The Evaluation of Multiple-Criteria Decision Making with GIS for Railroad Alternatives Analysis: the "DC2RVA" Case Study

Bridget Ward, MGIS Candidate

Advisor: Dr. Guangqing Chi

TABLE OF CONTENTS

Figures

Tables

Abstract

As Geographic Information Systems (GIS) continues to evolve, the software's role, and overall importance in site analysis, infrastructure planning, and general decision-making has exponentially increased. With the theoretical applications of multiple criteria decision making/analysis (MCDM/A) as a critical foundation for GIS in geospatial decision analysis, the prompt to integrate GIS and MCDM/A in more recent planning efforts has emerged as an innovative and efficient solution.

The following research evaluates the collaborative techniques of GIS and MCDM/A through the lens of a current United States (U.S.) high speed rail project; Washington, D.C. to Richmond, Virginia, "DC2RVA", High Speed Rail Project. This study presents an evolving trend in geospatial decision analysis by exemplifying the use of GIS and MCDM/A in a tangible and critical transportation scenario; the identification of a feasible rail alignment alternative in an 11-mile section of a 123-mile rail corridor. Utilizing both spatial (GIS) and statistical (MCDM/A) methods for a set of conceptual alternatives, this research presents a model approach in decision-making efficiency and optimization through site suitability analysis and the conclusive identification of a feasible alignment alternative. This fusion of MCDM/A techniques and geovisualization serves as a critical component in the ability of decision-makers to readily understand spatial relationships and the respective impacts among resources and alternatives.

Introduction

The focus of this research proposes that the integration of GIS with MCDM/A is a credible, viable, and effective approach in the process of land suitability analysis for rail transportation. As an application for rail infrastructure development, GIS and MCDM/A techniques are evaluated in the context of a current U.S. high speed rail project along the southeast corridor, extending from Washington, D.C. to Richmond, Virginia. In addition to transportation-based GIS and MCDM/A effectiveness, this research proposes that with the recent advancements in GIS and data-sharing, an increase of access and decision-support through its user interface for non-specialists can be widely achieved; it can be utilized for both high-level decision-making and more detailed criteria evaluation.

In the context of this research, GIS may be positioned as a relatively new technology resource in the realm of land and site-suitability projects; it was not until the late 1980s that GIS emerged as suitable software for project location analysis, and resultantly, spatial decision support. In contrast, the use of MCDM/A has been a historical, and prevalent, mathematical approach to projects that propose a multitude of alternatives and require decision makers to develop choices and identify preferences. However, as MCDM/A is both a computationally intensive and statistically rich approach, it is a difficult methodology that is not readily-understandable for non-specialists; it is a challenging discourse to examine the detailed processes at their finite levels. The majority of previous research cited originates from GIS and transportation planning-based journals, as research and methodological journals emphasize statistically-centered papers. Thus, this research argues that the integration of GIS with MCDM/A is an efficient methodology for projects requiring geovisualization and critical decision analysis.

While GIS and MCDM/A can be utilized as distinctly independent decision support tools, this research aims to evaluate and highlight their cooperative and collaborative relationship through a present-day case study of the Washington, D.C. to Richmond, VA High Speed Rail (HSR) project, commonly known as “DC2RVA”. This research employs a combination of geospatial processing and statistical modeling utilizing third-party software to identify a feasible alignment alternative through empirically weighted resource criteria.

Models of GIS for Spatial Decision Support & Planning Management

Over the last several decades, GIS has become a fully integral component in decision-making best practices for planning management, particularly in the environmental and land-use sectors (Malczewski 2004). In decision analysis modeling, GIS has applicable functionality for several approaches; at the highest tier these methods include descriptive, normative, prescriptive, and constructive analyses (Keeney 1992, Bouyssou et. al. 2006). Malczewski (2004) focuses a majority of his book on GIS as a critical spatial decision support system (SDSS) through the aforementioned analysis methods. The normative approach is most consistent with the "DC2RVA" case study and overall focus of this research, as it produces a comparative model of impacts in the real-world to the results produced in a spatial system; this theory provides outputs that enable decision makers to identify the optimal alternative. In a broader methodological approach, Jankowski (1995) discusses GIS in the rational model framework, outlining distinct, steps that appear universally applicable to decision-making processes; problem definition, search for alternatives and selection criteria, evaluation of alternatives, and selection of alternatives are required parameters (McKenna 1980). The second step, defined as the identification of feasible alternatives, is most often analyzed through GIS, particularly under the evaluation of pivotal criteria including the environmental, economic, social, and physical factors that negate or contribute to the feasibility of a certain alternative. Historically, GIS analyzes and represents spatial intersections of base criteria data and project areas – alternatives – through map overlay techniques, which were first introduced in the 1960s by Ian McHarg. Natural attributes and decision-maker--developed characteristics are combined into "transparent…x-ray like composite maps [to illustrate] intrinsic suitabilities for broad land-use classifications, such as conservation, urbanization, and recreation for the specific planning area" (Collins et. al. 2001). This map overlay technique is indicative of the efforts to be utilized in this study. The research focus of this paper also maintains a centralized theme in examining the relationship of criteria space and decision space in the combined efforts of GIS and MCDM/A; it positions GIS as a pivotal mechanism among engineers, public officials, and other key stakeholders as it promotes a transparent, interactive and collaborative alternatives review process.

MULTIPLE-CRITERIA DECISION ANALYSIS: OVERVIEW

The discourse on MCDM/A applications and research dates back to the 1950s, with the majority of theories and modeling based upon statistics and lengthy mathematical formulas. The field of study itself is a major component of operations research, focusing on solutions to complex decision problems. The Analytical Hierarchy Process (AHP) is the predominant MCDM/A technique utilized in this study. In their book, *Multicriteria Decision Analysis in Geographic Information Science*, Malczewski and Rinner (2015) describe the AHP method as grounded in "…three principles: decomposition, comparative judgment, and synthesis of priorities" (Malczewski, Rinner 2015). The efforts of this paper's research most closely resemble the AHP approach, which can be integrated into GIS through both estimated criterion weighting and the three aforementioned principles. Along with AHP, Chen et. al. 2010 delves into several MCDM/A functions, including the incorporation of sensitivity analysis (SA) with AHP methods. The research defines SA as "the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation, and how the model depends upon the information fed into it" (Saltelli et al. 2000). The combination of AHP and SA are instrumental in transportation planning, due in large part to the complexities of the project itself, as well as the varied groups of DMs and stakeholders, and the plethora of required criteria in the conceptual and preliminary engineering stages; parameters including technical, economical, and environmental elements aid in developing a compromise solution among conflicting parties that are dominant in mass transportation planning projects (Zak 2014). Both AHP and SA are incorporated into this research through resource criteria weighting and statistical suitability models.

