An Analysis of Spatially-enabled Mobile Decision Support Systems in a Collaborative Decision-Making Environment

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Abstract

The effectiveness of decision-making processes has been enhanced by integrating multi-criteria decision analysis (MCDA) and geographic information system (GIS) methods to solve more complex spatial problems that were not possible to solve using conventional GIS methods.

A spatial decision support system (SDSS) supports various stakeholders in the decision-making process, by processing data using GIS-MCDA methods.

A newer category of SDSS is spatially-enabled mobile decision support systems (MDSS) that can enable the accessibility of real-time spatial information over wireless networks while in the field. Using portable devices, MDSS provides a range of benefits in supporting mobile decision-makers.

In this research project, the aim was to illustrate the applicability of a spatially-enabled MDSS in a collaborative decision-making process. This was done by developing a prototype of a spatially-enabled MDSS that solved route optimization problems, in the context of creating race routes for running events. The project also provides a deeper insight to the various MCDA techniques and methods.

Although this research project shows the potentially huge value a spatially-enabled MDSS has in many different applications and the ability to make rapid decisions in the field, many limitations and obstacles came to light, such as some users' reluctance to use new technologies and prohibitive cost factors. Other stumbling blocks against using a MDSS for complex spatial problems were the lack of guidance for selecting the most appropriate MCDA method for a specific decision-making problem and the overall complexity of MCDA methods.

Keywords: multi criteria decision analysis, GIS, mobile decision support system, route optimization

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List of Abbreviations

AHP	**Analytic Hierarchy Process**
AI	Artificial Intelligence
ANP	Analytic Network Process
API	Application Programming Interface
AVG	Average
CSS	Cascading Style Sheets
DEM	Digital Elevation Model
DSS	Decision Support System
ELECTRE	ELimination Et Choix TRaduisant la REalité
ESTYLF	National Spanish Fuzzy Logic Society
GADM	Database of Global Administrative Areas
GCS	Geographic Coordinate System
GIS	Geographical Information Systems
GML	Geography Markup Language
GPS	Global Positioning System
HTML	Hypertext Markup Language
HTML5	Hypertext Markup Language revision 5
IDE	Integrated Development Environment
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MADA	Multi-Attribute Decision Analysis
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MAX	Maximum
MCDA	Multi-Criteria Decision Analysis
MDSS	Mobile Decision Support Systems
MIN	Minimum
MODA	Multi-Objective Decision Analysis
MVP	Minimum Viable Product
OSM	Open Street Map
PC	Personal Computer
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
SDK	Software Development Kit
SDSS	Spatial Decision Support System
SQL	Structured Query Language
SRID	Spatial Reference ID
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

TV	Television
UI	User Interface
UWP	Universal Windows Platform
WKT	Well-Known Text
WLAN	Wireless Local Area Network.
WLC	Weighted Linear Combination
XML	Extensible Markup Language

1. Introduction

1.1 Background

Geographic Information Systems (GIS) consist of an integrated set of components capable of analysing and visualising spatial data, and can among many things assist in decision making. Multi-criteria decision analysis (MCDA) consists of a framework and various algorithms used for the prioritisation and evaluation of various alternatives that can assist in the decision-making process. The symbiotic relationship that exists when integrating GIS and MCDA provides a wealth of benefits to decision-makers faced with spatial problems (Boroushaki & Malczewski, 2010).

The use of a GIS that integrates MCDA algorithms provides a useful platform to help facilitate decision-makers to express their thoughts about various spatial problems, to visualise the problems via digital maps, and to express their preferences regarding various alternatives.

Mobile Decision Support Systems (MDSS) is a relatively new category of decision support systems (DSS) that use portable devices such as smart phones and can communicate over wireless networks or the Internet. MDSS provides a range of benefits in supporting decision-makers that need to be mobile, such as in the case of investigating a dynamic environment that might influence a decision. In this case, the accessibility of real-time spatial information and GPS coordinates from mobile devices can supplement traditional web or desktop Spatial Decision Support Systems (SDSS) (Haghighi, 2013; Perez et al, 2008; Tsou, 2006).

