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Optimization of waste management regions using recursive Thiessen polygons

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ABSTRACT

Geographic Information Systems (GIS) are commonly employed to solve problems related to landfill siting and optimization of waste collection. This research aims to develop an easily implementable tool to optimize the topology of waste management regions in various Canadian jurisdictions using ArcGIS ModelBuilder. Landfill count, populated places, and road length are minimized using standard deviation to determine optimized tessellations. In Nova Scotia, reductions in standard deviation of 9.6–30.4% are observed between original and optimized tessellations. The results suggest that an optimized tessellation of Nova Scotia's Federal subdivisions may perform better than that of their waste management regions. In Saskatchewan, reductions in standard deviation of 4.9–46.1% were observed between original and optimized tessellations. Considering all Saskatchewan Federal Subdivisions, no optimization occurred. However, partitions of Saskatchewan Federal Subdivisions yielded better results, with vertical partitions yielding a 30% decrease in standard deviation of roads, while landfills and population were reduced in the horizontal subdivision by 20.0% and 38.0%, respectively. This suggests that a different approach may be required for waste management regions in Northern Saskatchewan. Saskatchewan transportation planning committees regions had the highest standard deviation across all parameters, and optimized at the fourth iteration (landfills and populated places), and first iterations (roads), despite the fact that this tessellation was developed in direct relation to roads in the province. The proposed tool, however, showed a limited application in the City of Regina given that land use planning within City limits. This work will improve the data driven aspect of regional waste management system design.

1. Introduction & literature review

Waste collection and transportation constitutes a large fraction of total municipal solid waste management budgets worldwide (Chalkias and Lasaridi, 2009; Richter et al., 2018; Rathore and Sarmah, 2019). Waste collection and transportation cost of a given waste management system to a large degree depends on the distance between generation and disposal sites, and thus optimization of shape and size of a waste management region (WMR) is vital in reducing total operation cost. In Athens, Greece, costs for the collection and transportation of waste may account for more than 70% of total waste management costs (Chalkias and Lasaridi, 2009). In Bilaspur, India, collection and transportation account for 50–70% of total waste management costs (Rathore and Sarmah, 2019). Richter et al. (2018) found that Canadians spent about 46% of local waste management budgets on the collection and transportation of waste.

Canadians have one of the highest waste generation rates in the world and send a majority of their waste to landfills for permanent disposal (Bruce et al., 2016; Wang et al., 2016; Richter et al., 2019). Despite the size of the country and its mediocre performance in waste diversion (Bruce et al., 2016; Wang et al., 2016; Pan et al., 2018), there is little published information on waste management systems in Canada (Lakhan, 2015; Zhu and Huang, 2017; Chowdhury et al., 2017; Richter et al., 2017, 2018). Fig. 1 shows the expenditure on collection and transportation at the local level in Nova Scotia (NS), Saskatchewan (SK), and Canada (CA). Nova Scotia is a leading Canadian province in waste diversion (Richter et al., 2017, 2018), whereas Saskatchewan ranks as at the bottom (Wang et al., 2016). Over time, there has been a steady increase in the cost of collection and transportation provincially and nationally. In fact, in Canada, there has been a 92% increase in the cost of

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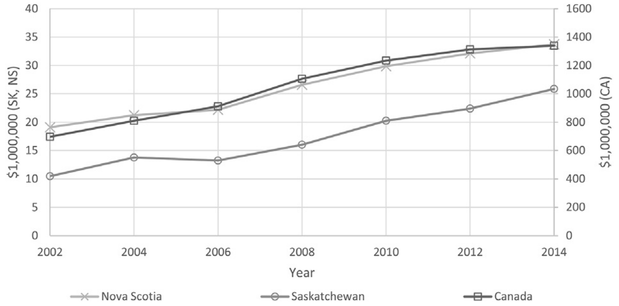

Fig. 1. Current expenditure on collection and transportation of waste in Canada from 2002 to 2014 (Data from Statistics Canada, 2019).

collection and transportation of waste between 2002 and 2014. Over the same time period, the cost of collection and transportation increased by 77% and 147% in Nova Scotia and Saskatchewan, respectively.

Landfill regionalization occurs when many smaller centres transfer their waste to larger, centralized facilities (Government of Saskatchewan, 2017). Generally, the bigger the landfill, the cheaper the cost of treatment due to economies of scale (Spigolon et al., 2018). In 1990, Bolton and Curtis (1990) proposed an environmental assessment process for the selection of solid waste disposal sites in small communities in Saskatchewan. At the time, the Saskatchewan Department of Environment, under whose jurisdiction waste management fell, encouraged the development of regional landfills. However, because of the strongly autonomous nature of prairie communities, movement towards regionalized landfills was difficult (Bolton and Curtis, 1990). Almost 30 years after Bolton and Curtis' study, the province of Saskatchewan is still intending to move towards regionalization (Government of Saskatchewan, 2017). Other Canadian provinces have had success moving towards regionalized landfills (Government of Nova Scotia, 1995; Government of Alberta, 2018). In 1995, Nova Scotia developed their Solid Waste Resource Management Strategy (Government of Nova Scotia, 1995), which proposed seven waste management regions (WMRs) in the province. Alberta began moving towards regionalized waste management facilities in the 1970s, with the goal of reducing the number of small municipal non-engineered "dumps" throughout rural areas of the province and moving towards the development of regionalized landfills with a network of transfer stations (Government of Alberta, 2018).

Because of the complexity in siting and transporting waste, GIS (Geographic Information Systems) is traditionally used to analyze spatial phenomena, such as siting of waste facilities and optimization of waste collection (Chalkias and Lasaridi, 2009; Tavares et al., 2009; Nguyen-Trong et al., 2017; Vu et al., 2018, 2019; Rathore and Sarmah, 2019). Recently, integration of GIS techniques in siting waste facilities and optimized transportation has become common, as shown in Table 1. In one of the few studies that discusses sectorization (or regionalization), Hanafi et al. (1999) propose a multi-objective 0–1 integer programming problem to divide Quito, Ecuador into a fixed number of sectors for weekly waste collection in order to minimize the largest workload in the sector. Chalkias and Lasaridi (2009) stated that sectorization of wider waste collection areas should be considered in future work, being based on spatial analysis rather than empirical approaches.

