Bridge Management System Development for Municipal-Sized Inventories in Western Canada

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ABSTRACT

Reid Crowther and a group of Western Canadian cities have collaborated in the development of a Bridge Management System (BMS) software application appropriate for municipal size inventories. Database functions are separated into Static (inventory) and Dynamic (visual inspection) modules that are suitable for bridge and culvert structures. The database modules are structured to include both essential and non-essential categories. A numerical 9-point visual condition rating system is used for inspection data. Data records can be maintained for both representative and worst condition of each inspected element. Analysis routines are provided that i) compute structure rating values, ii) establish networkwide management strategy options and iii) facilitate detailed site based present value computations. The Structure Ratings routines compute ratings for each structure site in each of nine Basic Rating categories from which an overall site "Sufficiency Rating" is computed. Present value based network analysis routines facilitate the prediction of a least cost long-term management strategy for each structure in the inventory. The least cost strategy prediction is based on an evaluation of estimated whole life costs associated with managing inventory structures by one of five so-called fundamental strategies. A 'What If' analysis feature is provided as a means to address various simplifying factors incorporated into the network analysis. The detailed site analysis routines facilitate detailed life cycle cost analysis of management options for User selected sites.

INTRODUCTION AND BACKGROUND

A group of six Western Canadian municipalities have collaborated with Reid Crowther in the development of a Bridge Management System (BMS) software application. The cities, which include Calgary, Edmonton, Lethbridge, Regina, Saskatoon and Winnipeg (see Figure 1 for location map), have populations ranging from approximately 70,000 to 800,000 inhabitants. Inventory values in this group, based upon estimated 'as new' structure replacement costs, range from about $50 million (CAN) to $800 million (CAN). The inventory sizes range from approximately 35 to 450 structures.

A primary objective of the collaboration was the collective development or selection of a BMS database and analysis software tool, to facilitate cost effective management for safe and serviceable bridges, appropriate for municipal size inventories.

Initiation of software development was preceded by BMS specification preparation and evaluation stages. Specific needs, wants and preferences of each participant were established from which a single base specification was developed. Although there was inherent in each of the participant's existing bridge management

Figure 1: City location map.

practices a degree of similarity, consistency did not exist in all aspects of these practices. Therefore the single base specification that was developed incorporated those needs and wants common to all participants. To address unique preferences of different members of the group, a specification proviso was included that required the software architecture be sufficiently flexible/modular to accommodate customization by individual Users to incorporate features absent from the base specification. A simple schematic depicting the essence of the specification is shown in Figure 2. AASHTO's *Guidelines for Bridge Management Systems* (*1*) was considered during the specification development process.

Upon completion of the specification an evaluation of two commercially available BMS software packages was undertaken. Subsequent to this evaluation process the partnership made the decision to proceed with the development of a customized BMS database and analysis software application.

The remainder of this paper presents an overview of salient characteristics regarding the database and analysis aspects of the development.

DATABASE CHARACTERISTICS

Introduction

The primary database functions are separated into a so-called Static Database Module and a so-called Dynamic Database Module.