According to Tsou (2006), by using wireless technology and advanced GIS tools, decision makers can benefit from real-time information obtained from in-field personnel, and in-field personnel can in turn benefit from more rapidly updated information from decision makers, which facilitates a more efficient decision-making process.

There are some usability and interoperability issues with regards to mobile Internet access, such as incompatibility of mobile devices with desktop operating systems (Perez et al. 2008). Usability issues include speed, small screen size, simplistic navigation controls, inconsistent format of web pages on mobile devices, and message size among others.

The advancement of certain mobile technologies, such as smart phones, has created new opportunities for the use of mobile devices and has provided a platform for the delivery of real-time data. However, questions remain regarding the integration of the information into the DSS and how this information is processed to enable real-time mobile decision-making (Perez et al., 2008; Haghighi, 2013).

According to Perez et al. (2008) there is a necessity to establish principles, methodologies and guidelines, in order to use the functionality of mobile devices effectively and efficiently.

Referring to the integration of a collaborative spatial decision support system (SDSS) architecture on both web and mobile platforms, Tsou (2006) states that only a few SDSS have used both technologies in a collaborative decision-making environment, with the fundamental problem being the lack of a communication framework to integrate internet and mobile GIS.

The issues stated previously regarding the interoperability between heterogeneous platforms, such as mobile and desktop operating systems (Perez et al., 2008), is further elaborated on by Tsou (2006), stating the need to facilitate and enhance the interoperability between various heterogeneous systems and platforms. According to Tsou (2006) a gap exists in the research of collaborative GIS with regards to the connection between GIS applications and usage and system design.

1.2 Research Objectives

The objective of this research project is to illustrate the applicability of a collaborative SDSS that can be used by various people involved in the decision-making process, across both desktop and mobile platforms. People involved in the decision-making process might need to be able to access the SDSS in a boardroom meeting on a desktop PC, whilst others might be out in the field verifying and providing 'real-time' feedback using mobile devices.

Gao (2013), in a literature analysis of mobile decision support systems research, has identified certain knowledge gaps in this field. One such gap is the lack of research on Group Support Systems (or collaborative MDSS), with only one paper out of thirty-two written on the topic during the period 2002 to 2012. In addition, there was no mention of spatially-enabled MDSS in the literature analysis.

Gao (2013) has suggested that the relevancy of MDSS research can be improved upon by conducting case studies and further elaborates by stating "MDSS research needs case studies to ensure that the research questions it is addressing are really relevant to the practices and that the contributions it makes can really benefit the professional community."

Since the literature analysis performed by Gao (2013), many research papers have been written about MDSS during the period 2013 to 2021, with the most frequent topic concerning commercial or healthcare applications of MDSS. However, during this period, only 5 research papers were found that were specifically on the topic of spatially-enabled MDSS (See Appendix 6). This confirms that insufficient research has been performed on the topic of spatially-enabled MDSS over the last decade.

To address the relevancy of the application (in practice) of an integrated mobile and desktop SDSS, an appropriate case study will be selected to showcase the benefits and limitations of the use of a collaborative, spatially-enabled MDSS for this particular purpose.

One such spatial problem that benefits from the integration of GIS and MCDA is that of route optimization. A route design system could be implemented using a GIS-MCDA approach, which would give decision makers the ability to make choices using a variety of route-selection criteria.

Since the applications of route optimisation systems are quite extensive, I have chosen to showcase the relevancy of this collaborative, spatially-enabled MDSS using a simple case study. That is, by building a system that could be used to assist decision makers during the design of a running race route of any length, from 5km to a marathon.

In the scenario of the design of a race route, decision-makers in a boardroom could benefit from the feedback coming from in-field colleagues using a spatially-enabled MDSS to verify or support decision alternatives.

The integration of GIS and specific MCDA method(s) used during the implementation of a multi-criteria spatial decision support system (MC-SDSS), across multiple platforms will be examined and will highlight the appropriateness of the selected MCDA method for the platforms in question. For example, the mobile platform might require a more simplistic MCDA method due to certain limitations already mentioned above.