Traditional GIS-based approaches on facility siting include location-allocation, overlay analysis, buffer analysis, and different types of multi-criteria decision analysis (Table 1). Instead of focusing on siting landfills and waste facilities, this paper specifically focuses on developing new WMRs with different size and shape to minimize transportation distance and cost. Topological optimization problems have successfully been applied in computer and structural engineering fields (Antonietti et al., 2017; Beghini et al., 2014; Talischi et al., 2010). This study attempts to apply topological optimization to develop WMR tessellations using recursive Thiessen polygons. The objectives of this study are to: (i) develop an algorithm in ModelBuilder to recursively build Thiessen polygons in order to minimize the standard deviation (SD) of three selected indicators (landfills, populated places, and road length), (ii) implement the proposed tool on a number of different starting tessellations at both the provincial and municipal level in Saskatchewan and Nova Scotia (both of which have distinct shapes), (iii) compare the results and examine how the development of WMRs may be improved. The use of the recursive Thiessen polygon method to delineate WMRs is novel, and may open a new subresearch area on the application of tessellation optimization to environmental problems. The proposed is equally applicable to other tessellation optimization problems such as zoning and urban planning.

2. Methodology & materials

2.1. Study areas - starting tessellations

A total of six starting tessellations are considered, as shown in Fig. 2a-f. In Nova Scotia, Federal census subdivisions (Fig. 2a) and historical WMRs (Fig. 2b) are investigated. Federal census subdivisions are municipalities or areas that are treated as municipal equivalents for statistical purposes by the Federal government (Statistics Canada, 2011). Nova Scotia's historical WMRs, shown in Fig. 2b, were first established in 1995 to facilitate regional cooperation, such that significant savings could be achieved by efficient economies of scale (Government of Nova Scotia, 1995).

Saskatchewan is over 10 times larger than Nova Scotia, with an area of 651,900 km^2 (Table 1). As such, Federal census subdivisions were investigated differently. An iterative method was used considering all the Federal subdivisions concurrently. Then, the province was partitioned in 2 different orientations: vertically, shown in Fig. 2 (c), and horizontally, shown in Fig. 2 (d). Saskatchewan Transportation Planning Committee regions were also investigated, as shown in Fig. 2 (e). Area transportation planning committees (TPCs) generally consist of about 40 rural municipalities (Government of Saskatchewan, 1997). They are geographic advisory boards developed to assist municipalities and the province in decision-making related to investments in transportation and the economy at the regional level (Government of Saskatchewan, 1997). The use of TPC regions for waste management in Saskatchewan may be effective due to the important relationship between transportation and waste management in Saskatchewan (Keith, 2015).

Finally, wards within the City of Regina, the capital of Saskatchewan, were also considered, shown in Fig. 2 (f). With an area of about 180 km^2 (Table 1), there are 10 wards within the City, developed under section 25 of the Urban Municipality Act, 1984 (City of Regina, 2019). The wards are established in such a way that they ensure the population is spread as evenly as possible (City of Regina, 2019).

2.2. Data acquisition and pre-processing

The majority of data in this study was obtained directly from local governments open data portals as shapefiles, however, some data required pre-processing or needed to be derived from various databases (Table 2). WMRs in Nova Scotia were developed by merging polygon data from Federal subdivisions. Point data of

Table 1
Summary of key literature for landfill siting and optimization of transportation.

Reference	Tools Used	Method Used	Location	Area (km^2)
Sumathi et al. (2008).	MCDA GIS	Suitable sites for landfills are found based on overlay analysis and buffering, using available data on several environmental factors.	District of Pondicherry, India	293
Adamides et al. (2009)	Soft System Methodology System Dynamics GIS Location Allocation	A Regional solid waste management system is developed using multi-methodological intervention. A bi-objective model is used with location allocation to determine locations for treatment facilities and transfer stations.	Achaia, Greece	3,721
Chalkias and Lasardi, 2011	GIS Network Analyst	Collection is optimized for waste bins in the study area. Where required, bins were reallocated (resectorized) based on a number of restrictions. The result was a reallocation of bins in different sectors, yielding optimized costs.	Nikea, Athens, Greece	6.65
Effat and Hegazy (2012)	Weighted linear combination Constraint Analysis	Environmental, economic, and social considerations are combined in a spatial multi-criteria decision support system to site potential locations for landfills.	North Sinai, Egypt	27,000
Blanco et al. (2018)	GIS, Remote Sensing Zone Buffer	Agricultural plastic waste was mapped within 10 municipalities. Information used to site collection centres for different types of agricultural plastic waste using density of plastic waste production.	Apulia Region, South Italy	1,530
Khan et al. (2018)	GIS Exclusion, preference, location allocation analysis AHP	Waste conversion facilities and transfer stations sited in census subdivisions in the province. Methods evaluate relative preference of environmental and social factors.	Alberta, Canada	661,185
Rathore and Sarmah (2019)	Mixed Integer Linear Programming GIS	Transfer stations are sited in order to improve economical management of SWM. Three scenarios are considered, taking into account various degrees of source separation and different types of transfer stations.	Bilaspur City, India	30.42
Demesouka et al. (2019)	Multi-criteria spatial decision support system GIS/MCDA UTASTAR	A raster-based tool (UTASTAR) is used to assess land-use suitability, helping to incorporate conflicting objectives in traditional GIS and MCDA approaches for landfill siting.	Thrace Region, Northeastern Greece	8,578
This study	GIS ModelBuilder Recursive Polygon Generation	Using existing waste management regions and federal/municipal boundaries, tessellations are optimized to reduce SD of landfills, populated places, and roads. Optimized tessellations are presented.	Various Canadian Provinces	651,900 (SK) 55,284 (NS); 180 (Regina)

landfill location for landfills in Nova Scotia was developed for this study. TPCs in Saskatchewan were geo-referenced in ArcMap (v. 10.5.1) from a JPEG image. Waste generation points for the City of Regina were derived from building footprints in the City. This was done in order to differentiate houses from garages in residential areas. The criteria for screening was based on trial and error, and the best results occurred when the house footprint was greater than 80 m^2. This criterion generally satisfied the selection of either houses or garages, which was deemed acceptable to model a singular waste generation point.

2.3. *Workflow and optimization*

Fig. 3 shows the workflow used in this study. First, the starting tessellations and point data (presented in Section 2.1–2.2) are loaded into ArcMap (v. 10.5.1). The tabulate intersection tool in ArcMap is used to count the number of landfills, populated places, and length of road (m) within each polygon in the tessellation. This tabulated information is imported to a spreadsheet and SD across each topology is calculated; this information is used to compare future iterations of the Thiessen polygon tessellation to check for optimization. The centroids of each sub-area in the starting tessellations are calculated and a new Thiessen tessellation is built based on these centroids. The tabulate intersection tool is used once again to count the number of landfills, populated places, and length of road within the newly generated Thiessen polygon tessellation. Landfills (LFs), populated places (Pop), and roads (Roads) are chosen as the parameters for optimization since they are crucial to the development of an integrated waste management strategy.

In this paper, landfills are permanent waste disposal sites as defined by the provincial governing body of that province (Government of Saskatchewan, 2018; Nova Scotia Environment, 2017). In Saskatchewan, this includes all waste disposal grounds operating with or without a permit (Government of Saskatchewan, 2018). The populated places dataset shows the location of towns and cities in the study areas (Esri Canada, 2014), and are the generation points for waste. The road network, which provides a link between landfills and waste generation points, is a representation of highways as well as major and minor roads (Esri, 2018).