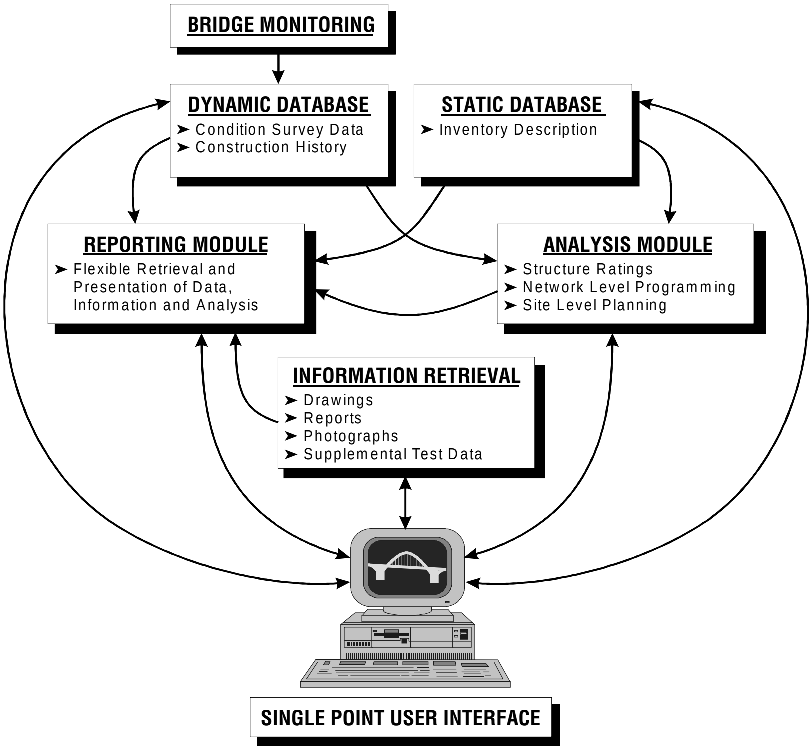

Figure 2: BMS software application specification schematic.

The Static Module organizes structure site data related to the infrequently changing or unchanging features of a site. This type of data is commonly referred to as Inventory data. Over 100 data fields are provided for each site. Portions of these fields are identified as so-called designated fields and *must* be complete in order for the Analysis and Inspection modules to function properly.

The Dynamic Module organizes inspection data on a site by site basis. Inspection data is limited to visual condition ratings. The number of data fields for each site depends upon the size and characteristics of the site, and to an extent upon User selected data preferences for each site. A portion of the data fields are identified as so-called designated fields and *must* be complete in order for the program Analysis routines to function properly.

Database manipulation (i.e., data entry, sorting, filtering, reporting) is consistent with common methods available in Windows® configured database software products.

Static Database

The Static Database Module facilitates the storage and viewing of inventory data for bridge and culvert structures. Inventory data includes those features of a site that are essentially unchanging (or infrequently changing, like a deck joint type for example).

The software interface organizes data on a site by site basis into sub-categories as presented in Table 1 and Table 2.

Table 1: Static Database Sub-Categories, Bridges

Data Sub-Category	Description of Data Contained
General	Identification, Location, Type of Service
Ratings	Traffic Volume & Type, Design Vehicle, Load Rating Information
Superstructure	Geometry, System Type, Material Descriptions (Excluding the Deck)
Joints/Bearings	Joint and Bearing Descriptions, Types and Locations
Decks	Geometric and Material Descriptions of Deck and Wearing Surface Systems
Substructure	Description of Pier and Abutment Systems
Age/History	Dates & Details of Construction and Rehabilitations, Names of Designer and Builder
Miscellaneous	Sidewalk Descriptions, Median Descriptions, Clearance Information, Record of Utilities Carried on Structure
Approaches/Slopes	Approach Slab and Slope Protection Descriptions
User	User Definable Fields

Table 2: Static Database Sub-Categories, Culverts (Buried Arches)

Data Sub-Category	Description of Data Contained
General	Identification, Location, Type of Service
Ratings	Traffic Volume and Type, Design Vehicle, Load Rating Information
Cells	Geometry, System Type and Material Descriptions of Culvert Cells
Roof	Geometry and Material Descriptions of Fill Over and any Wearing Surface Systems
Substructure	Headwall System and Exposed Areas
Age/History	Dates & Details of Construction and Rehabilitations, Names of Designer and Builder
Miscellaneous	Sidewalk Descriptions, Median Descriptions, Clearance Information, Record of Utilities Carried over/in Structure
Approaches/Slopes	Approach Slab and Slope Protection Descriptions
User	User Definable Fields

Each database sub-category contains both so-called designated and non-designated data fields. The designated fields *must* be complete for each structure site prior to initiating the Inspection and Analysis routines of the software. Inspection and Analysis modules rely on complete designated Inventory data fields in order to function correctly.

Non-designated data fields are not essential in the development of Inspection forms. Nor are data from these fields required for calculations undertaken within the Analysis module. As uch, data storage in these fields is optional and at the discretion of the User. The non-designated fields are considered to include useful information about a site. Inventory database completeness through the use of these fields should provide Users with the means to make bridge management decisions not otherwise obtainable from the Analysis and Inspection modules.

Dynamic Database

The Dynamic Database Module facilitates the storage and viewing of visual inspection data for bridge and culvert structures. The visual inspection rating system employed is numerical with a range of 1 to 9. Nine represents very good or new condition and 1 indicates a component is on the verge of failure. The numeric rating system is based most closely upon the Alberta Transportation & Utilities approach (*2*).