1.3 Statement of Purpose

Currently, most organisations that manage race events use methods such as in-field surveying of roads, physical maps, or digital maps such as Google Maps or Google Earth, to support the design or modification of race routes. I also discovered via feedback from a questionnaire that I sent to various event organisations that a common method is to ride a calibrated bicycle to verify the route (See Appendix 1: Questionnaire and Feedback from Questionnaire). Very few organisations use a spatial-decision-support system as a tool for the design of race routes, let alone a somewhat less sophisticated (standard) GIS.

This study aims answer the following research questions:

1.3.1 Is a spatially-enabled MDSS applicable to remote decision making?

It is important to examine whether a spatially-enabled MDSS can improve the decision-making process by providing decision-makers with valuable information from remote places, which can speed up the process and make it more cost-efficient.

1.3.2 What advances in technology make it possible to a create a spatially-enabled MDSS?

It is important to illustrate how advances in technology generally mitigate prohibitive factors to implementation such as cost, time, and complexity. In addition, it is necessary to investigate how the merging of GIS and MCDA methods provide the necessary technical foundations to build a spatially-enabled MDSS, capable of supporting decision-making processes.

1.3.3 What are the practical limitations of a spatially-enabled MDSS in real word scenarios?

Every system has limitations, and it is important to investigate what these are. Knowing the limitations of a spatially-enabled MDSS helps to understand what functionality such a system can provide. In addition, it is necessary to understand what limitations hinder the implementation of a spatially-enabled MDSS and what limitations might influence the accuracy of information, such a system provides in the decision-making process.

1.3.4 Why is there slow adoption of spatially-enabled MDSS in the industry?

It is important to understand why there are not so many spatially-enabled MDSS being used in the industry and only a few research papers on the topic, even though spatially-enabled MDSS provide obvious benefits to decision-making processes.

1.4 Study Area

I have decided to select the city of Prague in the Czech Republic, as the study area for the proposed spatially-enabled MDSS prototype system. Since I live in the area, any in-field testing and verification of the spatially-enabled MDSS would be possible to perform.

