperature during sunlight hour from September to November

2. Gamma distribution for wind speed with the following parameter:

Table 3-13: Distribution parameters for wind speed

Distribution Parameters	Input Data	Theoretical Distribution
Location: 5.0266	Maximum: 57	Maximum: ∞
Scale: 2.7127	Mean: 13.6358	Mean: 13.6358
(wind speed during daytime with no precipitation between September and November)	Minimum: 0	Minimum: −∞
	Std Deviation: 8.279	Std Deviation: 8.279

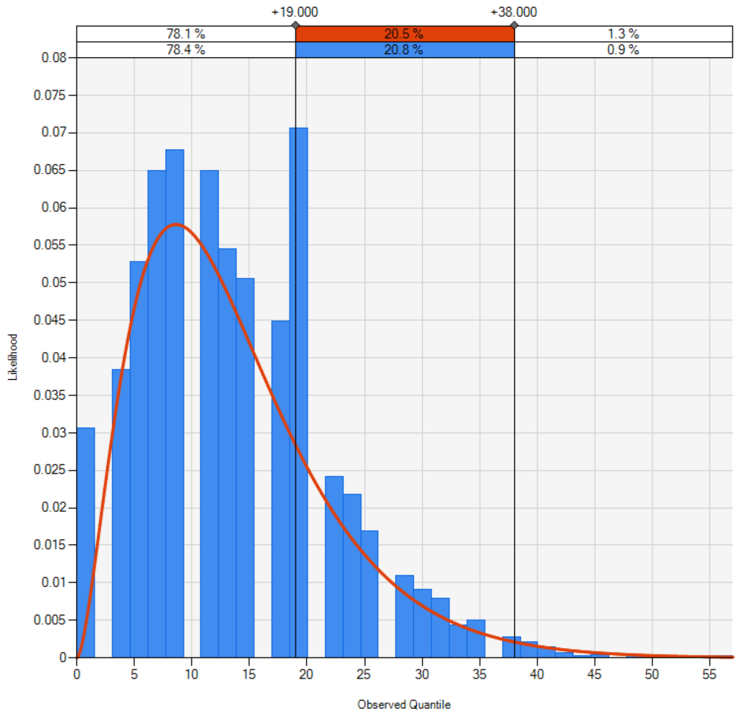
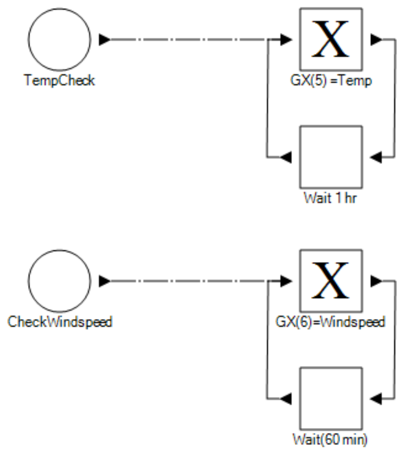


Figure 3-19: Distribution of wind speed during sunlight hour from September to November

3.4.3.1 Weather condition check

Weather conditions are checked in two composite parts, where one composite element takes air temperature and wind speed information, and sends the information as a global entity to the next composite element to determine the suitability of the weather to allow for paving. This weather sampling check is done on hourly intervals.



Temperature	Wind Speed
18.01	9.86
8.17	10.64
13.74	48.42
21.46	17.19
18.25	9.3
22.65	9.93
17.6	15.32
24.99	10.9
18.02	6.29
31.18	5.62
16.23	9.81
32.66	2.32
-4.36	26.01
15.68	6.94
6.75	6.95
18.04	22.66
19.73	8.84
35.44	13.73
12.15	12.16
21.07	3.36
9.39	0.68

Figure 3-20: Weather information simulation

While the other composite elements are used to check if the weather data is compatible with the weather limitation following the conditions derived from the City of Edmonton's weather limitation chart, for the basic model the weather check is done for 4°C air temperature condition and 50 mm pavement thickness. The paving entity is kept waiting for one hour in case the weather requirement is not met.

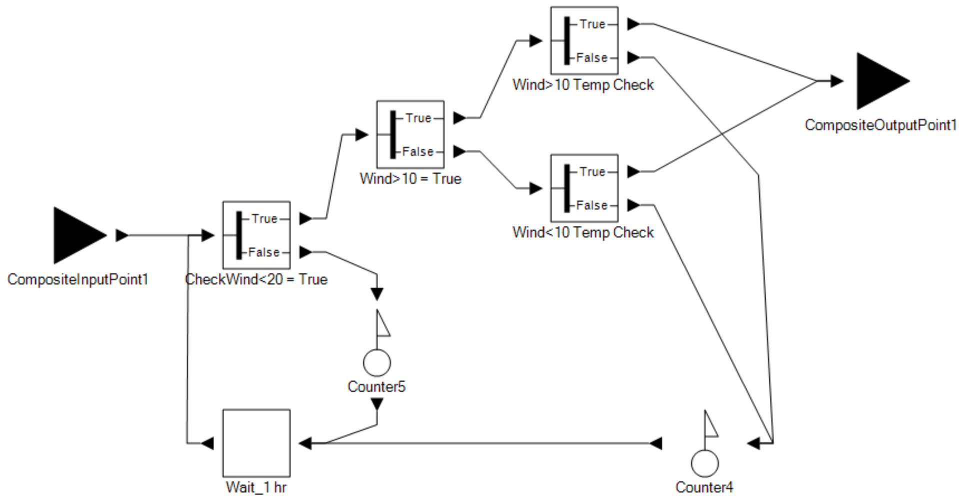


Figure 3-21: Weather limitation check

Two counters are used to determine the number of hours, which are summed up to reflect the total lost time due to work interruption during the entire simulation time or shoulder paving season.

3.5 Model verification

The verification of the model is carried out using the data of construction work for Rosenthal's neighbourhood road development work at different stages. Since total paving time in each stage at Rosenthal is considered as simulation time, and since, due to weather fluctuations, the paving time varies from simulation time, verification is done in terms of production rate (metres/minute) from the two outputs of the model—paving length and paving time. Table 3-14 shows a comparison of the production rates achieved actually and by the simulation in 100 runs using the changed limitations for varying pavement thicknesses according to the different development stages. For model verification, the limitation for 65 mm thick pavement is considered, in terms of temperature, in order to verify the results for 70 mm pavement thickness.