The objective of the Inspection process for which the database was structured is to record i) the average or representative condition of each inspected component, as well as to identify ii) the worst condition existing on any portion of the component. To obtain condition rating data consistent with this approach, ratings for each inspected component can be entered into the database in either one of the following two formats:

1. by recording the percent extent applicable to each one, or more, rating values (e.g., 70% of a wearing surface may register a 7 rating and 30% could rate as a 4),

or alternatively

2. by recording as a single average or representative rating, with the lowest rating also noted (e.g. the average or representative rating of a wearing surface may be assigned a 6, with a 4 noted as the lowest observed rating.)

Inspection forms for data entries are organized based on a standard group of inspection categories (refer to Table 3 and Table 4). Forms for each site are customized within the limits of the standard categories to suit the specific size and nature of each site, based upon the site description stored in the Static (inventory) database. Program interface form design is configured along the lines of a “paper inspection form.”

Each sub-category included on an Inspection form contains a series of “standard” and “non-standard” inspection fields. Also included is a single Overall Rating field for each sub-category. Standard inspection fields are default inspection fields comprising the minimum recommended features requiring regular inspection in a given inspection sub-category. Non-standard fields are additional to the standard fields. Non-standard fields are

Table 3: Dynamic Database Inspection Form Standard Categories, Bridges

Inspection Category	**Inspection Sub-Category**	**Description of Data Fields Contained**
General	General	Summary of Key Inventory Characteristics brought forward from Inventory Database
Utilities/Signage	Utilities/Signage	Condition of Utilities and Signage at the site
Approach	Approach	Condition of each bridge Approach
Superstructure:	Deck	Condition of Deck
	Joints	Condition of each Deck Joint
	Span (Truss or Girders)	Condition of each type of Span
	Bearings	Condition of each line of Bearings
Substructure:	Abutments	Condition of each Abutment
	Piers	Condition of each Pier
	Slopes	Condition of each Slope
Maintenance Recommendations	Maintenance Recommendations	Summary of Recommended Maintenance as noted by Inspector

Table 4: Dynamic Database Inspection Form Standard Categories, Culverts

Inspection Category	**Inspection Sub-Category**	**Description of Data Fields Contained**
General	General	Summary of Key Inventory Characteristics brought forward from Inventory Database
Utilities/Signage	Utilities/Signage	Condition of Utilities and Signage at the site
Approach	Approach	Condition of each Culvert Approach
Superstructure:	Roof	Condition of Culvert Roof
	Cells	Condition of each Culvert Cell
Substructure:	Culvert Ends	Condition of each Culvert End
	Slopes	Condition of each Slope
Maintenance Recommendations	Maintenance Recommendations	Summary of Recommended Maintenance as noted by Inspector

User defined. The non-standard fields allow Users to customize inspection forms to suit unique needs or preferences.

Following the same data integrity principles incorporated into the Static Database design, the Overall Rating fields are considered as designated fields that *must* be completed for each inspection. Completion of these designated fields is required in order for the Network Analysis routines to operate. The Overall Rating fields can be populated by either one of two methods, at the discretion of the User, as follows:

1. An inspector enters data into all standard inspection fields and in so doing initiates an automatic calculation of the Overall Rating based upon a predefined relationship that is built into the software,

or alternatively,

2. An inspector can input directly a single Overall Rating for the sub-category, ignoring data entry into all of the standard inspection fields, or over-riding the automatically calculated Overall Rating that is calculated whenever all standard data fields are populated.

An example of the three data field types (i.e., designated, standard and non-standard), tentatively established for the "Deck" inspection sub-category, is presented in Table 5.

Non-designated data fields are not required for calculations undertaken within the Analysis module. As such, data stored in these fields is optional and at the discretion of the User. The non-designated fields are considered to provide useful information about a site. Dynamic database completeness through the use of these fields should provide Users the ability to make more informed bridge management decisions.