Prague is the capital of Czech Republic, with a population over 1.3 million people. It is a historical city situated in the heart of Europe and is bisected by the Vltava River, which eventually flows into the Elbe River. Prague has an old town that consists of cobbled streets, picturesque squares and historical buildings. It has a sophisticated transport network, consisting of an underground metro system, trams and buses. The official language is Czech, although English is widely spoken. Some major sights include Charles Bridge, Prague Castle, Old Town Square and the National Museum. Below is a map that includes the central part of Prague (See Figure 1).
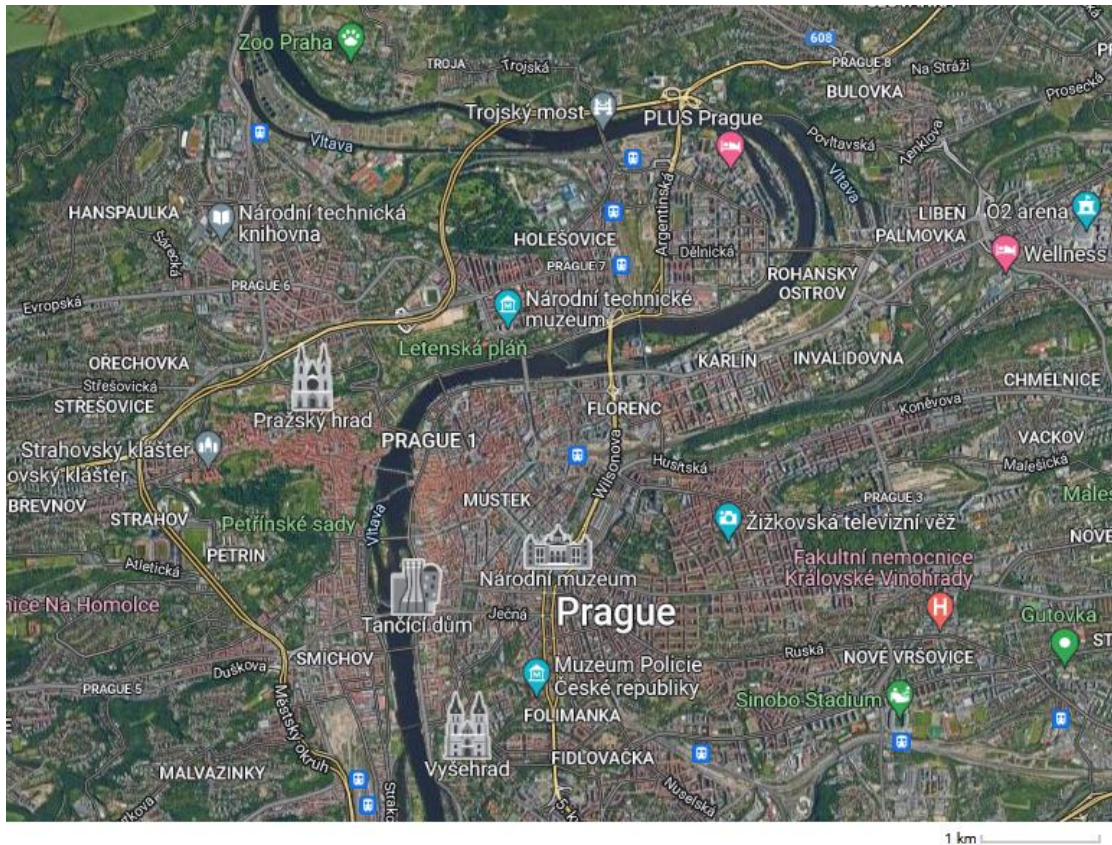
Figure 1: A map of central Prague, Czech Republic. Sourced from Google Maps.

1.5 Outline of Report

This report has been structured as five chapters. The first chapter introduces the thesis topic and gives a background to the problem being researched, discusses research objectives, provides a statement of purpose of the study, and defines the study area.

Chapter two provides further discussion and in-depth background information on the thesis topic. This chapter provides detailed information regarding GIS and network analysis; various MCDA algorithms that were considered for calculating criteria weights; routing algorithms that will be used to solve the research problem; and a discussion about advancements in technologies that enable the creation of a spatially-enabled MDSS, for example cross-platform technologies and spatial databases, to name a few.

The third chapter gives an overview of the methodologies, tools and data used in the study and the creation of the spatially-enabled MDSS and subsequent analysis. This chapter is sub-divided into sections covering Needs Analysis, Acquisition of Spatial Data, Preparation of Spatial Data, Implementation of the Route Optimizer Prototype, Testing of the Prototype in the Field, and Verification or Results using Spatial Analysis Tools.

The fourth chapter of this report contains the analysis of the results of the study and subsequent discussion related to the stated purposes of the study.

The fifth chapter consists of a conclusion which includes final thoughts, further discussion and recommendations.

2. Background Discussion

2.1 Decision Making

2.1.1 Overview

As humans we make many decisions every day. During almost every task we face, we decide on the best option from a limited set of decision alternatives. Since decision-making is so crucial to our very existence, we can find the study of decision-making in various fields such as Operations Research and Management Science, amongst others. Decision-making can range from structured to unstructured, but most spatial problems have both structured and unstructured elements in their decision making. Structured elements of decision-making can be handled automatically by a Spatial Decision Support System (SDSS), whereas unstructured elements can be handled by the decision-makers themselves (Perez et al, 2008; Malczewski & Rinner, 2015).

2.1.2 Optimization, Constraints and Models

The optimal solution to spatial decision problems can be found using spatial optimization models. Spatial optimization models aim to minimize or maximize objectives or criteria, while considering any constraints, in order to determine a set of acceptable decision alternatives (Malczewski & Rinner, 2015).