GIS AND MCDM/A: TRANSPORTATION & CRITERIA SCREENING ANALYSES

GIS and MCDM/A as a joint field of study has created immense opportunities for solving complex and spatial-based transportation projects. Chen et al. (2010) provide a very concise overview of GIS-based MCDM/A as it "…involves a set of geographically defined basic units, and a set of evaluation criteria represented as map layers or attributes. Based on a particular ranking schema, [GIS-MCDM/A] ultimately informs a spatially complex decision process" (Chen et al. 2010). Malczewski and Rinner (2015) provide a more detailed description of the GIS-MCDM/A relationship, proposing that GIS's problem-solving capabilities are strengthened by MCDM/A integration, such that "…a decision maker can introduce value judgments (i.e., preferences with respect to evaluation criteria and/or decision alternatives) into GIS-based decision making" (Malczewski, Rinner 2015). Their book concentrates on the cooperative and complimentary nature of GIS and MCDM/A, as MCDM/A can aid in translating the results of GIS analyses and provide a basic foundation for the decision maker to identify and defend the most viable solution; MCDM/A offers a systematic and defensible approach for utilizing GIS analyses in the decision making process. With specific regards to public transportation planning, the integration of GIS and MCDM/A improves the understanding of results by organizing information and visually presenting potential trends, relationships and anomalies in spatial-based decision making.

In the past twenty years, applications of GIS-MCDM/A for transportation planning, specifically for linear alignment projects, have emerged as successful mechanisms for conflict resolution among decision makers and key stakeholders. Zak (2010) presents a strong characterization of the role of the decision maker as "…the authorities play a double role of a stakeholder and decision maker at the same time. They have to satisfy, at least to some degree, contradictory interests and requirements…and add their own constraints and preference" (Zak 2010). The roles of groups and individuals in public transportation projects are of critical importance, and MCDM-A methods in GIS have emerged to develop compromise solutions among conflicted interests. An adaptation of the MCDM/A process, as proposed by Zak (2010), is illustrated in the following image (Figure 1). The following research presents an innovative application of GIS-MCDM/A for a high profile rail alternative analysis, in which stakeholders are engaged at the federal, state, local, and privately level.

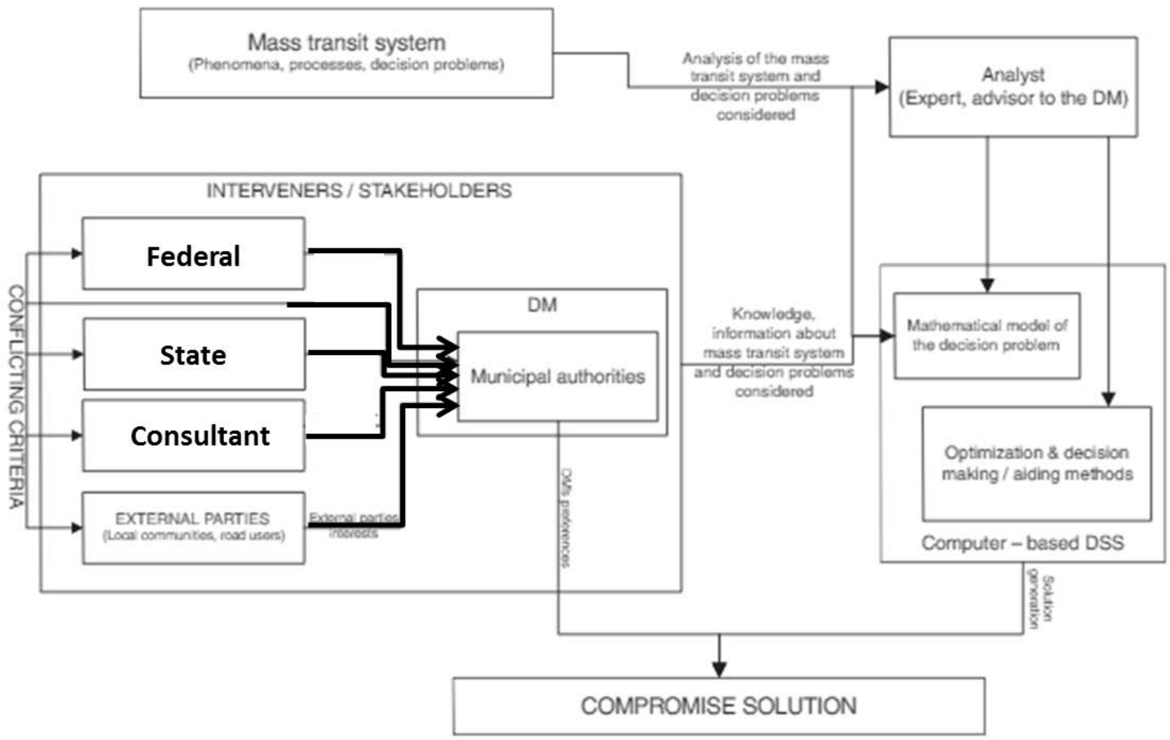


Figure 1. GIS-MCDM/A process, adapted from "The universal scheme of the MCDM/A process in mass transit systems", Zak (2010).

Research Approach

This research focuses on the Washington, D.C. to Richmond, known as "DC2RVA", High Speed Rail Project as the case study for the evaluation of rail alternatives analyses. The primary research goal is to identify and evaluate the synergistic relationship of GIS and MCDM/A through the analysis of a specific alternatives portion of the "DC2RVA" project. The "DC2RVA" rail corridor runs 123 miles north to south, and is geographically portioned, at regionalized segments, to evaluate alignment alternatives based upon environmental and social impacts. The "DC2RVA" area options are broken down into six sections, with a nomenclature that follows their approximate spatial locations; from north to south – Arlington, Northern Virginia, Fredericksburg, Central Virginia, Ashland, and Richmond.

Given the extensive nature of analysis that is required for the entire "DC2RVA" corridor, the analysis for this study was focused on the locality alignment options for Hanover County and the Town of Ashland, VA. This section of the corridor is approximately eleven miles, and is the most heavily contested region for Greenfield alignment proposals. The Town of Ashland was established based upon the rail line in the late 1800s, and is considered an authentic railroad town. Thus, there is significant community sensitivity to the impacts of new rail construction, in terms of community, environmental, and resource impacts. In this paper, three Ashland rail alternatives were analyzed utilizing GIS techniques and MCDM/A methods and theories; a fourth base option, identified as pre-existing track through the center of town, was incorporated for a comparative evaluation. The three options are ordered from east to west, intersecting a combination of both rural and urban land uses, including an alignment option along Interstate 95, as shown in Figure 2. As a locality-specific research, the four alternatives were identically screened with a combination of criteria from the official project screening efforts. The critical difference from previous impact screenings was the incorporation of criteria weights for each resource, as determined by the hypothetical project decision makers, for the sake of a modeling simulation. The alignment data, and all related rail components, were conceptually developed from publicly available mapping located on the DC2RVA project website.