Table 3-14: Verifying model result with Case study area information

Dev't. Stage	Pave Thickness (mm)	Actual			Simulation			Dif-fer-ence
		Paving Time (min)	Length (m)	Produc-tion Rate (m/min)	Mean Paving Time (min)	Mean Paving Length (m)	Produc-tion Rate (m/min)	
1	70 & 75	1350	1150	0.85	1051	873	0.83	2%
4	70	1740	1580	0.91	1423	1300	0.88	3%
5	65	2160	1902	0.88	1679	1475	0.88	

The simulation results show some error in some cases, in terms of production rate, compared to the actual production rate. The difference may be due to the following limitations of the model:

1. The weather is simulated for the entire paving season; however, for paving work at the case study area on specific dates based on recent weather forecast the work interruption due to weather would be less resulting in a higher production rate.
2. The data regarding the crew size, in terms of equipment were not fixed during actual production, which might also resulted in higher productivity.

In addition to these, for the simplicity of the model, human error or mechanical failure is not considered, which may result in higher production rates in simulation. Moreover, the paving is considered to be linear development and the variation in road width is included considering an average effective width for each development stage.

3.6 Analyses with simulation results

Using simulation results for a 9 m wide road, comparisons among the following outputs are made:

1. For HMA, total paving time and length during a period from September to November using the weather limitation for 50 mm pavement, where minimum allowable temperature is 4°C.
2. For HMA, total paving time and length during a period from September to November setting the minimum allowable temperature as 0°C for 50 mm HMA pavement.
3. For HMA, total paving time and length during a period from September to November setting the minimum allowable temperature as −4°C for 50 mm HMA pavement.
4. For WMA, total paving time and length during a period from September to November, setting the minimum allowable temperature as 4°C for 50 mm pavement.

5. For WMA, total paving time and length during a period from September to November setting the minimum allowable temperature as 0°C for 50 mm WMA pavement.
6. For WMA, total paving time and length during a period from September to November setting the minimum allowable temperature as −4°C for 50 mm WMA pavement.

Moreover, the compaction time is also checked for each condition to determine whether it meets the compaction time requirement for each situation. The outputs of the simulation for 100 runs is a normal distribution of data, from which the mean values were used to determine the minimum and the maximum range at 95% confidence interval. In addition to that, the outputs are subsequently used to determine cost of equipment during idle time, total paving cost, and expected additional return on investment to make a financial analysis.

3.7 Financial analysis

Financial analysis of the existing weather limitation is employed using the simulation model to check important financial outputs. Using a whole season of paving from September to November for HMA and taking it as the run time for the simulation model, it is determined how much paving can be completed for a 9 m of road width and 50 mm thick pavement. The existing weather limitation for this thickness, as well as the weather distribution for this period, is used to determine the total paving hours and total paving length.

3.7.1 Cost benefit analysis

The cost of paving depends on (but not limited to) the following items, such as:

1. Material cost
2. Shipping and transportation costs
3. Manpower costs
4. Other costs:
    a. Operating expenses
    b. Insurance and taxes
    c. Interest cost
    d. Inflation
    e. Energy cost
    f. Other utilities

Transportation of material has been included with the cost of material for this study. The workforce or equipment directly involved in the construction job as crew has also been included with the cost of work force and equipment. However, no cost had been considered for other related costs like utilities, insurance, interest etc. or a project manager. Also, the variable work rate during holidays or overtime has also been excluded to keep the model simple.

While the equipment or workforce remains idle during a construction job due to low temperature condition, it can add cost to the work. This is considered as idle resource cost in this study, which is a part of the operating cost. The idle resource cost is determined after running the model, considering the rental cost of equipment only. In practice, the depreciation value of equipment is charged as part of the overhead cost while quoting for paving or any other construction work. Meanwhile, when there are interruptions in paving the equipment must sit idle. Since this equipment may be rented for a longer duration of construction than stipulated in an optimistic schedule forecast, the equipment rental cost must be borne by the owner for idle time. For this analysis, we consider the equipment rental cost as the idle resource cost only, considering the work force will have alternative jobs during the work interruption.

For an entire shoulder season, i.e., from September to November, the following outputs were used for further analysis:

T_{paving} = Duration of Paving (hr)

L_{paving} = Length of Paving (m)

These two outputs were used to obtain further information on idle resource cost, construction cost, and expected benefit (as revenue) using the following formula:

$$IRC = (T_{simulation} - T_{paving}) * ER \tag{3.11}$$

$$Cost_{HMA} = T_{paving} * (LR + ER) + L_{paving} * 1343.79 / 1000 * C_{HMA/T} \quad (3.12)$$

Or,

$$Cost_{WMA} = T_{paving} * (LR + ER) + L_{paving} * 1292.76 / 1000 * C_{WMA/T} \quad (3.13)$$

Where,

IRC = idle resource cost while using HMA or WMA

$T_{simulation}$ = Length of the entire shoulder season

T_{paving} = Duration of Paving based on simulation

$Cost_{HMA}$ = Direct cost from construction for paving with HMA

$Cost_{WMA}$ = Direct cost from construction for paving with WMA

ER =Hourly rate of equipment

LR =Hourly cost for workforce

$C_{HMA/T}$ =Cost per ton of HMA

$C_{WMA/T}$ =Cost per ton of WMA

The benefit of paving depends on (but not limited to) the following items, such as:

1. Income or revenue produced
2. Potential savings from:
    a. Investment or opportunity cost
    b. Interest
    c. Energy consumption
    d. Environmental performance

According to the sales trend of the neighbourhood development sector, the developing lots are sold when the corresponding access roads towards the lots are developed. This paper calculates the potential revenue to be generated from selling of the lots in a developing neighbourhood, using a correlation and included that as a monetary benefit of paving work. If paving can be done additionally in a season by changing paving standard, it ensures early return of revenue. Early return of revenue can reduce the cost of fund by reducing interest cost. Also, this increases the opportunity for the business owners to make new business investment with the additional revenue. However, this study includes only the income, i.e. the potential revenue from the lots while calculating benefit of paving.