There are various models that can be used for decision-making. GIS-MCDA models can be classified as descriptive, normative, prescriptive, or constructive.

Descriptive models try to describe the behaviour of decision-makers and focus on how a decision is made. Spatial simulation modelling is an example of a descriptive model. Normative models are rather focussed on choosing the optimal alternative between competing alternatives. The main purpose of normative models is to provide a reference point whereby the efficiency of spatial systems that model the real world can be judged. Prescriptive models take it a step further by recommending an optimal state provided by normative models, considering the facts gained from descriptive models. This combination is useful in providing insights into the decision-making process itself (Dodgson et al, 2009).

Constructive models, as the name suggests, help decision-makers build their own model, tailored to a unique decision problem (Bouyssou et al. 2006). The aim is to develop a model focussed on the construction of preferences.

Decision-making problems can be defined as a single-criterion model (objective), if the problem only has a single criterion function. Multicriteria or multi-objective models have many criteria that are optimized concurrently (Malczewski & Rinner, 2015).

2.2 GIS and MCDA

2.2.1 Overview

A Geographic Information System (GIS) is a system that includes an integrated set of components, which can support decision making. However, it is a system primarily used for the input, storage, analysis and visualization of spatial data. The spatial data stored in a GIS system is usually geared for use in a problem-solving environment, in which it is manipulated and analysed to provide useful information that supports decision making (Boroushaki & Malczewski, 2010).

GIS systems are often limited in their ability to generate sets of decision alternatives by the set of spatial operations that are available to them. These include operations such as proximity, contiguity, connectivity, and various overlay methods. Consequently, GIS systems are, in their basic form, often unsuitable for processing and analysing data that is essential for decision making. Such data could consist of preferences (or value judgements), priorities, or opinions (Malczewski & Rinner, 2015).

On the other hand, MCDA approaches consist of various methods and tools that evaluate user preferences, resulting in the prioritisation and evaluation of various decision alternatives. The integration of GIS and MCDA emerged in order to solve more complex problems that were not possible to solve using conventional GIS methods and provides a platform that facilitates the decision-making process. GIS and MCDA benefit and complement one another: MCDA techniques can enhance the decision support capabilities of GIS by introducing value judgements into decision making processes, by assisting decision-makers clarify evaluation criteria, and by helping decision-makers understand any trade-offs between decision alternatives. MCDA answers the question 'What?'. Conversely a GIS can enhance conventional MCDA by enabling the analysis and visualization of spatial relationships within the decision alternatives and answers the question 'Where?' (Greene et al, 2011).

Malczewski & Rinner (2015) go on to say that when viewed at a rudimentary level, one can describe GIS-MCDA as a systematic process that merges the use of spatial data and the preferences of decision makers, to provide decision makers with information and ultimately prioritised decision alternatives that have been evaluated against the preferences.

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2.2.2 Spatial Decision Support Systems

The main objective of spatial decision support systems (SDSS) is to support various stakeholders in the decision-making process, by processing data using MCDA and GIS methods, and providing optimized information and alternatives that fulfill the objective of the spatial problem being evaluated (Perez et al, 2008; Guarini, 2018).

The effectiveness of the decision-making process is enhanced by combining MCDA and GIS methods, that are used in the analysis of spatial and non-spatial data, with the knowledge and experience of the decision-makers involved in process. In addition, SDSS enables the participation of non-experts and experts in collaborative and participatory GIS decision-making (Malczewski & Rinner, 2015).

2.3 MCDA Approaches and Method Selection

2.3.1 Criteria

Malczewski & Rinner (2015) refer to criteria as possessing specific attributes and objectives, which describe the decision scenario and are used to evaluate decision alternatives. Objectives define the desired outcome of a spatial decision problem. On the other hand, attributes define relational properties of spatial entities that have a measurable quantity or quality; for example, having the objective of determining the 'best' route may be evaluated against criteria such as time, distance, and traffic congestion, to name a few.