A toolbox was developed using ArcMap ModelBuilder (v. 10.5.1) in order to expeditiously carry out the iterative process. The recursive polygon tool recorded and stored the tabulate intersection data in a geodatabase. Analysis of the tabulate intersection data was done via Microsoft Excel. The SD across each subdivision of the topology was calculated and compared to the SD of the tessellation in the previous step. If the SD increased, the iterative process continued. The SD trend with respect to iteration numbers was monitored for the optimized solution. The SD for each parameter (landfills, populated places, and roads) does not necessarily optimize at the same iteration, and therefore optimization was carried out until all parameters were optimized. The results, presented in section 3.0, will explicitly state which tessellation is optimized for which parameter.

2.4. *Thiessen Polygons*

Thiessen polygons were used in this study to recursively build the tessellations. Thiessen polygons are derived from a topological relationship between a set of points (x, y) in two-dimensional space (Mu, 2009). Mathematically, assume P is a finite set of pints in the Euclidean plane, $P = \{p_1, \ldots, p_n\}$, where $2 \le n \le \infty$ (equation (1)). Suppose x is any location in the planar space and the Euclidean distance between x and p_i is $d_e(x, p_i)$. Then, let $T(p_i)$ denote the Thiessen polygon of the point p_i, then:

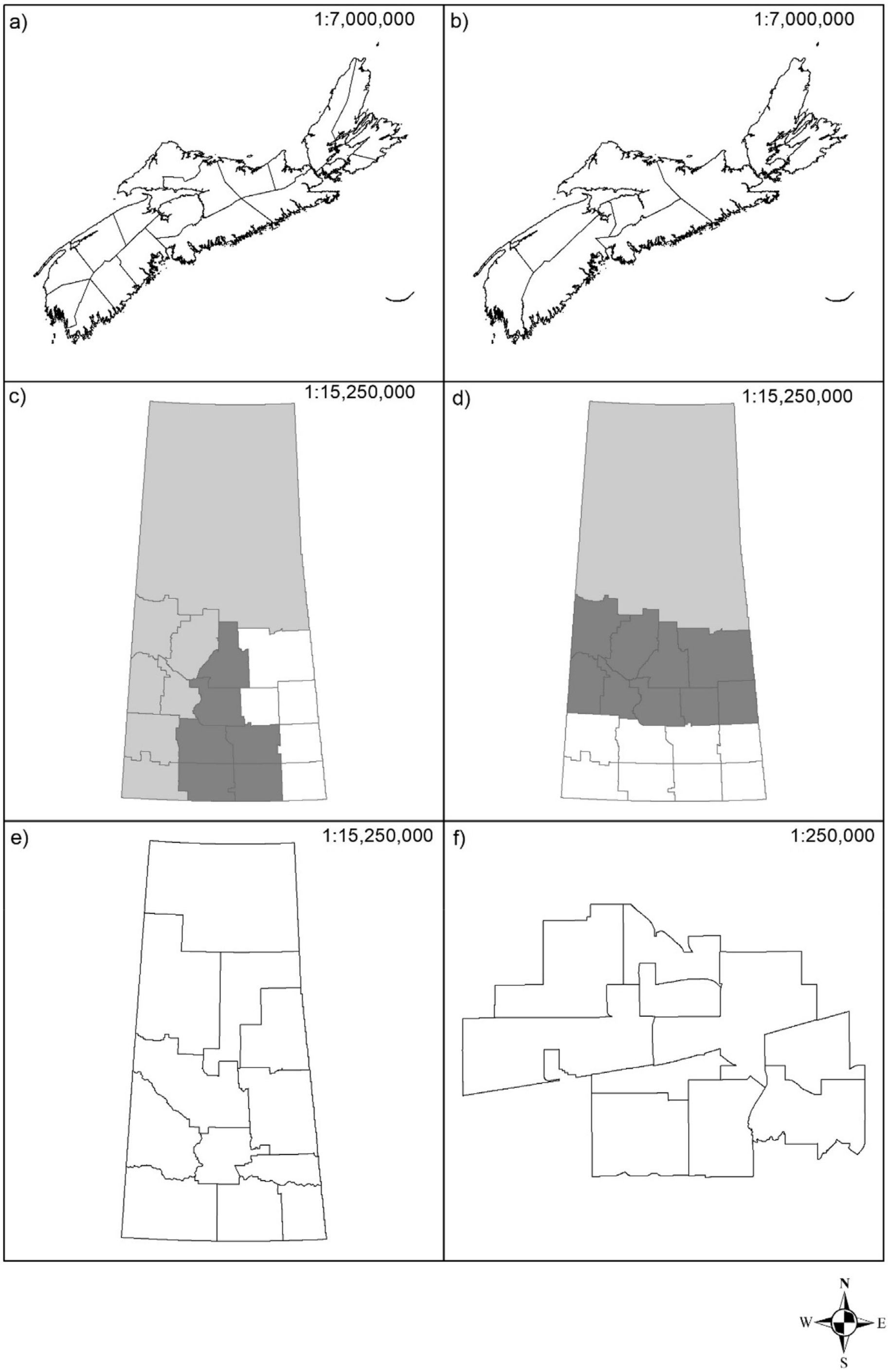

Fig. 2. Starting tessellations – (a) Nova Scotia Federal Subdivisions, (b) Nova Scotia Waste Management Regions, (c) Saskatchewan Federal Subdivisions (partitioned into vertical strips), (d) Saskatchewan Federal Subdivisions (partitioned into horizontal strips), e) Saskatchewan Transportation Planning Committee Regions, and (f) City of Regina Wards.

$$T(p_i) = \left\{ x \middle| d_e(x,\ p_i) \leq d_e\left(x,\ p_j\right),\ for\ all\ j,\ j \neq i\ and\ i,\ j\ \leq n \right\} \qquad [1]$$

Thiessen polygons serve as a proximity method and are a basic structure in geographic information systems (Mu, 2009). In this study, Delaunay triangulation method is used (ArcMap v.10.5.1) to build the recursive Thiessen polygon. The Delaunay criterion requires that a circle drawn through two nodes of a triangle in the triangular irregular network (TIN) can contain no other point (Mu, 2009). Each TIN edge is perpendicularly bisected, which forms the Thiessen polygons, and the centers of the TIN become vertices of the Thiessen Polygons (Mu, 2009). Thiessen polygons have been successfully applied in siting of waste facilities (Khan et al., 2018), solving geographical problems (Reitsma et al., 2007), and planning rail station locations (Mota et al., 2014).

2.5. Minimization parameter

Standard deviation (SD) is a commonly used measure of

Table 2
Data type and acquisition details for data used in this study.