According to some literatures, choosing WMA for paving, instead of HMA, reduces energy consumption at production plant and the paving process reduces environmental impact by reducing CO_2 emission. However, the scope of this study did not cover these potential benefits of WMA while conducting the cost benefit analysis.

From the case study data, using the paving hour data and calculating the approximate lot size in each stage, a linear correlation is developed between paving hours and accessible lot area using regression analysis in Microsoft Excel (details included in table 3-6). The output chart is shown in Figure 3-22:

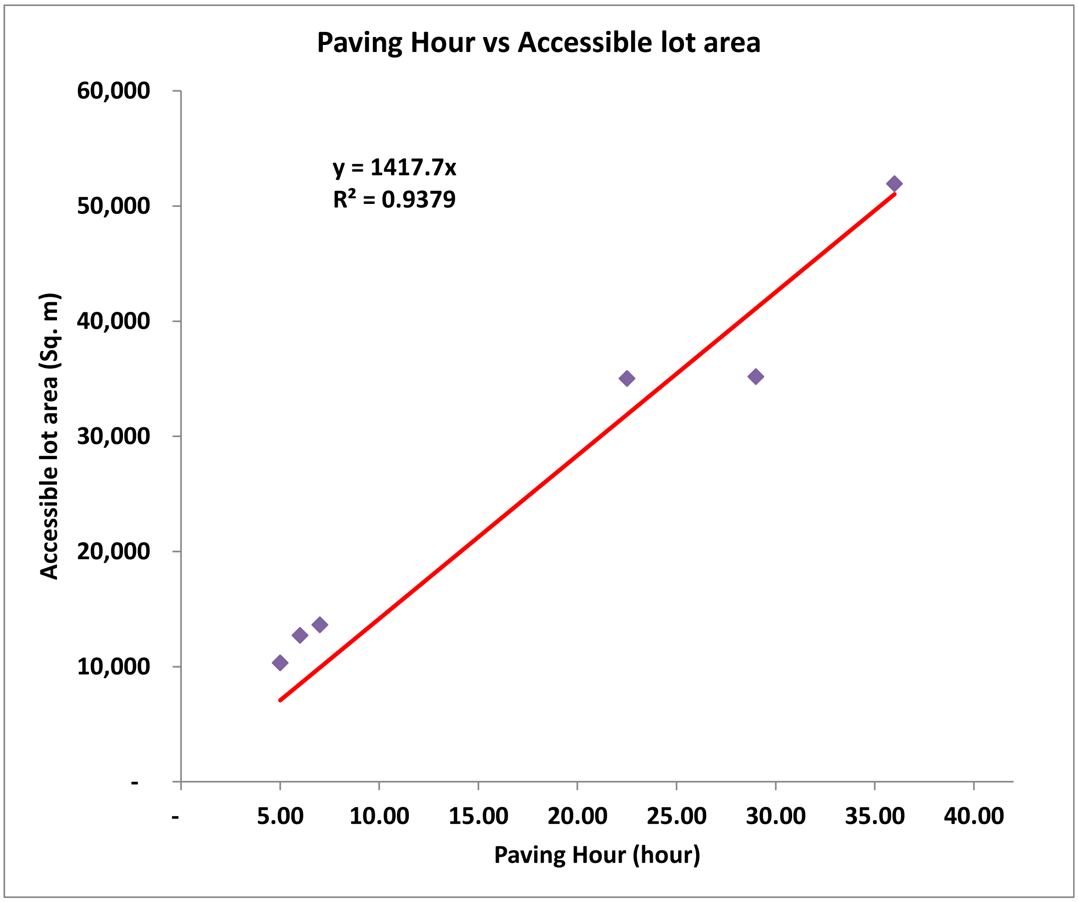


Figure 3-22: Correlation between paving hours and accessible lot area

In this analysis, in order to determine the expected revenue from the sellable lot area it is assumed that the price of land is \$350.00 m^2. The assumption of this price is made using an average of the assessed value of the lots at Rosenthal from the City of Edmonton's neighbourhood map. In addition, it was also assumed that, the developed roads providing accessibility to the total lot area of these neighbourhood is considered as the sellable area in this calculation which is expected to generate revenue for the developer.

For the outcomes of different scenarios from the simulation, these values are taken in order to obtain the total cost of paving and to determine cost-benefit ratio, such as:

$$Total\ Paving\ Cost_{HMA} = IRC + Cost_{HMA} \tag{3.14}$$

Or,

$$Total\ Paving\ Cost_{WMA} = IRC + Cost_{WMA} \tag{3.15}$$

For revenue, using the equation for each case of HMA and WMA derived from the curve in Figure 3-22,

$$Revenue = 1417.7 * T_{paving} * 350 \tag{3.16}$$

Thereafter cost-benefit analysis is carried out taking the ratio of cost to revenue for each scenario.

4 CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The simulation model is designed to simulate the paving process for the entire shoulder season, starting from September and extending to the end of November. The output of the model is used to carry out further financial analysis after 100 runs. For example, the resulting paving progress and achievable construction hours are checked using HMA under the current weather standard, as well as in a changed temperature limitation, where the temperature limitations are set to 0°C and −4°C, respectively. Similar temperature scenarios are also checked for WMA. The resulting outputs are used to make a comparative study of the financial performance of each scenario.

Each time the model terminates after having run for the maximum time, where the maximum time is set equal to the length of shoulder season (September to November), considering the daylight hours only, which is equivalent to approximately 963 hours. On a typical run for 50 mm HMA setting the temperature limitation at 4°C , the average paving duration with the existing standard for 50 mm thick pavement is found to be 675 hours, with a standard deviation of 15.5 hours and minimum and maximum of 638 and 708 hours, respectively. With the mean value and standard deviation, a 95% confidence interval has been generated for each scenario. Since the key focus of this study is to extend the paving season, in studying the weather analysis portion of the simulation model the paving process segment of the model is found to be in a simpler form considering only linear development work; this is sufficient to ensure that the model as a whole produces valid results.