Table 5: Standard and Designated Inspection Fields for Deck Sub-Category

Field Name	**Designated**	**Standard**	**Non-Standard**
Overall Deck Rating	Yes		
Wearing Surface Condition		Yes	
Wearing Surface Rideability			Yes
Deck Drainage			Yes
Median Condition			Yes
Deck Underside Condition		Yes	
Sidewalk Condition			Yes
Curb Condition		Yes	
Traffic Barrier Condition		Yes	
Pedestrian Rail Condition			Yes

ANALYSIS FUNCTIONS

Introduction

The Analysis Module facilitates three distinct operations as follows:

- Structure Ratings Determination
- Network Analysis
- Detailed Site Analysis

More specifically analysis routines have been developed which i) compute site by site structure rating values, ii) establish networkwide management strategy options and iii) facilitate detailed present value computations for developing structure work plans.

The Static database (inventory) module and the Dynamic database (inspection) module contain the majority of the data required for analysis operations. Additional assumptions and settings are confirmed with the User when initiating an analysis.

Structure Ratings

The Structure Ratings routines compute a rating in percentage for each structure site in each of the following Basic Rating categories:

1. Superstructure Condition
2. Substructure Condition
3. Approach Condition
4. Slope and Channel Condition
5. Deck Surface Condition (Rideability)
6. Structural Capacity
7. Road Width
8. Structure Clearances
9. ADT Importance

The first five of these ratings are computed based directly upon condition survey data stored in the dynamic database. The remaining ratings are computed based upon typically unchanging (or infrequently changing) characteristics of a site which are stored in the static database. A tenth rating is also computed which is a weighted combination of the nine Basic Ratings. This tenth rating is commonly referred to as a “Sufficiency Rating.”

Weighting factors, as well as the relationships defining the Basic Ratings, as specified by different organizations vary [(e.g., the FHWA’s *Recording and Coding Guide for Structure Inventory and Appraisal of the Nation’s Bridges* (*3*) or AT&U’s *Bridge Inspection and Maintenance System Inspection Manual* (*2*))]. The Basic Rating values are computed with simple relationships built into the software application. The weighting factors for computing the Sufficiency Ratings are specified by the User during program operation.

Network Analysis

Network analysis routines facilitate the prediction of a least cost long-term management strategy for each structure in the inventory.

The least cost strategy prediction made by the program is based upon an evaluation of estimated whole life costs associated with managing inventory structures by one of five so-called fundamental strategies. The five fundamental strategies have been established to represent a broad range of distinct management approaches that an agency could apply to structures within its inventory.

The five strategies can be characterized either in a descriptive manner or numerically, in terms of an estimated condition rating level at which rehabilitation work would likely be initiated, as presented below:

1. *Do Nothing Management*—perform only the most basic activities on an as needed basis, such as accident repairs and pothole repairs, which would be considered essential in order to keep structures safe and operational while in service, but otherwise invest no money in structure maintenance. Allow bridge and culvert components to deteriorate until safety is compromised or functional needs are no longer met, resulting in the need for component and/or structure replacements. Estimated Condition Rating at Work Initiation = 2.5.
2. *Reactive Management*—perform basic annual activities, such as accident repairs and pothole repairs, and undertake major repairs and rehabilitation only when the need is visually apparent, i.e., after significant deterioration processes have resulted in structure damage. Normally only one to three cycles of reactive repairs will occur after which structure component replacement is more cost effective in lieu of repairs. Estimated Condition Rating at Work Initiation = 3.5.
3. *Proactive Management*—perform basic annual routine maintenance, including accident repairs, deck washing, pothole repairs, and deck seal replacements, and undertake major repairs and rehabilitation in a planned approach, performing major rehabilitation on a scheduled basis normally before need is clearly apparent. Undertake several cycles of repairs until functional obsolescence or economic factors warrant allowing structure deterioration until safety is compromised and structure replacements are required. Estimated Condition Rating at Work Initiation = 5.0.
4. *Proactive* '+' *Management*—perform more than basic annual routine maintenance, including accident repairs, deck washing, pothole repairs, and deck seal replacements, and undertake major repair and rehabilitation in conjunction with major maintenance of structure protection systems (e.g., paint, membranes, seals) and deck wearing systems in a planned approach, performing these major maintenance/repair/rehabilitation activities on a scheduled basis normally before need is visually apparent. Undertake several cycles of repairs until functional obsolescence or other factors warrant structure replacements. Estimated Condition Rating at Work Initiation = 6.5.
5. *Like New Management*—perform constant routine maintenance, including accident repairs, deck washing, pothole repairs, and deck seal replacements, and undertake major maintenance activities on the bridge protection systems (e.g., paint, membranes, seals) and deck wearing systems in an ongoing process, well before need is

visually apparent in order to maintain bridges in an as new condition and if possible avoid the need for major repair and rehabilitation. Structures remain in service until functional obsolescence or other factors warrant structure replacements. Estimated Condition Rating at Work Initiation = 7.5.