According to van Herwijnen & Rietveld (1999), each criterion must be measurable and can be spatially explicit or implicit. Criteria that are spatially explicit describe spatial features of decision alternatives, such as the length of a road segment (distance) in the above example. Conversely, spatially implicit criteria use spatial data to calculate the quantity or quality of the criterion in question. Travel time could be a spatially implicit criterion, derived from road length, speed limit, traffic congestion etc.

Criteria should be extensive – encompassing all facets of the decision problem – but can also be decomposed into smaller components to simplify the decision-making process. The number of criteria should be kept to the absolute minimum necessary to express the decision-making problem adequately, while at the same time avoiding redundancy. As stated by Su et al. (2010), too many criteria could overwhelm the decision-maker's cognitive capacities in information processing.

Objectives and attributes maintain a hierarchical relationship, where objectives are more general in nature and are at the highest level. At lower levels in the

relationship are more detailed objectives and then attributes associated with those objectives (Saaty, 1980; Malczewski & Rinner, 2015).

2.3.2 Weighting and Value Scaling

The relative importance of a criterion in relation to other criteria can be indicated by assigning a weight to it. Weighting methods can either be global or local. Global methods assign a single weight to each criterion. In order to compare criteria, the criteria weights must be ratio scaled (Hobbs & Meier, 2000).

Criterion weighting methods include the ranking, rating, pairwise comparison, proximity-adjusted and range-based methods (Malczewski, 2006). The ranking method proposes that the decision maker ranks the criteria in order of preference and thereafter criteria weights are assigned according to the order of the criteria. It is simple and, therefore, quite a popular method.

Malczewski & Rinner (2015) state that when using the rating method, the weights of criteria are determined using a predefined scale. The highest number in the scale is given to the most important criterion, with proportionally smaller weights assigned to less important criteria. The weights are then normalized.

The pairwise comparison method generally uses a linear scale to compare two criteria, although the scale could also be geometric, logarithmic or even verbal. An example of an MCDA method that uses pairwise comparison is the analytic hierarchy process (AHP), which usually employs a linear scale that consists of values $1 - 9$. The value of 1 indicates the two criteria are equal and 9 indicates that the first criterion is much more important than the second criterion. The process continues by comparing each pair of criteria, until all criteria have been compared. The comparisons are usually organized into a matrix to make the comparison procedure easier. Saaty (1980) developed the pairwise comparison method while creating AHP and generally the pairwise comparison method is the most popular method to estimate weights for GIS-MCDA applications.

On the other hand, the proximity-adjusted method modifies preferences according to both the relative importance of the criterion and the spatial relationships between a reference point and an alternative or between various alternatives.

To be able to evaluate criteria against each other, they need to be transformed into comparable units using procedures such as value scaling or the score range procedure, which is a common standardization method used in GIS-MCDA environments (Malczewski & Rinner, 2015).

Catrinu-Renström et al. (2013) refer to two different approaches to value scaling – decomposed scaling and holistic scaling. Decomposed scaling is explicit scaling of impacts and requires subjective value functions to be specified for each criterion.

Holistic scaling, on the other hand, is implicit scaling, shown by the preferences of decision-makers for specific project profiles, thus avoiding the complications of specifying value functions for each criterion.

2.3.3 Decision Alternatives

Spatial decision alternatives can be defined as consisting of an action and a location and present the decision-maker with various options from which to choose within the context of a spatial problem (Chakhar & Mousseau, 2008; Malczewski, 1999). A decision alternative can be represented by a single geographic entity or a group of entities. The values of decision variables, or properties of a particular geographic entity, are measurable and define the overall desirability of a decision alternative.

Decision variables, on the other hand, can be categorized as having binary, discrete or continuous values. Feasible and infeasible decision alternatives are determined through constraints on the values of decision variables, where a feasible alternative fulfils all constraints. Decision alternatives can be represented in a decision matrix, where each decision alternative is a row in the matrix and columns represent the evaluation criteria. By examining an element in the matrix, the performance of the decision alternative against a specific criterion can be determined (Malczewski & Rinner, 2015).