4.2 Results from simulation

The simulation result are summarized in the following sections for the four different scenarios of the model.

4.2.1 Paving duration

The paving duration for paving with HMA using the temperature standard of 50 mm thick pavement (i.e. 4°C) gives a mean paving time of 675 hours, with a standard deviation of 15.52 hours. At 95% confidence interval the paving hour ranges from 672 to 678 hours for 4°C. On the other hand, if the temperature standard is lowered to 0°C, at 95% confidence interval, the paving hour ranges from 712 - 717 hours and at −4°C the paving hour ranges from 732 - 737 hours. The mean paving time increases by 40 hours and 60 hours, respectively for changing the limitation to 0°C and −4°C. This represents, at 95% confidence interval, if temperature limitation is changed from 4°C to 0°C construction hours will be increased by 6 - 7% and if temperature limitation is changed from 4°C to −4°C construction hours will be increased by 9 - 10%during the shoulder season.

While WMA is taken in the simulation at similar temperatures standards, at 95% confidence interval, it shows similar increase in construction hours, since the change in temperature limitation is the same. That is, for 0°C construction hours will be increased by 6 - 7% and for −4°C construction hours will be increased by 9 - 10% during the shoulder season. Figure 4-1 summarizes the increase in mean paving hour for changing the temperature limitation for 50 mm paving, i.e., 6% and 9% if the temperature limitation is changed to 0°C and −4°C, respectively, from 4°C.

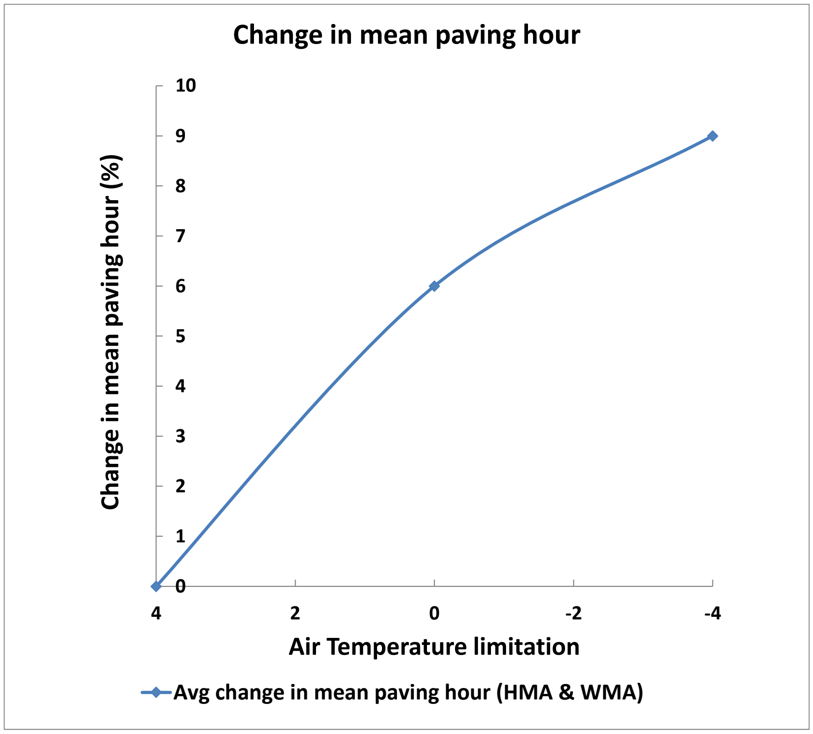


Figure 4-1: Change in mean paving hours (average) corresponding to change in temperature limitation

4.2.1.1 Idle equipment cost

In this analysis, the cost of idle resources is considered for hourly rental of equipment only. The idle resource cost has been calculated from the difference between shoulder season and paving hour considering it as the idle time and using the rental value for the respective idle time for each temperature condition for one set of paving equipment. The resulting dollar amount has been converted as the idle resource cost per meter of paving.

For HMA and WMA , at 95% confidence interval, when the temperature limitation is 4°C, the potential idle resource cost ranges from 5.25 - 5.46 $/m. At 0°C it ranges between 4.26 - 4.44 $/m and at −4°C it ranges between 3.76 - 3.97 $/m.

The average decrease in idle equipment cost for the mean paving hour associated with lowering the air temperature limitation for HMA and WMA is shown in Figure 4-2:

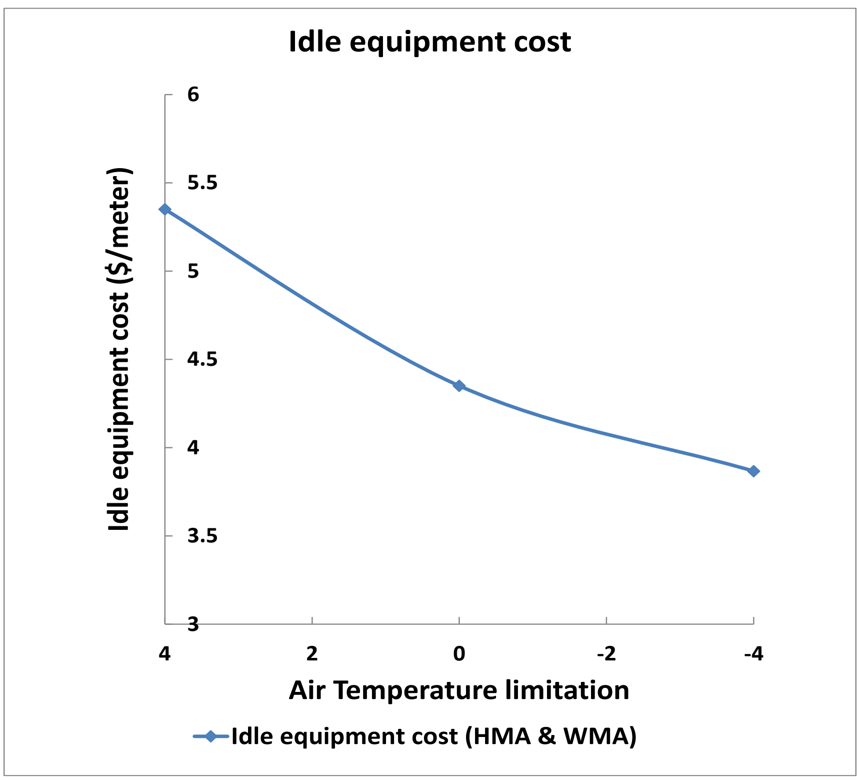


Figure 4-2: Average idle equipment costs under different air temperature limitation