Table 6 presents a succinct comparison of these five fundamental strategies in terms of general maintenance and rehabilitation activities.

The *5 Fundamental Strategies* analysis process is site specific and capital cost based only, with site expenditure estimates driven by condition predictions only. The objectives of this networkwide analysis are i) to predict an appropriate long term management strategy for structures in the inventory, and ii) to estimate an approximate funding demand associated with each of the five different management strategies.

The analysis does not take into account so called ‘user costs’ (e.g., cost to society in the form of repair or accident costs due to potholes on a road, costs associated with reduced traffic flow during repairs, etc.). Nor does analysis consider coordination with other potentially related works (e.g., utility or roadwork in the vicinity of a bridge site) that should normally be considered as structure work plans are finalized. Functional obsolescence considerations and structure capacity improvements are not directly considered. Finally, the analysis does not take constrained funding into account directly—the networkwide analysis is completed assuming unlimited funding is available. However, consideration can be given to each of these ‘other’ factors in an indirect manner, through a ‘What If’ alternative strategy selection feature that is provided.

The program analysis routines facilitate development of life cycle cost based management strategies for each structure site in the inventory, following the steps outlined on the next two pages.

Table 6: Fundamental Management Strategies, Activities Matrix

Management Strategy	**Maintenance & Rehabilitation Activities**							**Estimated Condition Rating At Work Initiation**
	Safety Repairs	Routine Maintenance			Major Rehabilitation		Protection System Maintenance	
		Basic	Basic +	Like New	Reactive	Proactive		
Do Nothing	√							***2.5***
Reactive	√	√			√			***3.5***
Proactive	√		√			√		***5.0***
Proactive ‘+’	√		√			√	√	***6.5***
Like New	√			√		√	√	***7.5***

STEP A. The program establishes the current Overall Rating Value (ORV) of each primary element of each site. The User confirms the minimum tolerable condition rating below which the program will assume that a maintenance and rehabilitation action is required.

The primary elements for a bridge structure are considered to be i) the Deck, ii) the Span (which consists of girders or trusses that make up the superstructure, excluding the deck), and iii) the Substructure consisting of the abutments and the piers.

The primary elements for a culvert or arch structure are considered to be i) the Culvert Cells and ii) the Culvert Ends.

The Overall Rating Value (ORV) is a single condition rating value associated with each of the primary elements. The most current ORV of each element is automatically retrieved from the Dynamic database for use in the analysis.

The program analysis routines that predict management expenditures into the future assume these expenditure events occur when projected condition rating levels at a site fall to a preset *Work Initiation Condition Rating* level. Users can either accept the preset program default values for these limiting Condition Rating settings (as per Table 6) or modify the default values prior to initiating an analysis.

STEP B. The User confirms the Deterioration Equations that will be used by the program to predict the time dependent performance of each primary element of each site.

The estimated future performance of each type of primary element of a site is predicted with a bilinear deterioration relationship that relates the ORV with time.

Default deterioration equations are provided which the User can modify.

The deterioration equations confirmed by the User are further modified within the analysis on a site by site basis by so-called influencer coefficients. These coefficients are automatically determined in the analysis based upon the inventory database description of a site. The values of the coefficients reflect site specific characteristics that are considered to influence the rate of deterioration of the primary elements of a structure.

STEP C. The User confirms the analysis period and discount rate, assumed unit repair costs, and average annual maintenance costs for use in the present value analysis calculations.

The five fundamental strategies network analysis is based upon present worth analysis methodology. This methodology is widely used and details of its use are reported upon in other references [e.g., (*4*) and (*5*)].

Several variables must be predefined for successful execution of the analysis, as follows:

i) the *Analysis Period* (i.e., the time over which a long term management plan will be considered),
ii) the *Discount Rate* (i.e., average cost of borrowing money in percent assumed over the analysis period),
iii) the cost of *Discrete Expenditures* (i.e., the cost of major rehabilitation/replacement/ repairs),
iv) the cost of *Annual Expenditures* (i.e., the cost of annual maintenance), and
v) *Salvage Value* of a structure at the end of an analysis period.