Data	Data Type	Reference
Nova Scotia		
Federal Subdivisions	Tessellation (Polygon)	Statistics Canada (2016)
WMRs	Tessellation (Polygon)	Derived from Statistics Canada (2016)
Landfills	Point	Derived from Nova Scotia Environment (2017)
Population	Point	Esri Canada (2014)
Roads	Line	GeoNova, 2015
Saskatchewan		
Federal Subdivisions	Tessellation (Polygon)	Statistics Canada (2016)
TPCs	Tessellation (Polygon)	Derived from Government of Saskatchewan, 2015
Landfills	Point	Government of Saskatchewan (2018)
Population	Point	Esri Canada (2014)
Roads	Line	Esri (2018)
City of Regina		
Wards	Tessellation (Polygon)	City of Regina (2017)
Waste Generation Points	Point	Derived from City of Regina (2014)

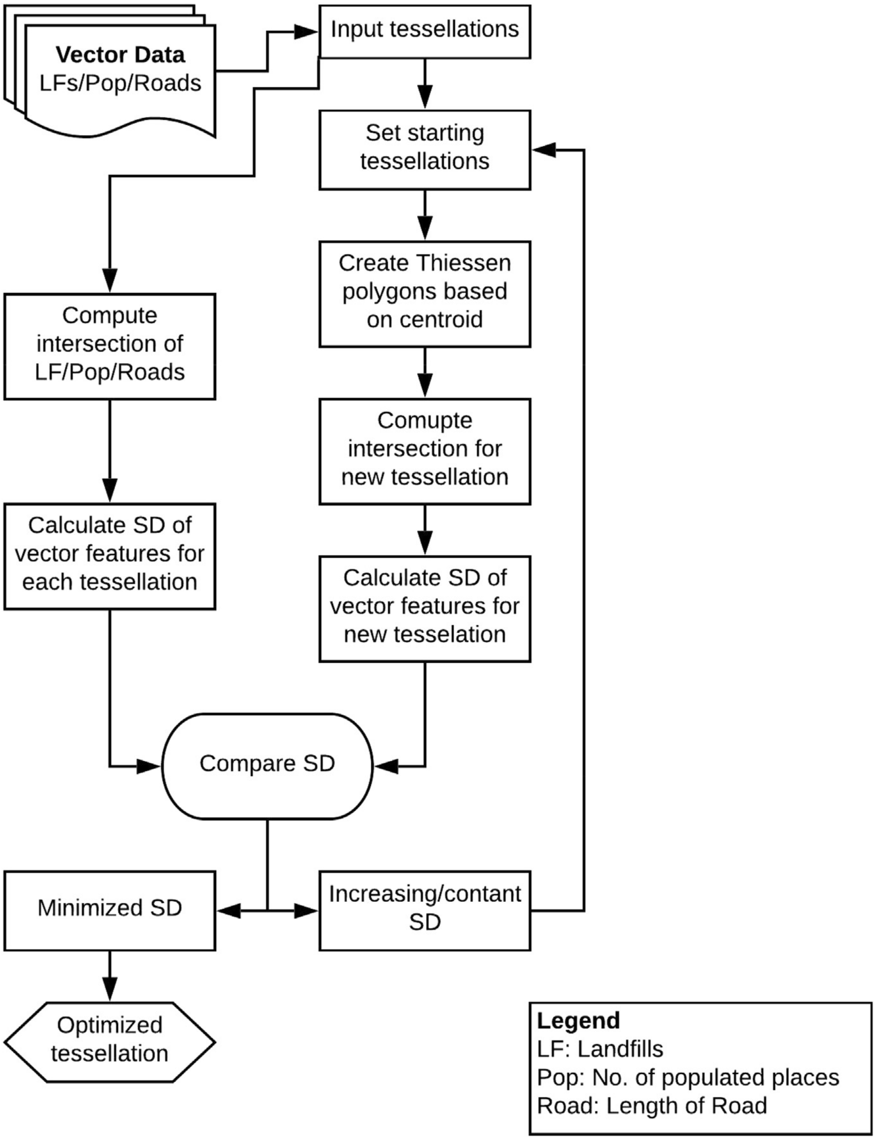

Fig. 3. Workflow used in this study.

variation, and is defined below (Mendenhall and Sincich, 2007).

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \qquad [2]$$

Where y_i is any measurement in the set, ⌈ is the mean of the set, and n is the sample size. Standard deviation, coefficient of variation, and variance-to-mean ratio were all used to measure the variation of the count within the optimized tessellation in the trial runs. In this model, the average is constant in each trial, and therefore SD was chosen as the most representative metric given the study's objectives. The stopping criteria for the iterative process of developing the optimized topology was a minimized SD. A minimized SD implies that the allocation of parameters (landfills, populated places, and roads) is as equal as possible in all subdivisions of the respective tessellation. It is believed that this equalization will help to create practical and efficient WMRs throughout each area.

Two separate validation checks were done. The first was a manual visual inspection of data in the GIS, where the number of points within a polygon were confirmed with the data recorded in ArcMap. The second was done using Excel, where the SD was confirmed to stay constant throughout each trial.

3. Results & discussion

3.1. Nova Scotia

Fig. 4 shows the optimized topology for Nova Scotia's Federal Subdivisions (a, b) and WMRs (c,d); where the parameters (landfills, population, and roads) are minimized across each polygon in the tessellations. Considering landfills in Federal Subdivisions (Fig. 4a) no observed optimization occurred by applying recursive generation of Thiessen polygons, meaning that the starting tessellation was favourable when considering the spatial distribution of landfills. Fig. 4 (b) shows the optimized tessellation where SD is minimized for populated places and road length, which occurs at the first iteration. The difference in SD between the starting and optimized topology was 16.52 and 20.37% for populated places and roads, respectively.

Considering Nova Scotia's WMRs, Fig. 4 (c) shows the optimized tessellation for landfills, which optimized at the 13th iteration. Population and roads optimized at the 14th iteration, shown in Fig. 4 (d). Between the original and optimized tessellation, there was a difference of 10.32, 30.41, and 9.63% for landfills, populated places and roads, respectively. This starting topology required the highest number of iterations for optimization to occur. One possible reason for this was the clustering of waste management facilities in the region. With respect to landfills, there was a sharp variation in SD through iterations 13–16 (not shown). This occurred because the boundary of one of the polygons was in the process of moving through a cluster of closely located waste management facilities (shown in Fig. 5a–d), which may be related to the high population density (Richter et al., 2018) in Nova Scotia and the spatial distribution of facilities in the province.