4.2.2 Change in paving length for changing air temperature limitation

The potential paving work (in metre) for HMA paving, at 95% confidence interval, using the existing standard of 50 mm thickness ranges between 31,433 - 31,716 m for 9 m wide road. On the other hand, if the standard is relaxed to 0°C, at 95% confidence interval, the potential paving work (m) ranges between 33,292 - 33,533 m and if the standard is relaxed to −4°C, the paving work ranges between 34,236 – 34,491 m due to the increase in available paving hours.

On the other hand, if WMA is used instead of HMA with the same standard, at 95% confidence interval, using the existing standard the potential paving work ranges between 31,884 - 32,152 m. This is due to the fact that the lower specific gravity allows WMA to be paved to a greater length with similar carrying capacity per truck. Again, in the context of a changed paving standard in terms of temperature i.e., changing the standard from 4°C to 0°C, at 95% confidence interval, the potential paving work ranges between 33,829 - 34,077 m and if the standard is relaxed to −4°C, the paving work ranges between 34,866 - 35,118 m due to the increase in available paving hours. A comparison of these results in terms of percentage change in mean paving length is shown in Figure 4-3.

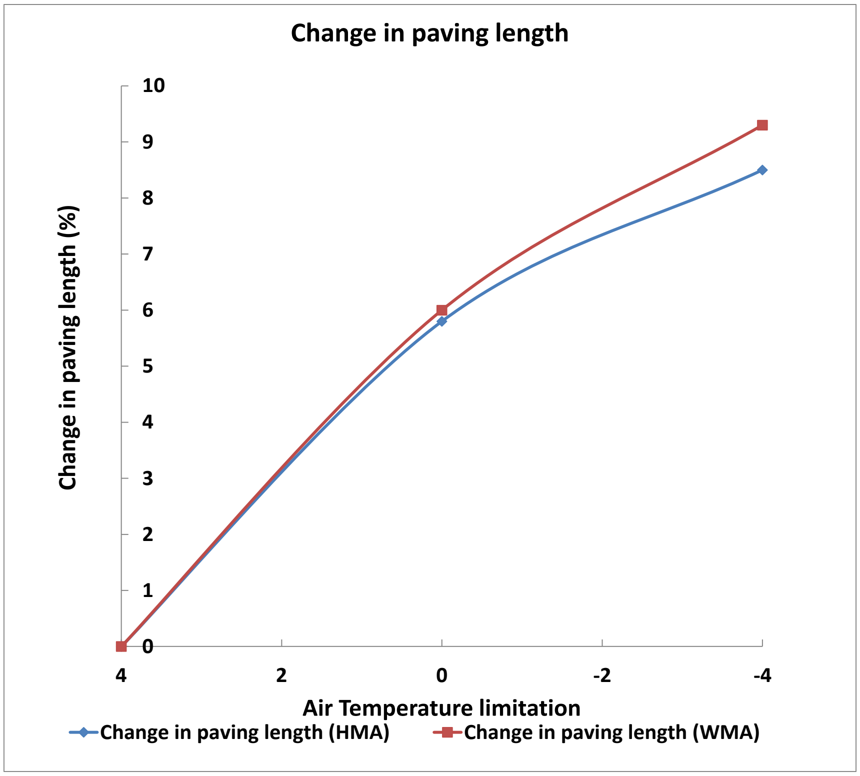


Figure 4-3: Change in paving work for changing the air temperature limitation

Based on the paving length under different temperature limitations, the average production rate for paving for HMA is found to be 46.8 m/hr, while the average paving rate for WMA is 47.6 m/hr. According to the literature review, WMA uses the same paving technique and has a lower specific gravity than HMA; hence, it is expected that paving can be performed faster if WMA is used.

4.3 Financial analysis

Financial analysis is performed to check the cost performance associated with changing the standards or using an alternative material. Comparisons are made in terms of paving cost per metre and expected revenue based on the simulation results and the cost-benefit analysis of each scenario.

4.3.1 Cost of paving per unit length

Cost of paving per unit length for this analysis is calculated by taking the sum of direct costs of construction and the idle resource costs for each condition. Direct cost is calculated taking the material cost of HMA or WMA (per ton) and hourly rate of equipment and workforce. Using the simulation results in terms of paving length and paving hour, total cost of paving and paving cost per unit length is calculated.

While comparing the unit cost per length of paving for HMA and WMA in each temperature limitations, WMA is found to have a higher cost per length, although the use of this material permits the completion of a greater amount of paving. Considering the costs included in this study, WMA, on an average, costs approximately 7% higher than HMA for each metre of paving.

Since relaxation in temperature limitation potentially enables to perform greater volume of paving, unit cost of paving gets lower for changing the temperature limitation from 4°C to 0°C or from 4°C to −4°C. At 95% confidence interval, for a shoulder season when the temperature limitation is 4°C, the potential unit cost of paving with HMA ranges between 146.9 – 147.1, on the other hand, unit cost of paving with WMA ranges between 157.2 – 157.4. Again, when the temperature limitation is 0°C, unit cost of paving with HMA ranges between 146.0 – 146.1, on the other hand, unit cost of paving with WMA ranges between

156.2 – 156.4 and when the temperature limitation is −4°C, unit cost of paving with HMA ranges between 145.5 – 145.6, on the other hand, unit cost of paving with WMA ranges between 155.8 – 155.9.