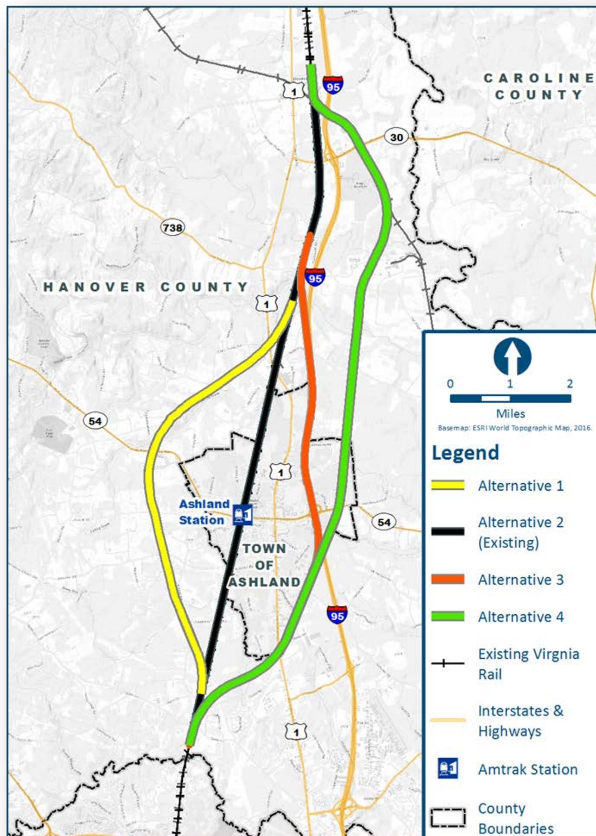


Figure 2. Rail Alignment Options (Bridget Ward, 2017).

METHODOLOGY

INTRODUCTION

The previous project screening efforts, employed directly by the "DC2RVA" project team, were succinct in terms of reviewing and comparing explicit acreage impacts among the alternatives; standardization methods were not utilized to incorporate decision maker preferences or prioritized criteria rankings. These alternative screenings instead grouped criteria into distinct sets at each stage, as an effort to produce a basic representation of the required (mandated by the Department of Transportation, Section 4(f) and Section 6(f)) data screenings for transportation projects. Due to the limited nature of publicly available data, the following study consolidated the resources screenings into one process. However, all of the screened datasets were normalized through weight assignments within each alternative. Following the criteria weight assignments, total scores for each criteria and its resultant normalized acreage impact were calculated for comparison among the four alternatives. Both Esri ArcGIS and Clark Labs' TerrSet, third-party software, were employed for spatial simulation methods of the calculated impacts. The following sections discuss the data acquisition, organization, and initial analysis required prior to the criteria weighting process.

BASE DATA DEVELOPMENT

Base data, including the proposed rail alignments and their respective right-of-way widths, were manually approximated from data displayed on the DC2RVA project website (Ashland/Hanover County Alternatives, 2016). A single, centerline track was first developed for each alternative, in order to create a basis for the impact area widths within each option. Derived from a combination of CSX standards and DC2RVA's Basis of Design (BOD) document, proposed typical maximum right of way widths ranged from 135 feet to 150 feet. Additionally, the location of this study's proposed alignments in new Greenfield areas influenced the right of way width to encapsulate a minimum of 135 feet; 140 feet was the final determined right of way/impact width to maintain a conservative impact review among the three alternatives. For the purpose of this study, the right of way/impact areas were the primary base data features in the screening process.

CRITERIA CONTENT AND GIS ANALYSIS

Following the base data creation, criteria resources were acquired through a thorough research of publicly available data. Table 1 presents the criteria data utilized in this study, along with a general assessment of the impact severity. As shown, impact severity was rated on a three-tiered scale, in which criteria was rated "high", "medium", or "low" based upon a combination of regulatory significance and mitigation requirements. While this study succeeded in acquiring a range of criteria resources, the absence of additional critical data, including cultural features, was a noted challenge to impact results. Data "gap" instances were prevalent, due in large part to much of the original project criteria resources maintaining non-disclosure agreements with the DC2RVA project team; specific county and city contracts also restricted data to exclusive private project use.

Table 1. Criteria Resources and Impact Severity

Criteria	Source	Impact Severity	Geometry
Cultural	Hanover County GIS Data; "Historic Sites"	High	Vector, Polygon, Point
Schools	Hanover County GIS Data; ESRI Community Facilities NA Streets	High	Vector, Polygon, Point
Parks	Virginia Department of Conservation and Recreation (VDCR); ESRI Community Facilities NA Streets	High	Vector, Polygon
Agricultural & Forestal Districts	Virignia Department of Forestry (VDOF)	Medium	Vector, Polygon
Wetlands	National Wetlands Inventory (NWI)	Low	Vector, Polygon
Wildlife Corridors	VDCR – Natural Landscape Assessment (NLA)	Medium	Vector, Polygon
Land Use	National Land Cover Database (NLCD)	Low	Vector, Polygon

Through the utilization of ESRI's ArcGIS Desktop Modelbuilder, the criteria resource data were automatically screened to each alternative impact area's given extent (Figure 3). By means of a basic overlay technique, "Clip" and "Intersect" functions were executed within the model on each of the resources to ensure a uniform and quality-controlled process. The output of this model resulted in raw vector acreage impacts for the resources in each alternative. The resultant criteria impact layers from this initial screening process were then standardized and converted to raster format, which is the required modeling format for subsequent multi-criteria decision analyses.