When comparing differences in tessellations for Federal Subdivisions (Fig. 4a and b) and WMRs (Fig. 4c and d), it is observed that Fig. 4 (c) and (d) appear almost identical to each other compared to Fig. 4 (a) and (b). This is not surprising, considering that the largest change in tessellations occurs in between the zeroth and first iteration, when the input tessellations are first changed to Thiessen polygons. In the case of Nova Scotia's WMRs, it is very likely that both the 13th and 14th iterations (Fig. 4c and d)

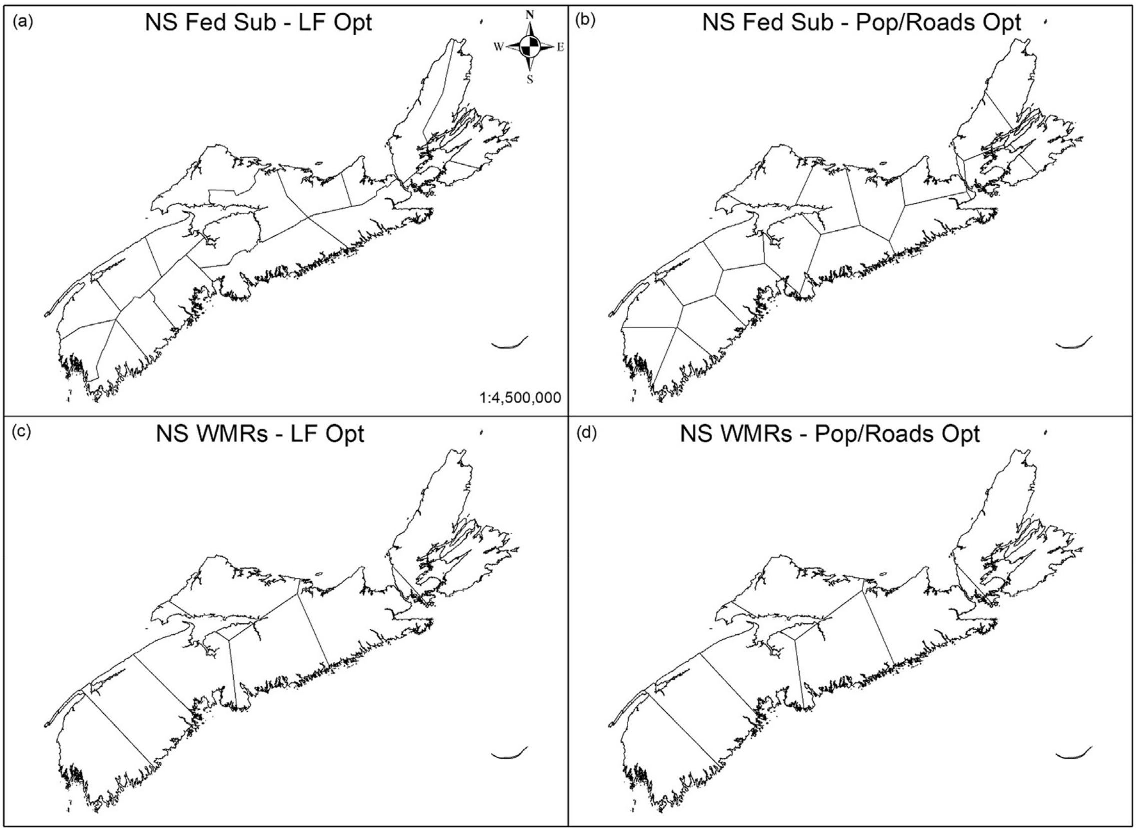

Fig. 4. Optimized tessellations based on Nova Scotia Federal Subdivisions for (a) landfills, and (b) population and roads. Optimized tessellations based on Nova Scotia's Waste Management Regions (WMRs) for (a) landfills, and (b) populated places and roads.

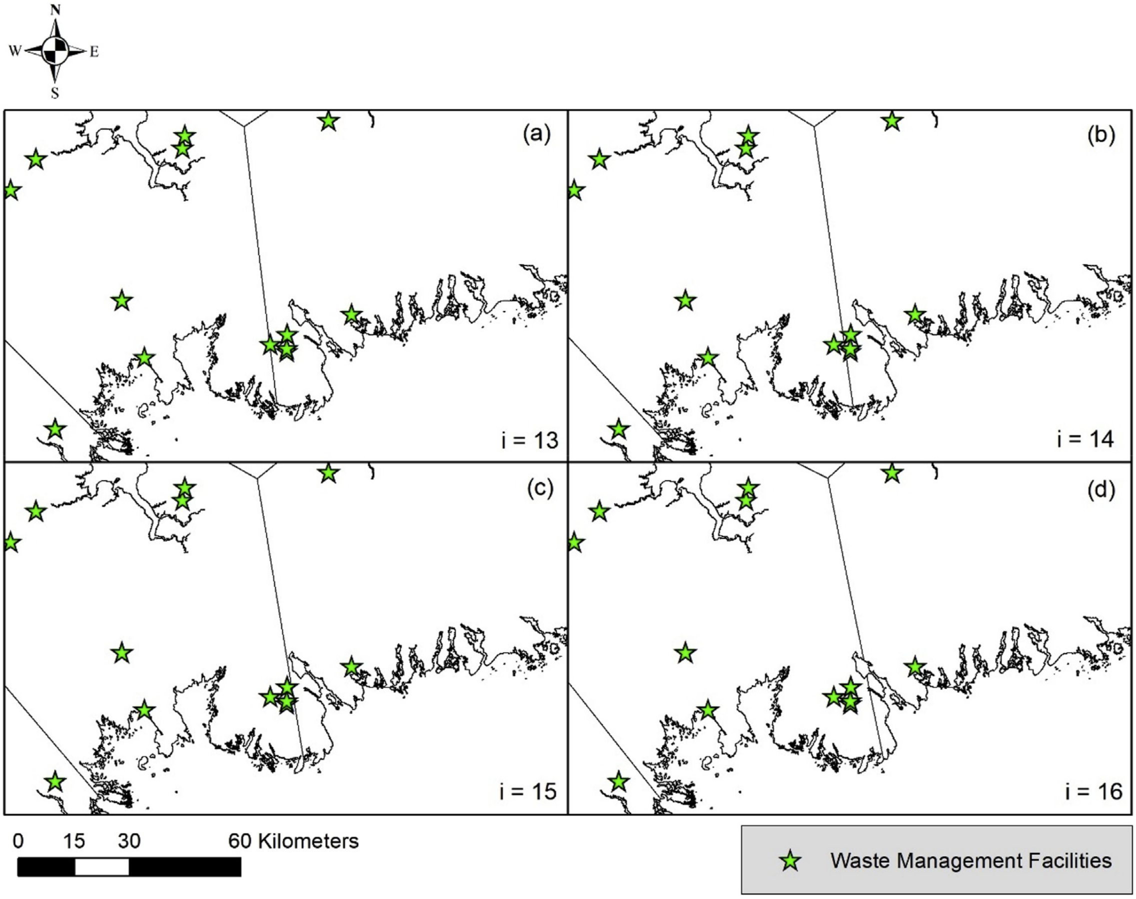

Fig. 5. Boundary of polygons moving through cluster of waste management facilities in Nova Scotia for iterations (a) 13, (b) 14, (c) 15, and (d) 16.

could be suitable to implement, regardless of the fact that optimization for different parameters occurs at different iterations. Note that the same cannot be said for Nova Scotia's Federal Subdivisions (Fig. 4a and b) due to the large differences between the two optimized tessellations. In this case, the decision on which tessellation would be better suited for further development of regions should therefore be based on which parameter (landfills, populated places, and roads) is more important. This decision will be region specific and depend on a number of factors. The proposed method, however, provides a data-driven tool for policy makers.