The potential mean paving cost per unit length for different paving temperature for HMA and WMA has been shown in figure 4-4:

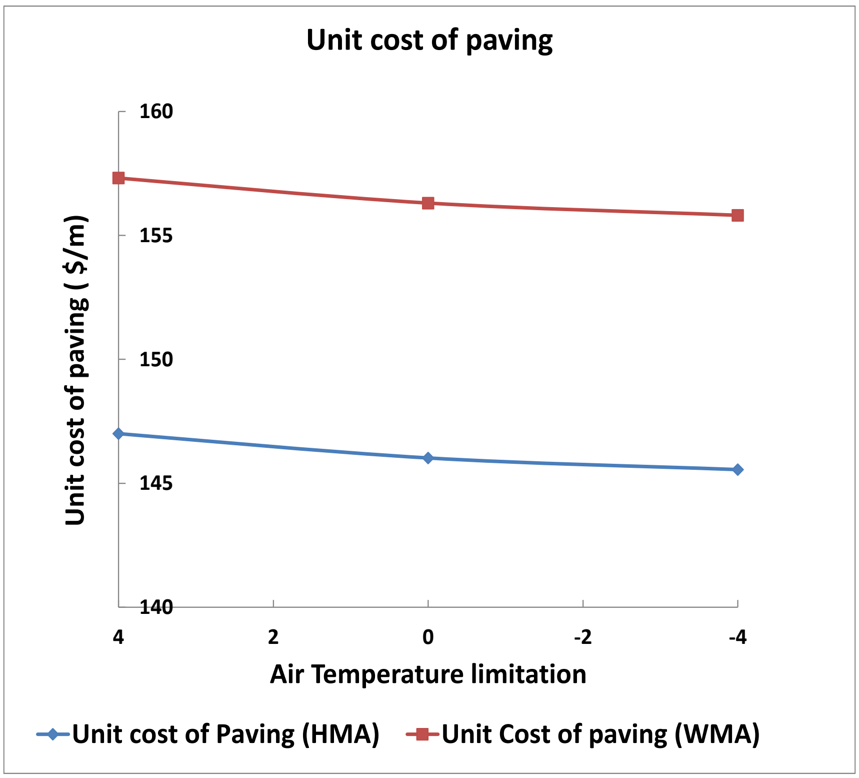


Figure 4-4: Unit cost of paving work at different air temperature limitations

The paving cost per unit length indicates that changing the weather limitations results in approximately a 1% decrease in cost per unit length of paving for both HMA and WMA. However, switching to WMA from HMA serves to increase the cost per unit length of paving by 7%. Hence, based on the cost structure of each of the construction elements as discussed in this study, changing the weather limitation gives a better cost result than switching from HMA to WMA.

4.3.2 Expected revenue

Equation (3.16) is used to calculate the expected revenue for each scenario of the simulation model, which relates the paving hours with revenue. At 95% confidence interval, the paving work with HMA during a shoulder season when the temperature limitation is 4°C, can potentially generate revenue between 333.22 – 336.24 million dollars; similarly, paving with WMA can generate between 332.64 – 335.44 million dollars. Again, when the temperature limitation is 0°C, paving with HMA can potentially generate revenue between 353.08 – 355.67 million dollars; similarly, paving with WMA can potentially generate between 352.91 – 355.50 million dollars and when the temperature limitation is −4°C, paving with HMA can potentially generate revenue between 363.09 – 365.83 million dollars; similarly, paving with WMA can potentially generate between 363.78 – 366.42 million dollars.

Changes in revenue are calculated by comparing the mean potential revenue when the air temperature limitation is either 0°C or −4°C with the expected revenue when the air temperature limitation is 4°C. The change in expected revenue is shown in Figure 4-5:

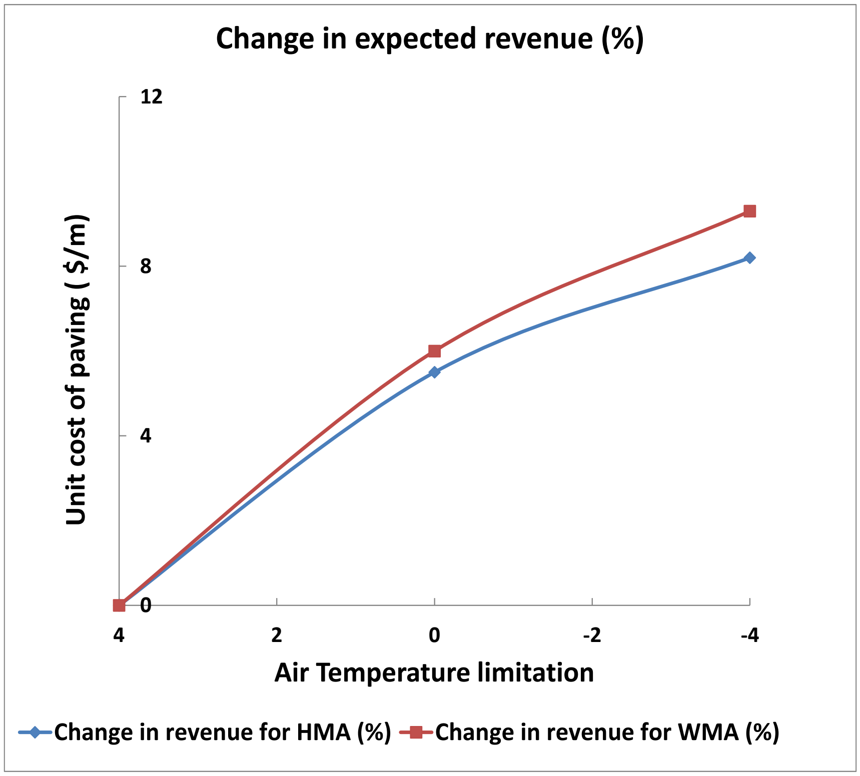


Figure 4-5: Change in expected revenue

The equation used to determine expected revenue is calculated based on the paving hours in a given season. However, in practice changing the product will not affect the paving hours; rather, additional construction hours may be achieved by changing the weather condition limitations. Hence, the equation used here cannot be used to compare expected revenues from different paving materials. This equation is derived from the observed data of construction work at different stages of a particular neighbourhood development, and it is noted that different neighbourhood data may generate different correlations between these two factors, i.e., paving time and expected revenue.