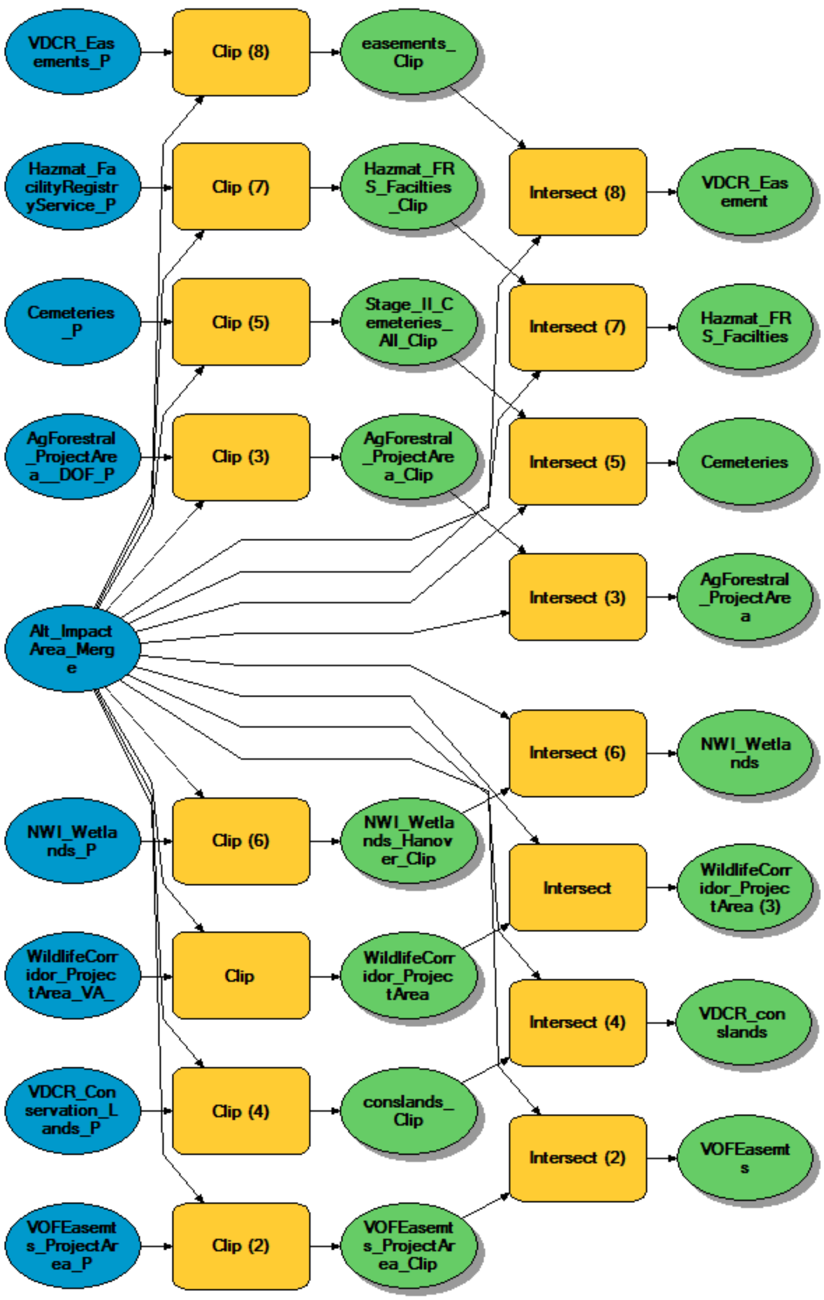


Figure 3. Initial Modelbuilder Screening of Criteria Data (Bridget Ward, 2017).

Standardization & Conversion

The standardization and conversion process required that the data be projected to a consistent coordinate system, be uniformly converted to raster format, and be normalized to a standard value scale for conclusive suitability analysis; raster is the required format for weighting techniques, due to its continuous surface to account for imprecisions in given criteria phenomena . First, the criteria impact feature layers were projected to the Virginia State Plane South FIPS 4502 US Feet coordinate system, which aligns with the project's geographic location and maintains readily-understandable feet measurement units. In order to then convert the data to raster and develop scaled values, a standard raster cell-size needed to be calculated for all criteria data. Since all of the criteria data was clipped to identical alternative extents, a basic python code was utilized for a feature layer containing all four alternative areas used in the study (Figure 4). Upon raster conversion, the criteria were then reclassified on a valued scale of 0-3 for a simplified interpretation of the final results with decision maker weight applications. As shown in Table 2, a majority of the resources were scaled in binary format, with the exception of wetlands and land use, which maintained tiered-values by feature subtype.

```
ext=arcpy.Describe("your-layer").extent
if ext.width < ext.height:
    cellsize=ext.width/250
else:
    cellsize=ext.height/250
print cellsize
```

Figure 4. Standard Formula for Cell-Size Calculation (Esri, 2017).

Table 2. Scaled Criteria Values for Raster Processing

Criteria	Resource	Value	Key
C1	Cultural	0/1	
C2	Park	0/1	
C3	School	0/1	
C4	Agricultural and Forestal District	0/1	
C5	National Wetlands Inventory (NWI)	0	No Impact
		1	Lakes, Ponds
		2	Wetlands
C6	Wildlife Corridor	0/1	
C7	National Land Cover Database (NLCD)	0	No Impact
		1	Open Space
		2	Agriculture
		3	Urban

A standardization of criteria weighting techniques was also employed in this study's process. In both ArcGIS and TerrSet analysis, criterion weights maintained the following base properties, as prescribed by Hobbs and Meier (2000):

$$0 \leq w_k \leq 1 \text{ and } \sum_{k=1}^{n} = 1$$

Global criteria weighting was utilized throughout this study based on the relatively homogenous project area across each alternative. Malczewski (2006) defines global weighting as a method that maintains the assumption that the alternatives are spatially consistent. Based upon the proximity of alternatives to one another, and also their geographical extent of approximately 11 miles north to south, the additional steps required for a more spatially explicit criteria method were deemed unnecessary.

In the following analysis scenarios, Part I and Part II respectively, the criteria acreage results within each alternative were normalized similar to the initial weighted criteria and summarized in two distinct processes; weighted sum approach utilizing ArcGIS and a weight linear combination technique through TerrSet IDRIS GIS Analysis processing.

Analysis & Results Part I: ArcGIS & Weighted Sum

The first set of MCDM/A analyses were performed in ArcGIS utilizing the "Weighted Sum Tool", which is a simplified variation of additive overlay analysis. Based upon the reclassified raster values from Table 2, a factor weight of "1" was modeled in the tool in order for the results to output a direct summation of the originally assigned values. On a scale of 0 to 6, the resultant weighted sum output is shown in tabular and spatial format through Table 3 and Figure 5, respectively.

Table 3. ArcGIS Weighted Sum Results

Weighted Sum Results	Value (Pixel Count)						
Alternative Option	1	2	3	4	5	6	Total
Alternative 1	535	758	350	151	12	2	1808
Alternative 2	300	71	342	61	5	0	779
Alternative 3	608	297	873	77	29	7	1891
Alternative 4	584	531	524	84	11	2	1736