Table 3 shows the absolute value of SD for each optimized tessellation with respect to landfills (LF), populated places (Pop), and road network (Roads). There was a significant difference (77.0%) between the SD for population between the two tessellations. The difference between SD for landfills for the two tessellations was 37.9%, while the difference between SD for roads for the two tessellations was 38.4%. This may indicate the location of populated places is more sensitive with respect to optimization.

It is interesting to note that the number of subdivisions in the starting tessellations are different in Nova Scotia. There are 17 Federal Subdivisions (Figure 2a) and 7 WMRs (Fig. 2b). Results from Table 3 indicate that Federal Subdivisions have a smaller relative SD for all parameters studied. This may imply that a starting tessellation with more subdivision results in higher reduction in SD, although it is not clear what the optimal number of subdivisions would be. Future work may include investigation of an optimal number of regions.

Because of the lower overall SD, it appears that the use of Federal Subdivisions may be more advantageous in Nova Scotia compared to WMRs (Table 3). However, one must also consider the complex nature of planning for waste management regions. Nonetheless, the results indicate that since WMRs are simply the amalgamation of Federal Subdivisions, there may still be room for improvement with respect to the minimization of standard deviation of landfills, populated places, and roads. The use of specific optimized tessellations (shown in Fig. 4) would depend heavily on a number of other factors, including the purview of decision makers in the province.

Table 3
Optimized SD for landfills, populated places, and roads in Nova Scotia (optimized iteration shown in square brackets).

	Standard Deviation		
	LF	Pop	Roads
NS – Fed Subs	2.2 [0]	88.4 [1]	727,090.3 [1]
NS – WMRs	2.9 [13]	183.1 [14]	1,011,910.0 [14]

3.2. Saskatchewan – Federal Subdivisions

The recursive polygon tool was applied to Saskatchewan Federal Subdivisions in three different ways given the size and shape of the province. First, all Saskatchewan Federal Subdivisions were iterated through at the same time (vertical and horizontal partitions were not applied) and no optimization occurred (iteration = 0 in Table 4). The original tessellation of Federal Subdivisions are shown in Fig. 2c and (d), ignoring vertical and horizontal partitions. The fact that no optimization occurred when the entire tessellation was considered

Table 4
Optimized SD for landfill, populated places, and roads considering all Federal Subdivisions (optimized iteration shown in square brackets).

	Standard Deviation		
	LF	Pop	Roads
SK – Fed Subs	7.7 [0]	66.6 [0]	2,286,286 [0]

Table 5
Optimized SD for landfill, populated places, and roads considering vertical and horizontal partitions of Saskatchewan Federal Subdivisions (optimized iteration shown in square brackets).

	Standard Deviation		
SK - Vertical	LF	Pop	Roads
West	8.9 [1]	47.3 [0]	1,116,435 [0]
Central	3.7 [1]	72.3 [0]	2,848,966 [0]
East	10.2 [0]	19.6 [7]	844,382 [1]
Average	7.6	46.4	1,603,261
SK - Horizontal			
North	3.4 [1]	12.2 [1]	636,950.9 [1]
Central	8.8 [0]	36.8 [4]	2,007,528.0 [1]
South	6.4 [1]	74.9 [0]	2,218,642.0 [0]
Average	6.2	41.3	1,621,040

with partitioning is interesting, considering that Federal Subdivision are directly related to census statistics, as mentioned previously.

3.3. Saskatchewan Federal Subdivisions –vertical and horizontal partitions

Saskatchewan Federal Subdivision were partitioned vertically (Fig. 2c) and horizontally (Fig. 2d) in order to further investigate optimization in the province. When applying the recursive polygon tool, optimization occurred at different iterations for landfills, populated places, and roads. For vertical partitions, Fig. 6 (a) shows the optimized tessellation considering landfills, while Fig. 6 (b) shows the optimized tessellation for populated places, and Fig. 6 (c) shows the optimized tessellation for roads. In most cases, each subdivision optimized at a different iteration. Information on SD and optimized iteration is presented in Table 5.

For the vertical topological partition, landfills, population, and roads optimized at the same iteration in both the Central and West divisions, while more iterations were required for the East division, especially for population. Compared to the SD for populated places in the East division, there was an 82.8% and 114.7% difference between the West and Central divisions, respectively. The exact reason for this anomaly is unclear. Compared to the West and Central divisions, the East polygons are much more regular and square (Fig. 2c), which may indicate that the starting tessellation and the spatial distribution of landfills, population, and roads is important with respect to the application of this tool. Similar to Nova Scotia's Federal Subdivisions (Fig. 4), each of the optimized tessellations (for landfills, populated places, and roads) are quite unique. Between the original and optimized tessellation, there is a reduction of 4.91, 19.48, and 7.61% for the average SD of landfills, populated places, and roads.

Results for the horizontal partition of Saskatchewan's Federal Subdivisions are shown in Fig. 6(d –f) for landfills, populated places and roads, respectively. Table 5 summarizes the SD and optimized iteration for horizontal partitions. Between the original and optimized tessellation, there is a reduction of 5.2, 17.68, and 5.01% for the average SD of landfills, populated places, and roads. Unlike the Vertical partitions of the province (Fig. 6 a-c), we can see that there appear to be more similarities in the optimized tessellations for