4.3.3 Cost-benefit ratio

A comparison was made to in terms of cost-benefit ratio (CBR), taking the total cost of paving and expected revenue into account. The cost-benefit ratio and the percentage change using the mean value for each temperature condition are summarized in the following figure:

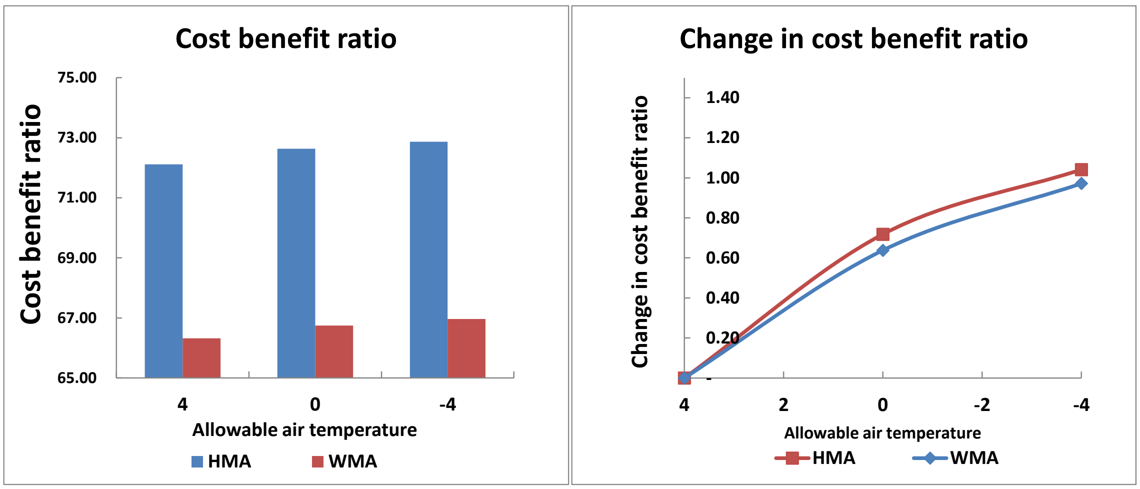


Figure 4-6: Cost benefit ratio for each scenario and its percentage change

Relaxing the weather limitation from 4°C to any lower temperature, the CBR increases. Using HMA generates a higher CBR than does the use of WMA. For example, when air temperature limitation is 4°C, at 95% confidence interval, the potential CBR for HMA is between 72.07 – 72.16, while for WMA it is between 66.29 – 66.35; similarly, when air temperature limitation is 0°C, the potential CBR for HMA is between 72.60 – 72.67, while for WMA it is between 66.72 – 66.77 and again at −4°C, the potential CBR for HMA is between 72.83 – 72.90, while for WMA it is between 66.94 – 66.99. .

A change in weather limitation for HMA increases its potential CBR only by around 0.72% at 0°C and by 1.04% at −4°C. Similarly, for WMA the CBR increases by only 0.64% at 0°C and by 0.97% at − 4°C. The large investment in paving work by the neighbourhood development industry still can generate a greater return on investment, although the percentage change of CBR associated with changing the temperature limitation is low. In addition, using WMA does not generate better results but rather reduces CBR, as can be observed from the results.

This indicates that changing the weather limitations for asphalt paving by changing either the temperature limitation or the product, or both, impacts the CBR, while changing the limitation brings more benefit to neighbourhood developers in terms of return on their investment. Early return on investment results in decreased capital costs for neighbourhood developers. For example, if we compare the expected revenue from using HMA at 4°C and 0°C, the additional potential revenue is around $20 million according to the results, which allows the developer the opportunity to invest in new lots or other development initiatives, which can generate additional return on investment. For example, if the additional revenue is be invested in government bonds, which ensures a minimal but secure return, a moderate return of 1.5% can be expected in every year (Bank of Canada, 2015). This will result in an additional amount of approximately $300,000 per year.

However, since the calculation does not encompass the entire development cost of a neighbourhood, the CBR described above may differ from the actual.

4.4 Conclusion

This research develops a basic framework of financial analysis of neighbourhood road development work, taking a small sample of observed data from a developing neighbourhood. These findings provide better understanding of the existing neighbourhood development practice as well as suggest alternative paving options and air temperature limitations.

5 CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This Chapter summarizes the contributions of this research work, limitations of the methodology, and gives recommendations for future work.

5.1 General conclusion

This research develops a methodology using the weather limitation, weather data and cost component of asphalt paving work to quantify the economic impact of the limitations on asphalt paving in colder regions such as greater Edmonton, Alberta. Quantification of the impact of the limitations is carried out based on analysis of data from a developing neighbourhood in Rosenthal, Edmonton, to verify the framework of paving rate used at the latter stage as an input for the financial model. The paving process described in the model is developed by observing the process at the construction site as well as comparing it with the literature review carried out. The other inputs, such as weather limitations and the weather data, are taken using a thorough analysis of weather limitations on asphalt in different jurisdictions and studying the weather information, such as temperature, wind speed, and precipitation taking an average for the years 2008-2014 for the entire year, especially for the shoulder season.

Based on the simulation results discussed in the previous chapter, the research draws the following conclusion:

1. Lowering temperature standard for HMA can potentially increase the paving hour in a given shoulder season, which results in increased paving works, reduced unit paving cost and increased potential revenue. The potential increase in cost benefit ratio for the investor may encourage in reduction in housing cost and thus increase housing affordability.

2. Switching to alternate paving material, such as WMA, doesn't improve the potential cost benefit ratio because of its higher cost, hence, this might not increase housing affordability.

5.2 Research contributions

This research contributes to the field of neighbourhood development through the quantification of weather limitation of asphalt on neighbourhood work. Specific contributions are summarized below:

- Helping neighbourhood developers and policy makers to have a thorough understanding of the financial impact of the weather limitation of asphalt making comparisons in terms of different weather limitation scenario and alternative paving options and providing useful insight about construction investment and its return with respect to the available options.

- Providing information based upon the weather analysis to develop a method by which to predict the available paving time in a season which will enable the neighbourhood developers to make a precise target of construction work for an entire season.

- The research lays a foundation for experimental research to evaluate the physical performance of HMA or WMA poured in lower temperature to determine their performance compliance or adaptability.