Key:	
(grey)	Existing Conditions
(yellow)	Lowest Impact Counts

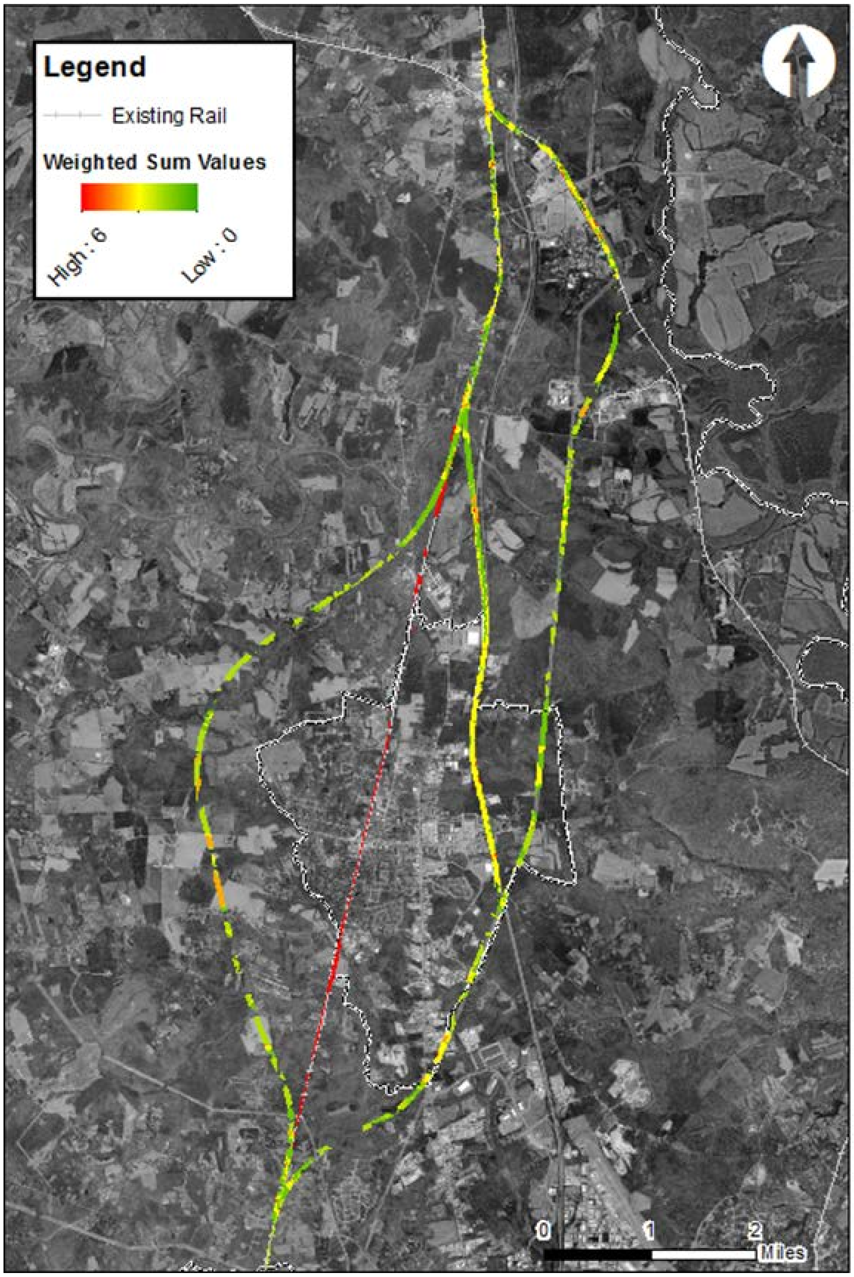


Figure 5. Weighted Sum Raster Output (Bridget Ward, 2017).

As shown in Table 3, Alternative 4, or the easternmost alternative, was identified as the alignment option was the lowest pixel counts (impact values) among all potential options; alternative 2, the existing rail alignment, was shown in the output for a comparative review of the existing conditions.

While a user can extrapolate the effects of applying weighted sum values other than "1" to each of the criteria, the goal of this study's use of the ArcGIS Weighted Sum Tool was to present how site-feasibility decision making is enhanced through spatial suitability modeling. An expanded discussion on the potential limitations to this particular software tool is included in the conclusion and recommendations.

Analysis & Results Part II: TerrSet & Weighted Linear Combination

Following an initial analysis of the criteria through the ArcGIS Weighted Sum Tool, a more in-depth analysis was conducted utilizing Clark Lab's TerrSet Software. TerrSet, and specifically the IDRISI GIS Analysis Software, is a suite of GIS applications designed by Clark Labs at Clark University in Worcester, MA for manipulating raster geospatial datasets; a large portion of the modeling software is dedicated to decision support and uncertainty management, which is implemented in this research. In contrast to ArcGIS, TerrSet offers expanded mechanisms in terms of decision maker input and foundational statistical weighting, thus offering a more accredited decision-making approach. For the purposes of this study, the Multi-Criteria Evaluation (MCE) Tool and the Spatial Decision Modeler (SDM) were employed for a comprehensive weighted suitability analysis.

Through the MCE Tool, which offers a variety of weighting options, the selected weighting method was a variant of Ordered Weighted Averaging (OWA), being that of the Weighted Linear Combination (WLC) technique. In terms of tradeoff and risk, the WLC method, as discussed by the TerrSet developers, is neither risk-averse nor risk-taking; this approach is a conservative approximation of weighting resources with consideration for full tradeoffs and medium-level risk (TerrSet Manual, 2016).

This study's analysis was performed through TerrSet beginning with the development of a SDM that reclassified the criteria for each alternative into standardized "fuzzy" sets; a monotonically increasing curve was applied to each criterion with control points 0 and 1, to reflect the range of suitability values. Following this fuzzification process, the MCE Tool was employed to select the WLC technique and establish preference weights.

The resultant overall suitability output for each alternative was produced following the MCE weight assignment process. An example structure of the SDM for this research is shown in Figure 6.

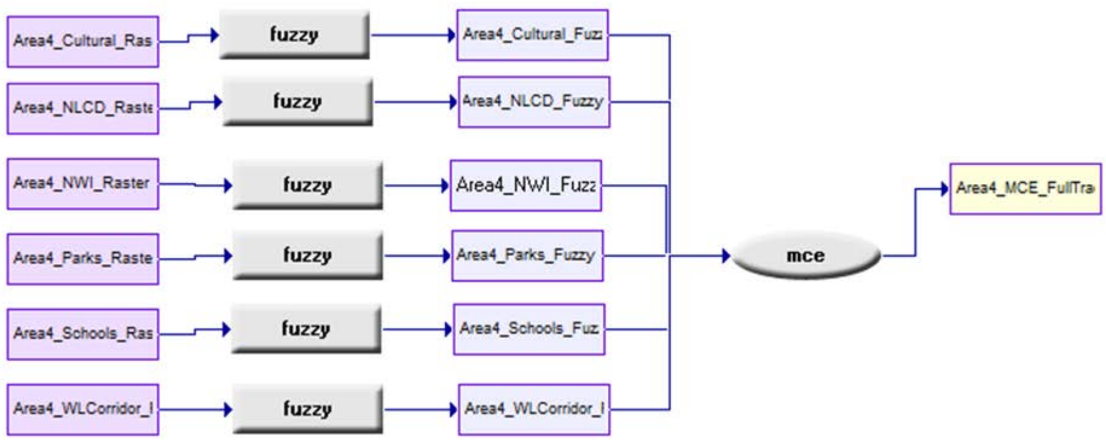


Figure 6. TerrSet Spatial Decision Modeler (Bridget Ward, 2017).