Default values for the *Analysis Period* and *Discount Rate* are provided which the User can modify.

Discrete Expenditures representing the cost of major rehabilitation events are triggered when the predicted deterioration level for a primary element reaches a preset value (see STEP A, above). The costs of these rehabilitation expenditures are computed as the product of a preset unit cost of repair, and a defining area of the site. Default unit repair cost values are provided which Users are required to review and adjust as required.

Annual Expenditures represent the cost of annual reoccurring maintenance/ inspection activities. In the analysis these costs are computed to equal a set percentage of a site replacement cost. Default percentage maintenance values are provided which Users are required to review and adjust as required.

The *Salvage Value* assumed remaining in a site at the end of the analysis period is calculated by the program as the sum of the prorated replacement costs of each primary element. A prorated element replacement cost is calculated as the product of the new component replacement cost and the ratio of the component ORV to 9 (9 being like new condition).

STEP D. The User initiates the network analysis and accesses results of the analysis.

Network analysis can be initiated once a User is satisfied that all settings as described in STEPS A to C are suitable.

The results of the analysis are stored within the database and can be accessed for viewing and/or performing further 'What If' adjustments (see STEP E).

Network analysis results present the estimated whole life cost for managing each structure in an inventory following each one of the five fundamental strategies. Year by year funding demand predictions for each strategy are presented.

The estimated whole life cost for managing an entire inventory following each one of the fundamental strategies is also presented. Since the least costly (*Minimum Whole Life Cost* based) strategy can vary for different sites in an inventory, a sixth networkwide strategy is also developed which consists of a blending of the least costly of the five fundamental strategies for each site.

STEP E. The User initiates 'What If' adjustments to develop bridge management strategies other than the *Minimum Whole Life Cost* strategy.

The *Minimum Whole Life Cost* strategy predicted by the network analysis may be considered to be the best strategy for an inventory in the long term so long as management funding constraints do not exist and/or so long as non-financial factors are not requiring consideration (e.g., road user costs, political factors, project coordination, funding program conditions, etc.).

To allow for consideration of the impact of constraining factors the User is allowed to manipulate the *Minimum Whole Life Cost* strategy to develop *Alternative* inventorywide strategies. The *Alternative* strategies are built through the selection of other than minimum cost fundamental strategies for some or all sites in an inventory. In this manner short term or year specific funding demands can be changed selectively by the User. Year by year funding demand predictions for the *Alternative* strategies so created are presented.

Detailed Site Analysis

The Detailed Site Analysis feature permits detailed life cycle cost analysis to be completed for sites selected by the User. This feature is intended to provide the User with a management/planning tool that supplements the results of the network analysis.

The network analysis completed by the program is intended to provide broad planning input for the management of a structure inventory. The results of the network analysis are based upon simplifying assumptions and imperfect prediction methods. Therefore it is recommended that the network analysis results be supplemented with more detailed considerations for those structures scheduled for maintenance and rehabilitation activities in the near future. The detailed analysis feature is intended primarily for refined planning of such work.

The network analysis predicts future deterioration and management needs based on visual condition survey data and simplified imperfect deterioration relationships. As well, the predicted management expenditures in the network analysis are based upon averaged unit area based repair costs. The detailed analysis feature permits the User to focus in on specific repair procedures to determine best solutions based upon site specific characteristics, supplementary inspection data (data like chloride samples, CSE half-cell maps, chain drag maps, etc.) and appropriate amounts of engineering judgement.

CLOSING

The collaborative effort of a group of six Western Canadian municipalities and Reid Crowther has resulted in the development of a BMS software application suitable for use by cities with small to medium size inventories. The application was developed to address common data management and analysis needs and preferences of the group.

A comprehensive inventory and inspection database structure coupled with three distinct analysis functions together forms the basis of the development. The BMS application provides the group with an effective tool that facilitates informed bridge management decision making.

ACKNOWLEDGMENTS

This paper reports on bridge management work completed collaboratively by Reid Crowther and Partners Ltd., and the cities of Calgary, Alberta; Edmonton, Alberta; Lethbridge, Alberta; Regina, Saskatchewan; Saskatoon, Saskatchewan; Winnipeg, Manitoba. The author expresses his appreciation for the support and investment of all partners involved in this initiative.

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