5.3 Research limitations

The limitations of this research are presented as follows:

- The weather data used for this analysis requires hourly data, since for construction work it is important to note the hourly weather change during paving construction. However, the Climate Canada database has the hourly data for only a few stations for a smaller range of years and the wind speed data is not entirely consistent. A longer range of precise data from the nearest station would help to make more accurate weather predictions.

- The paving work model developed in Simphony cannot accommodate the high level of work complexity characteristic of paving activities, but instead assumes a linear pavement development. However, it can serve as a basic framework.

- For developing the correlation between working hours and accessible lot area, only one neighbourhood under development is available for observation, and since the neighbourhood is under development Google Maps cannot provide precise information in terms of distance covered or lot area during paving. The limited information also may not reflect an accurate correlation between these two mentioned features.

- WMA is discussed as one of the alternative options for this study and is included in the financial analysis. However, its performance according to road design requirement and its comparison with hot mix asphalt (HMA) is not included in this study, since this is outside the scope of this research.

5.4 Recommendations for future studies

The developed methodology can be a foundation for future studies in different fields of development and planning, such as the following:

- Establishing a guideline for HMA or for alternative material, such as warm mix asphalt (WMA), for paving work in cold region, such as, greater Edmonton. The guideline should be comprehensively cover the asphalt performance under different weather parameters according to industry need.

- Experimental research needed to be performed at laboratory or fields to determine the physical performance of different types of asphalt poured for neighbourhood road development work.

- Life Cycle Cost Analysis (LCCA) can be performed based on the long-term physical performance in trial construction work to be constructed during lower temperature as well as conducting further study to precisely quantify environmental performance of HMA and WMA in terms of reduced fuel use or carbon emissions, as discussed in numerous other studies.

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APPENDIX (1)

1. Edmonton

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
35	7	5	Not permitted when rain or snow is imminent, or the surface to be paved is wet, icy, snow covered or frozen at any point within 150 mm of the surface, unless waived by the city.	ROADWAYS Design Standards Construction Specifications (2012) (Pg 3 of Section 02741) City of Edmonton Transportation
50	4	10		
65	3	10		
75	2	10		
85	2	15		
100	2	25		

2. St. Albert

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
All	2	None	Not permitted when rain or snow is imminent, or the surface to be paved is wet, icy, snow covered or frozen at any point within 150 mm of the surface, unless waived by the city or during excessive wind conditions	City of St. Albert Municipal Engineering Standards (April, 2013) (Pg 3 of Section 3) City of Edmonton Transportation

3. Spruce Grove

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
All	2	None	Not permitted if compaction cannot be completed during daylight hours and the road surface is not dry	Municipal Development Standards 2014 (Pg 38) City of Spruce Grove

4. Leduc

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
<40	7	10		The City of Leduc Minimum Engineering Design Standards (April, 2006) (Pg 3 of Section 3) & Engineering Design Standards Drawing, City of Leduc (Chart 3.16)
50	4	10		
75	2	10		
100	2	15		

5. Calgary

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
Less than 50	7	None	Not permitted unless rising than the specified temperatures according to thickness and the road surface is 5°C or higher and not permitted after sunset	Roads Construction 2012 Standard Specifications (Pg 76) Transportation Department, City of Calgary, ROADS
Greater than 50 and less than 70	4			
Greater than 70	2			

6. Saskatoon

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
All	None	None	Previous requirement was 2°C for any thickness. The waived this clause in the recent version published in 2015.	Page 10 of Section 04015 of https://www.saskatoon.ca/sites/default/files/documents/transportation-utilities/construction-design/construction-services/04015_jan02_2015.pdf

7. Regina

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
All	2	None		Page 1 of Section 2350 of https://www.regina.ca/opencms/export/sites/regina.ca/residents/roads-traffic/.media/pdf/placement_of_asphaltic_concrete_2350.pdf

8. Alberta

Paving thickness (mm)	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
All	5	None	Moisture content is 1.0% or less as measured by any individual test.	Standard Specifications for Highway Construction (2010) (Pg 8 of Specification 3.5 Asphalt Stabilized Base Course) Alberta Transportation

9. Ontario

Course type	Min temp (°C)	Max corresponding wind speed (km/h)	Other	Source
Binder	2	None		Ontario Provincial Standard Specification (November 2012) (Pg 11 of Construction Specification for Hot Mix Asphalt) Alberta Transportation
Surface	7	None	For SMA and Superpave 12.5 FC2, the air temperature at the surface of the road shall be at least 12°C.	

Note: No asphalt paving work is allowed to be performed in any of the jurisdictions listed above during any amount of rain or snowfall.

APPENDIX (2)

Paving thickness: 50 mm

Road width: 9 m

Duration of shoulder season (daylight hour): 963.17 hours

Cost components:

Cost of material, HMA: 87 ($/T)

Cost of material, WMA: 95 ($/T)

Cost of manpower: 569 ($/hr)

Cost of equipment: 588 ($/hr)

<u>For HMA</u>

Temp Limitation (°C)	Simulation result							
	Paving hour				Paving work			
	Mean Paving Hour (Hr)	Std Deviation (Hr)	at 95% Confidence interval		Mean Paving Length (m)	Std Dev (m)	at 95% Confidence interval	
			Min Paving (Hr)	Max Paving (Hr)			Min Paving (m)	Max Paving (m)
4	675	15.52	672	678	31,574	722.25	31,433	31,716
0	714	13.30	712	717	33,412	616.00	33,292	33,533
-4	735	14.06	732	737	34,364	650.48	34,236	34,491

For WMA

Temp Limitation (°C)	Simulation result							
	Paving hour				Paving work			
	Mean Paving Hour (Hr)	Std Deviation (Hr)	at 95% Confidence interval		Mean Paving Length (m)	Std Dev (m)	at 95% Confidence interval	
			Min Paving (Hr)	Max Paving (Hr)			Min Paving (m)	Max Paving (m)
4	673	14.38	670	676	32,018	682.65	31,884	32,152
0	714	13.33	711	716	33,953	631.92	33,829	34,077
-4	736	13.59	733	738	34,992	643.42	34,866	35,118