The MCE Tool is perhaps the most critical element of the decision support analysis performed in this study. Upon the selection of WLC as the decision strategy, the "WEIGHT" Module was implemented to prioritize criteria based upon decision maker preferences. This module incorporates the use of pairwise comparisons, based upon the Analytical Hierarchy Process (AHP), which is grounded in operations research theory and considered one of the most extensive approaches to multicriteria decision analysis (Saaty 1980). In this study, the pairwise comparisons equipped the decision maker to rank the relative importance of each criterion to one another (Figure 7).

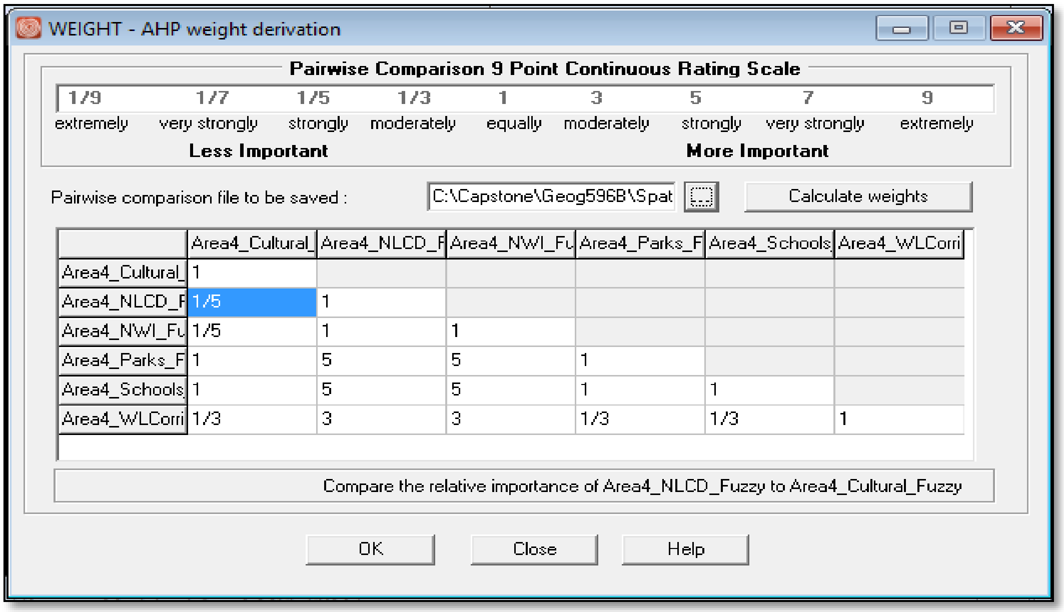


Figure 7. Pairwise Comparisons Rated Through the Weight Module (TerrSet, 2017).

Upon ranking the criteria resources relative to one another, the module calculated the criterion weights for each alternative, inclusive of a consistency ratio score. The consistency ratio, which must be less than or equal to 0.1 for an "acceptable" weighting calculation, determines how well-fit the resultant weightings are; large deviations among the pairwise comparisons would contribute to an "unacceptable" consistency ratio. The average consistency ratio among the four alternatives for this study was .015. The following figure summarizes the calculated weights and the corresponding consistency ratio (Figure 8). Although all criteria were not present in every alternative, equivalent pairwise comparisons (preferences) were assigned across each alternative option.

Criteria Weights Assigned by AHP Pairwise Comparisons				
	Alternative			
Criteria	1	2	3	4
C1…	0.4665	0.5596	0.5596	0.2648
C2…	0	0	0	0.2648
C3…	0	0	0	0.2648
C4…	0.1939	0	0	0
C5…	0.0728	0.0955	0.0955	0.0481
C6…	0.1939	0.2495	0.2495	0.1094
C7…	0.0728	0.0955	0.0955	0.0481
Consistency Ratios:	CR = 0.01	CR = 0.02	CR = 0.02	CR = 0.01

Criteria	Resource
C1	Cultural
C2	Park
C3	School
C4	Agricultural and Forestal District
C5	National Wetlands Inventory (NWI)
C6	Wildlife Corridor
C7	National Land Cover Database (NLCD)

Figure 8. Criteria Weights, Consistency Ratios, and Key (Bridget Ward, 2017).

After developing "acceptable" criteria weights, spatial and tabular results were produced for each alternative option. The SDM outputted both a raster display and numeric histogram to interpret the WLC results for each alternative; the detailed histograms and suitability maps are included in this report in Appendix A. Each of the alternatives was scaled from 0 to 1 for suitability, with the tabular impact results divided into equal class widths of 0.1 to simplify the comparisons of the frequency values. The following table provides a succinct, summarized view of each alternative's impact frequencies (Table 4).

Table 4. OWA–WLC Summarized Results

OWA–WLC Results			Alternative Option Impact Frequencies			
Class	Lower Limit	Upper Limit	1	2	3	4
0	0	0.099999	180333	180746	180445	180310
1	0.1	0.199999	228	10	50	94
2	0.2	0.299999	82	116	170	375
3	0.3	0.399999	0	42	59	192
4	0.4	0.499999	106	0	3	
5	0.5	0.599999	41	8	175	
6	0.6	0.699999	68	49	62	
7	0.7	0.799999	113		4	
8	0.8	0.899999			2	
9	0.9	0.999999			1	

Key:	
(grey)	Existing Conditions
(yellow)	Lowest Impact Counts

Similar to the results of the ArcGIS process, the TerrSet modeling identified rail alternative alignment 4 as the least-impacted option. However, it is critical to reflect on the subjective weighting process that was implemented through the TerrSet analysis to result in an identical output to the first analysis. In contrast to ArcGIS, TerrSet enabled the decision maker to evaluate preferences and make specific judgments for each criterion screened, with criteria weights then appropriately scaled based on their importance. Through TerrSet, the decision maker was able to reach a similar conclusion, with the added foundation of statistical theories to further validate and bring credibility to this decision-making process.

Conclusion & Recommendations

The objective of this research was to identify and evaluate the synergistic relationship of GIS and MCDM/A through the analytical case study of the DC2RVA High Speed Rail Project. Inclusive of this objective was the goal to produce a single, feasible alignment option among the four rail alternatives. Through the analyses performed in both ArcGIS and TerrSet, alternative four was identified as the "optimal" rail alignment option. However, it is important to note the caveats associated with this conclusion; alternative four was identified as the most "feasible" option strictly based upon the limited availability of data. Furthermore, this alignment selection does not provide consideration for alignment connectivity to the remainder of the corridor operating to the North and to the South of the study area. While this study presents a model approach for integrating GIS and MCDM/A, the specific results, in their current form, should be interpreted as a "snapshot" analysis of the larger rail corridor that should be further evaluated in future studies.