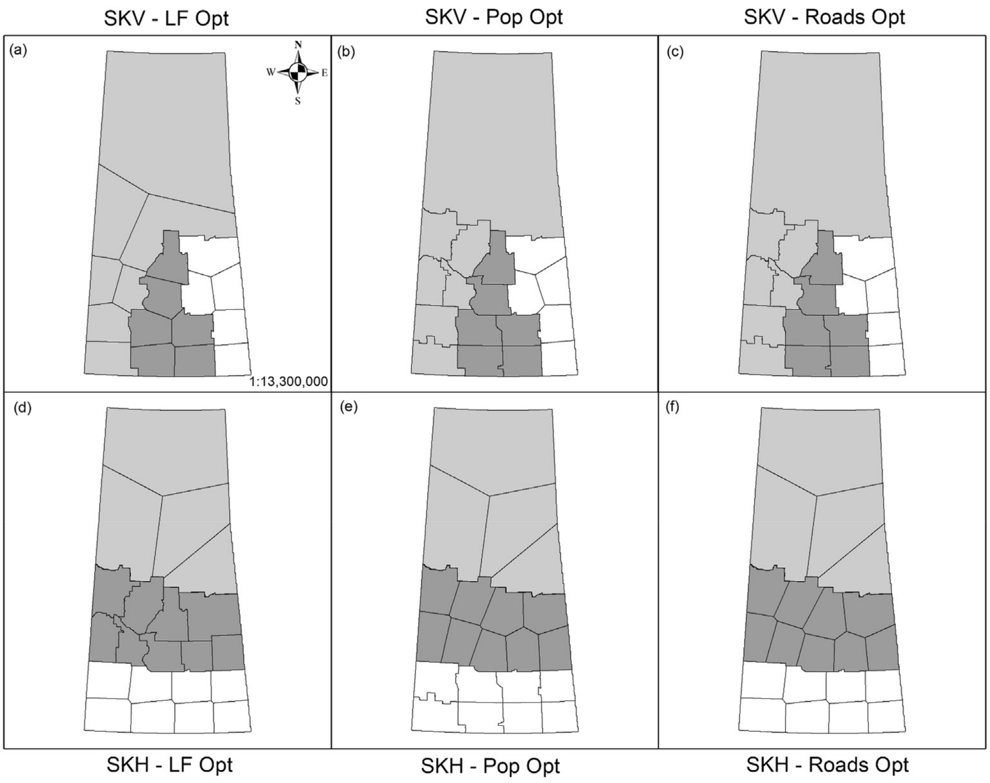

Fig. 6. Tessellation optimization for vertical (a, b, c) and horizontal (d, e, f) partitions of Saskatchewan Federal subdivision.

each parameter (Fig. 6 d-f); especially considering the Northern partition (shown in light grey) which optimized at the first iteration for all parameters.

When comparing the results considering all SK Federal Subdivisions (without partition) in Table 4, to the average partitioned results (Table 5) we see that the SD is reduced for all parameters (landfills, populated places, and roads) when partitioning was applied. Since the average SD for horizontal subdivisions was smaller for landfills and populated places (Table 5), this topological separation may be preferable, since the number of landfills and populated places are more evenly spread out across each polygon in the tessellation.

The results suggest that considering the province in terms of regions (vertical or horizontal partitions) is beneficial when applying the methodology compared to considering all Federal Subdivisions without partition. One possible reason may be the scarcity of population in the Northern part of the province. This may suggest that northern and remote communities would not benefit from regionalization and require specialized approaches to waste management. Lakhan (2015) studied the economic challenges related to recycling in remote Northern and rural areas of Ontario, Canada. The results from the study suggested that removing recycling programs such as the Blue Box significantly reduced costs while having little impact on the provincial diversion rate. Heske et al. (2018) highlighted the complex nature of waste management in Canada's circumpolar regions and highlighted the need for innovative approaches to waste management in these areas. The results from this study suggest that there is an opportunity for innovation in development of waste management regions in rural and remote communities.

There was a 1.3%, 35.7% and 35.1% difference between the entire province (Table 4) and vertical subdivisions (Table 5) considering average SD for landfills, populated places and roads, respectively. Between the unpartitioned Saskatchewan Federal tessellation (Table 4) and horizontal partitions (Table 5), there was a 21.6%, 46.8% and 34.1% difference with respect to the average SD for landfills, populated places and roads, respectively. Populated places tended to have the highest percent difference, similar to the results in Nova Scotia (section 3.1). Vertical subdivisions yielded higher reductions in average SD for roads (decrease = 29.9%), while horizontal subdivisions yielded higher reductions in average SD for landfills (decrease = 20.0%) and population (decrease = 38.0%). In Saskatchewan, the equal spreading (minimization of SD) of roads across the polygons in the tessellation may be more important due to the state of roads in the province. Saskatchewan is located in a semi-arid climate, and the presence of shrink-swell conditions in the expansive clays result in damage to pavements (Ito and Azam, 2009). Furthermore, Keith (2015) pointed out that regionalization may require long haul distances leading to increased wear and tear on provincial roads. Based on the aforementioned issues related to pavement structure and hauling distances in Saskatchewan, tessellations that reduce the SD for road length may be more important compared to optimization of landfills and populated places.

3.4. Saskatchewan – transportation planning committees

When considering Area Transportation Planning Committees (TPCs), optimization occurred at iteration four for landfills and population (Fig. 7a), and iteration one for roads (Fig. 7b). Between the original and optimized tessellation, this represents a decrease of 27.1, 34.5, and 46.1% for landfills, populated places, and roads, respectively. While other tessellations have, on occasion, optimized at the zeroth iteration (meaning that they showed no improvement in SD during recursive re-generation of Thiessen polygons), this tessellation, which was developed specifically with respect to road infrastructure, never optimizes at the original tessellation. This may occur because area transportation planning committees were developed in 1997 (22 years prior to this study), and no longer accurately represent an equal spread of road infrastructure within the province, or that different classes of roads require different amounts and types of maintenance. The tessellations are quite different for each respective parameter. Although it may be

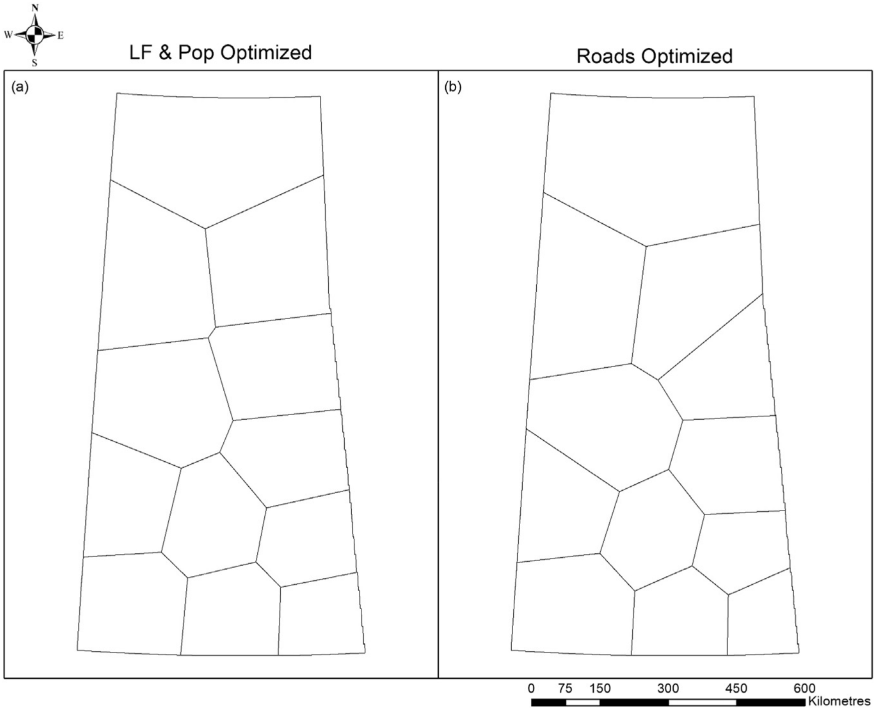

Fig. 7. Optimized tessellations for Saskatchewan TPCs for (a) landfills and population, and (b) roads.

tempting to conclude that because landfills and populated places optimize at the same iteration, that this tessellation would be preferable; the fact that collection and transportation of waste is responsible for 46% of municipal government expenditure on waste management in Canada (Richter et al., 2018) complicates this decision.