2.3.4 Decision Rules

A decision rule, otherwise known as a combination rule, is basically a method or process of evaluating and ordering a group of decision alternatives. Decision rules can be extracted from a decision table, which is a table that specifies conditions that must be satisfied in order to perform the decision (Tzeng & Huang, 2011).

Combination rules merge criterion values and criterion weights (decision maker's preferences) into a consolidated evaluation of the alternatives. Decision rules can be compensatory or non-compensatory, where the former uses trade-offs when evaluating criteria and the latter does not. Furthermore, decision rules can be classified into two groups: multi-attribute decision analysis (MADA) and multi-objective decision analysis (MODA) (Hwang & Yoon 1981).

MADA methods focus on the evaluation and selection process on a limited number of known alternatives. MODA methods rather focus on a process-oriented design and search approach and differentiate between decision criteria and decision variables, which are related to one another using objective functions (Malczewski & Rinner, 2015).

2.3.5 GIS-MCDA Method Approaches

GIS-MCDA methods follow three distinct approaches to spatial decision making (Malczewski 1999; Malczewski & Rinner, 2015). The first approach is aspatial and applies conventional MCDA to spatial decision making. The second approach uses newer, spatially explicit MCDA methods that are specifically designed to solve spatial problems. The third approach is spatial multi-objective optimization, which again uses newer spatially explicit methods.

Conventional MCDA methods usually do not consider the fundamental properties of spatial heterogeneity and spatial dependency and are simply extensions of current MCDA methods, which are used to analyse spatial problems. The spatial homogeneity of the preferences of decision makers are often assumed when using these methods. In addition, conventional MCDA methods only have implicit spatial relations, such as proximity, adjacency, and contiguity, on which evaluation criteria are performed (Ligmann-Zielinska & Jankowski, 2008; Herwijnen & Rietveld, 1999; Malczewski & Rinner, 2015).

On the contrary, spatially explicit MCDA methods use spatial location to distinguish predicted behaviours; in other words, decision alternatives should be geographically defined by having an action and a location. Additionally, when using spatially explicit methods, the ranking of decision alternatives is not constant when their location changes (Malczewski & Rinner, 2015).

Spatial multi-objective optimization methods are usually distinguished from other methods in that decision alternatives have a specific geographic meaning, which could be connectivity, location, boundary length and shape of area, to name a few. These methods are purposefully designed to model spatial systems and to find the best solutions to spatial problems, which can be illustrated on maps. Some spatial problems that use spatial multi-objective optimization methods include, but are not limited to, site-search problems, vehicle routing problems, and land allocation problems (Krzanowski & Raper, 2001; Malczewski & Rinner, 2015).

Presently some of the most common MCDA methods include the weighted linear combination, ideal point methods, analytic network process (ANP), analytical hierarchy process (AHP), outranking methods, multi-attribute utility theory (MAUT), MACBETH, ELECTRE, TOPSIS and PROMETHEE (Guarini, 2018; Malczewski & Rinner, 2015).

The following sections gives an overview of five of the most common MCDA methods.

2.3.5.1 Weighted Linear Combination Method

The most regularly used GIS MCDA method is the weighted linear combination (WLC), which is made up of two parts consisting of criterion weights and value functions, which when combined provide the overall value of a particular alternative at a specific location. The value function can also provide values of alternatives with respect to individual attributes. The preferred decision alternative has the highest value returned by the value function. In order to coherently evaluate the value of a criterion weight, the range of criterion values, which defines the value function, needs to be determined (Malczewski & Rinner, 2015; Keeney, 1992; Hobbs and Meier, 2000).

While this method is quite intuitive for decision makers and can be implemented easily in a GIS environment via the use of map algebra functions, the premises behind the WLC method can be extremely arduous to implement in spatial decision problems (Malczewski, 2000; Malczewski & Rinner, 2015).

The proximity-adjusted WLC model is a spatially explicit version of the WLC model. In this model preferences are adjusted pursuant to various spatial relationships that exist between decision alternatives, or to a specific reference location, and location of the alternative is considered during decision making – not only the relative importance of the criteria for the alternative in question (Malczewski & Rinner, 2015; Ligmann-Zielinska & Jankowski, 2012).