Since this study was an abbreviated analysis of a much larger project, there are several recommendations that should be given consideration for prospective additional studies. First and foremost, a modeled simulation of the remaining DC2RVA study area should be performed; 110 miles remain in the corridor, which may widen the possibility for bypass routes beyond the alternatives examined in this study. Additionally, more variables could be incorporated into the screening analysis, both quantitative and qualitative in nature. Future criteria factors may include demographics, real estate assessments, vetted historical resources, and train modeling characteristics such as elements of speed, curve, and slope. Along with increased screening variables, the project decision makers may also consider the screening process as an opportunity for public involvement and citizen-based criteria rankings.

However, based upon the successful approach to identifying a feasible alignment option through this research, this study should validate the proposed claim that the implementation and synergistic relationship of GIS and MCDM/A is an effective approach for rail alignment suitability analysis. Both GIS and MCDM/A provide complimentary processes in spatial and statistical modeling, including each component's ability to facilitate hierarchal decision-making structures, to prioritize factors, and to engage decision makers and stakeholders through each procedural step. Additionally, MCDM/A techniques and geovisualization have readily presented the criteria impacts and concurrently enabled the decision-maker to recognize the trade-offs among criteria weight assignments. Through a combination of the foundational criteria-weighting techniques and the incorporation of decision-maker preferences, this research should contribute to setting a precedent for a GIS-based approach to alternative analyses. In this effort, GIS and MCDM/A have identified one viable solution among four seemingly feasible options through readily-understandable quantitative and qualitative results.

WORKS CITED

"Ashland/Hanover County Alternatives." D.C. to Richmond Southeast High Speed Rail. 2016. Accessed April 20, 2017. http://dc2rvarail.com/about/ashland-alternatives/.

Bouyssou, D. Evaluation and Decision Models with Multiple Criteria: Stepping Stones for the Analyst. New York: Springer Science Business Media, 2006.

Chen, Ye, D. Marc Kilgour, and Keith W. Hipel. "Screening in Multiple Criteria Decision Analysis." Decision Support Systems 45, no. 2 (2008): 278-90. Accessed October 12, 2016. doi:10.1016/j.dss.2007.12.017.

Chen, Y., J. Yu, and S. Khan. "Spatial Sensitivity Analysis of Multi-criteria Weights in GIS-based Land Suitability Evaluation." Environmental Modelling & Software 25, no. 12 (2010): 1582-591. Accessed October 13, 2016. doi:10.1016/j.envsoft.2010.06.001.

Collins, Michael G., Frederick R. Steiner, and Michael J. Rushman. "Land-Use Suitability Analysis in the United States: Historical Development and Promising Technological Achievements." Environmental Management 28, no. 5 (2001): 611-21. Accessed October 8, 2016. doi:10.1007/s002670010247.

"DC2RVA_SEHSR_Final_Basis_of_Design_02-24-2015.pdf." D.C. to Richmond Southeast High Speed Rail. February 24, 2015. Accessed April 18, 2017. http://dc2rvarail.com/resources/documents/.

"D.C. to Richmond Southeast High Speed Rail :: Home." D.C. to Richmond Southeast High Speed Rail :: Home. Accessed November 08, 2016. http://dc2rvarail.com/.

"GeoPlanner for ArcGIS." Prepare your data for weighted overlay—GeoPlanner for ArcGIS | ArcGIS. Accessed March 29, 2017. https://doc.arcgis.com/en/geoplanner/documentation/prepare-your-data.htm.

Hobbs, Benjamin F., and Peter Meier. "The Application of MCDM Methods." International Series in Operations Research & Management Science Energy Decisions and the Environment, 2000, 15-44. doi:10.1007/978-1-4615-4477-7_2.

Jankowski, Piotr. "Integrating Geographical Information Systems and Multiple Criteria Decision-making Methods." International Journal of Geographical Information Systems 9, no. 3 (1995): 251-73. Accessed October 13, 2016. doi:10.1080/02693799508902036.

Jankowski, Piotr, Natalia Andrienko, and Gennady Andrienko. "Map-centred Exploratory Approach to Multiple Criteria Spatial Decision Making." International Journal of Geographical Information Science 15, no. 2 (2001): 101-27. Accessed October 9, 2016. doi:10.1080/13658810010005525.

Keeney, Ralph L. "On the Foundations of Prescriptive Decision Analysis." Utility Theories: Measurements and Applications Studies in Risk and Uncertainty, 1992, 57-72. Accessed October 10, 2016. doi:10.1007/978-94-011-2952-7_3.15

Malczewski, Jacek. Gis-based Land-use Suitability Analysis: A Critical Overview. Oxford: Elsevier, 2004.

Malczewski, Jacek, and Claus Rinner. "Multicriteria Decision Analysis in Geographic Information Science." Advances in Geographic Information Science, 2015. doi:10.1007/978-3-540-74757-4.

McKenna, Christopher K. Quantitative Methods for Public Decision Making. New York: McGraw-Hill, 1980.

Saaty, Thomas Lorie. The analytic hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill, 1980.

Saltelli, A., K. Chan, and E. Marian. Scott. *Sensitivity Analysis*. Chichester: Wiley, 2000.

Stich, B., and J. H. Holland. "Using a Multiple Criteria Decision-Making Model to Streamline and Enhance NEPA and Public Participation Processes." Public Works Management & Policy 16, no. 1 (2011): 59-89. Accessed October 13, 2016. doi:10.1177/1087724x10390227.

"TerrSet-Manual." Clark Labs. October 2016. Accessed April 12, 2017. https://clarklabs.org/wp-content/uploads/2016/10/Terrset-Manual.pdf.

Zak, Jacek. "The Methodology of Multiple Criteria Decision Making/aiding in Public Transportation." Journal of Advanced Transportation 45, no. 1 (2010): 1-20. Accessed October 11, 2016. doi:10.1002/atr.108.