Absolute values of SD and optimized iterations are shown in Table 6. Saskatchewan TPCs had the highest standard deviation across all parameters. Comparing these results to those of the SK Federal Subdivisions (without partition) seems to indicate that having a higher number of polygons within the tessellation leads to a decrease in SD, similar to the results obtained in Nova Scotia (Section 3.1).

Because of the more complex starting tessellation of TPCs, partition into horizontal and vertical strips was not possible. However, as discussed previously, the sparse nature of communities in the Northern part of the province may cause the relatively higher standard deviation observed for this starting topology.

3.5. *City of Regina – wards*

Results for wards at the City of Regina indicate that there was no optimization, meaning that wards in the City were already optimized. The optimized tessellation can be seen in Fig. 2 (f) and is omitted from this section for conciseness. Table 7 shows the SD and optimization results for the City of Regina.

There is only one landfill for the entire City, and landfill count was not considered in the optimization process. Because wards are developed such that there are approximately the same amount of people in each ward, it is not surprising that optimization did not occur through the process of recursive polygon generation. As a result, it is believed that the proposed methodology may be more applicable on a provincial level, and not at the municipal level, where Cities may already benefit from more consideration with respect to land use and planning than other regions.

3.6. *Practical implications & areas of future work*

The method presented in this paper is an attempt at applying topological optimization to the problem of defining regions for waste management. Although optimization is observed when using regular Thiessen polygons with respect to the parameters studied, the use of different types of Thiessen polygons may be advantageous. Thiessen polygons are used to study geometric proximity in a plane. It allows for the identification of coverage areas and regions of influence and lends itself well to facility locations and zoning (Mota et al., 2014). However, other types of Thiessen polygons, such as weighted Thiessen polygons (Mota et al., 2014) may provide better results. A weighting factor is used to draw tessellations and instead of using straight lines to build the tessellation, Appollonian circles are used, creating a curvature in the polygon tessellations (Mota et al., 2014). This should be considered as an area of future work.

The integration of remote sensing data and the use of different types of vector data should also be considered in the future, as it may help to provide an even better method to delineate data-driven waste management regions. For example, the current study does not take into account changes in elevation. Most of the Canadian Prairies were formed during the last glaciation (Ito and Azam, 2009), and as a result has a relatively flat topography. In the future, a 3D topology optimization could be carried out for mountainous regions. Other tools in ArcGIS may also be applied, such as point density and raster to polygon.

The authors recognize that the development of waste management regions is much more complex than spatial distribution of landfills, populated places, and roads. In fact, the use of current Federal subdivisions may be beneficial from a financial aspect. However, some municipalities in Saskatchewan have already formed regional waste management partnerships, which are separate legal entities, and are funded by the participating municipalities (Government of Saskatchewan, 2017). This method may have limited applications where regions have already been formed, but may provide guidance for regions that have not yet been formed.

The development of waste management regions would require the use of transfer stations in each of polygons within the optimized tessellations presented in this paper. A method such as that applied by Rathore and Sarmah (2019) to site transfer stations using mixed-integer linear programming and GIS could be useful to find the optimal location of these facilities within the region.

Unlike many other studies which aim to site landfills, the goal of this study was to define optimized regions before the actual siting of landfills. A number of different approaches could then be used to site the best locations for landfills and transfer stations within the proposed optimized tessellations. This may include the use of location-allocation tools and cost analysis tools in a GIS. The integration of environment, economical, and social matters can be implemented more efficiently at this stage in the process.

4. Conclusions

This research develops a novel tool (using ArcGIS ModelBuilder) to recursively generate Thiessen polygons while minimizing the count of parameters such as landfills, populated places, and roads in order to generate an optimized tessellation for waste management regions in provinces and cities in Canada. The largest changes in tessellations occurred between the zeroth (original) and first tessellation, where the original polygons changed to Thiessen polygons. Landfills, populated places, and roads generally did not optimize at the same iteration. The final decision on which tessellation to apply would depend on a number of factors including the purview of decision makers in each respective jurisdiction. Nova Scotia Federal Subdivisions optimized at iteration 0 (landfills) and 1 (populated places and roads). These results had a lower standard deviation (37.9–77.0 percent difference) compared to Nova Scotia WMRs. Compared to the original tessellations, reductions in SD of 9.6–30.4% were observed for the chosen parameters in Nova Scotia. Saskatchewan Federal Subdivisions were the only tessellation that did not optimize (the original tessellation had the lowest SD). Vertical and horizontal subdivisions of Federal subdivisions in Saskatchewan yielded optimization, which may point to a need for specialized approaches with respect to waste management systems

Table 6
Optimized SD for landfills, populated places, and roads for SK TPCs (optimized iteration shown in square brackets).

	Standard Deviation		
	LF	Pop	Roads
SK – TPCs	29.0 [4]	213.0 [4]	8,236,218 [1]

Table 7
SD for, populated places, and roads considering City of Regina warsd (optimized iteration shown in square brackets).

	Standard Deviation		
	LF	Pop	Roads
Regina - Wards	–	810.0 [0]	29,667.09 [0]

in Northern and remote communities. Reductions in average SD of 4.9–19.5% were observed between original and optimized tessellations with horizontal and vertical subdivisions. Saskatchewan Transportation Planning Committees optimized at the fourth iteration for landfills and populated places, while optimizing at the first iteration when considering roads, representing observed reductions in SD between the original and optimized tessellations of 27.1–46.1%. This is interesting considering that the areas were developed in specific relation to road infrastructure in the province. This methodology is flexible and could be applied simply to the development of area transportation planning committees and could easily use different classes of roads as an input to the model.

Results for the City of Regina show that the tessellation was already optimized, which is not surprising considering that wards a developed based directly on the spatial distribution of population and land use planning. Future areas of work may include the use of different tools in ArcGIS to improve the data driven aspect of this project.

Declarations of interest

None.

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