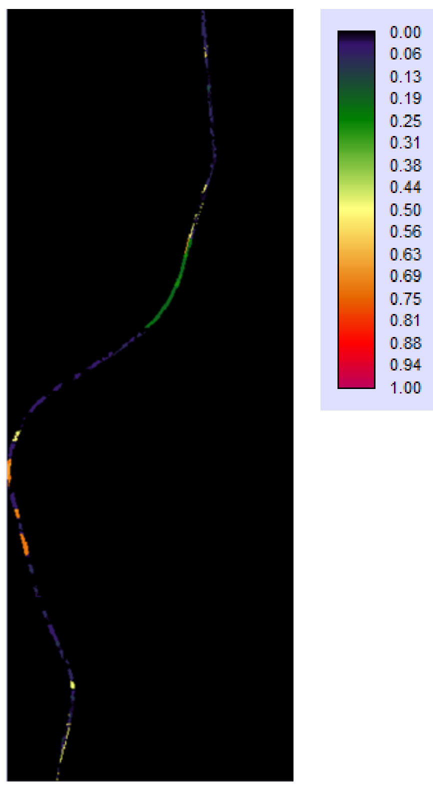
Żak, Jacek, Szymon Fierek, and Mirosław Kruszyński. "Evaluation of Different Transportation Solutions with the Application of Macro Simulation Tools and Multiple Criteria Group Decision Making/Aiding Methodology." Procedia - Social and Behavioral Sciences 111 (2014): 340-49. Accessed October 12, 2016. doi:10.1016/j.sbspro.2014.01.067

Appendix A - TerrSet Weighted Linear Combination Histograms

Histogram of Alternative Area 1

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
0	0	0.0999990000	180581	0.9978449586	180581	0.9978449586
1	0.1000000000	0.1999990000	0	0	180581	0.9978449586
2	0.2000000000	0.2999990000	109	0.0006023064	180690	0.9984472650
3	0.3000000000	0.3999990000	0	0	180690	0.9984472650
4	0.4000000000	0.4999990000	0	0	180690	0.9984472650
5	0.5000000000	0.5999990000	13	0.0000718347	180703	0.9985190997
6	0.6000000000	0.6999990000	0	0	180703	0.9985190997
7	0.7000000000	0.7999990000	15	0.0000828862	180718	0.9986019860
8	0.8000000000	0.8999990000	0	0	180718	0.9986019860
9	0.9000000000	0.9999990000	0	0	180718	0.9986019860
10	1.0000000000	1.0999990000	253	0.0013980140	180971	1.0000000000

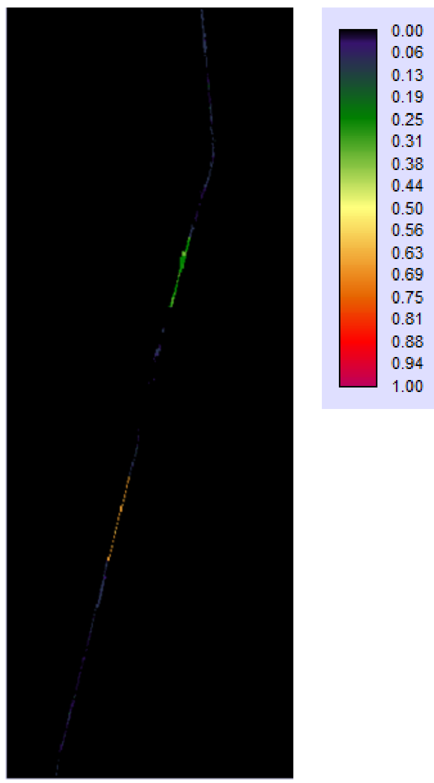
Class width	0.1000000000
Display minimum	0
Display maximum	1
Data minimum	0
Data maximum	1
Mean	0.0016466727
Stand. Deviation =	0.0630993541
N	180971



Histogram of Alternative Area 2

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
0	0	0.0999993450	180746	0.9987567069	180746	0.9987567069
1	0.1000000000	0.1999993450	10	0.0000552575	180756	0.9988119643
2	0.2000000000	0.2999993450	116	0.0006409867	180872	0.9994529510
3	0.3000000000	0.3999993450	42	0.0002320814	180914	0.9996850324
4	0.4000000000	0.4999993450	0	0	180914	0.9996850324
5	0.5000000000	0.5999993450	8	0.0000442060	180922	0.9997292384
6	0.6000000000	0.6999993450	49	0.0002707616	180971	1.0000000000

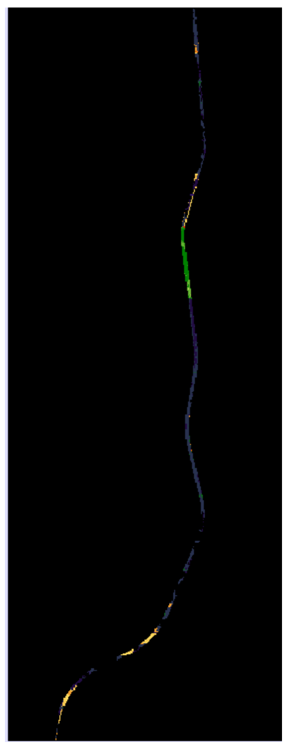
Class width	0.1000000000
Display minimum	0
Display maximum	0.7000000477
Data minimum	0
Data maximum	0.6550344825
Mean	0.0006634154
Stand. Deviation =	0.0517986109
N	180971

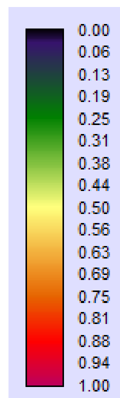


Histogram of Alternative Area 3

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
0	0	0.0999990955	180445	0.9970934570	180445	0.9970934570
1	0.1000000000	0.1999990955	50	0.0002762874	180495	0.9973697443
2	0.2000000000	0.2999990955	170	0.0009393770	180665	0.9983091214
3	0.3000000000	0.3999990955	59	0.0003260191	180724	0.9986351404
4	0.4000000000	0.4999990955	3	0.0000165772	180727	0.9986517177
5	0.5000000000	0.5999990955	175	0.0009670058	180902	0.9996187234
6	0.6000000000	0.6999990955	62	0.0003425963	180964	0.9999613198
7	0.7000000000	0.7999990955	4	0.0000221030	180968	0.9999834228
8	0.8000000000	0.8999990955	2	0.0000110515	180970	0.9999944743
9	0.9000000000	0.9999990955	1	0.0000055257	180971	1.0000000000

Class width	0.1000000000
Display minimum	0
Display maximum	1
Data minimum	0
Data maximum	0.9045094848
Mean	0.0017878129
Stand. Deviation =	0.0550840307
N	180971





Histogram of Alternative Area 4

Class	Lower Limit	Upper Limit	Frequency	Prop.	Cum. Freq.	Cum. Prop.
0	0	0.0999996390	180310	0.9963474811	180310	0.9963474811
1	0.1000000000	0.1999996390	94	0.0005194202	180404	0.9968669013
2	0.2000000000	0.2999996390	375	0.0020721552	180779	0.9989390565
3	0.3000000000	0.3999996390	192	0.0010609435	180971	1

Class width	0.1000000000
Display minimum	0
Display maximum	0.4000000060
Data minimum	0
Data maximum	0.3610000014
Mean	0.0011915943
Stand. Deviation =	0.0521902683
N	180971