2.3.5.2 Analytic Hierarchy Process Method

The Analytic Hierarchy Process (AHP) is founded on the principles of decomposition, comparative judgment, and synthesis of priorities, and according to Saaty (1980) one of the most extensive methods of multicriteria decision analysis. Decomposition entails breaking-down the decision problem into a hierarchical structure that reflects the basic components of the decision problem. Comparative judgment uses pairwise comparisons to evaluate the different components on a specific level within the hierarchy. The synthesis of priorities builds a composite set of priorities of decision alternatives, which are deducted from the ratio scale priorities found on the different levels of the hierarchy. The AHP method therefore consists of the following four steps: First, the problem is structured by constructing the AHP hierarchy; next, allocating weights or priorities to the elements of the hierarchy using pairwise comparison; followed by performing a consistency check; and finally performing a sensitivity analysis (Ishizaka & Nemery, 2013).

The AHP method is a variation of the WLC method and is an equivalent of WLC that has had weights determined by pairwise comparison, where the hierarchy comprises three levels – the goal, attributes, and alternatives. However, AHP presents a formal

structure for the decision maker to use when determining all the important components of a decision problem, which is a big advantage AHP has over the WLC method. Another advantage is that the pairwise comparison method used within AHP is viewed as a good tool for determining relative importance of criteria and is evaluated using a scale with the values 1- 9 (Ishizaka & Nemery, 2013; Malczewski & Rinner, 2015).

2.3.5.3 Analytic Network Process Method

The AHP assumes that all the components of the hierarchy are independent of one another, but real-world spatial problems are composed of complex relationships and dependencies between the various components of the spatial problem. The Analytic Network Process (ANP) was developed by Saaty (1996) to handle these spatial relationships and dependencies within a decision problem. ANP is an extension of AHP that addresses the limitation of the assumed independence between criteria in the hierarchical structure of AHP (Tzeng & Huang, 2011) and provides a means for dependent criteria to be modelled (Ishizaka & Nemery, 2013).

Although ANP is also based on the same principles of decomposition, comparative judgment, and synthesis of priorities, it is structured using a network, which replaces the hierarchy. Clusters consisting of nodes and linked by arcs are the basic building blocks of the network. Dependencies between nodes are indicated by the direction of the arcs that connect them. Dependencies can by one-way, two-way or a self-dependency (indicated by a loop) and can be between nodes and clusters (Ishizaka & Nemery, 2013). Pairwise comparisons are used to evaluate the relative importance of different components within a specific cluster in the network. A super-matrix, which consists of sub-matrices that in turn are made up of a set of relationships between two clusters or elements, is used to synthesize priorities (Tzeng & Huang, 2011).

AHP and ANP methods are very popular in the industry. This is because these methods are both easy to use and are flexible enough to be applied to a wide variety of spatial decision problems such as land suitability, site selection, impact evaluation - in application domains such as transportation, waste management and agriculture, to name just a few. However, some reprehension against the use of AHP and ANP methods include the ambiguity of relative importance when comparing one component to another, the use of an irregular scale of 1 to 9, and the number of pairwise comparisons needed for larger problems (Malczewski & Rinner, 2015).

2.3.5.4   Ideal Point Methods

Ideal point methods use a reference point (target or goal), which is used to evaluate potential decision alternatives. In contrast to additive methods, such as WLC, AHP and ANP, ideal point methods prioritize decision alternatives based on their distance from the reference point using the distance metric. The reference point could be either a positive ideal point or negative ideal point, with the best solution having either the shortest distance to the positive ideal point, or the furthest distance to the negative ideal point (Ishizaka & Nemery, 2013; Hwang & Yoon 1981). Ideal point methods are play an important role in GIS-MCDA and are especially prominent in the area of land-use suitability analysis, and in application domains such as, water resources management, environmental assessment and management, and rural land use planning, to name a few.

2.3.5.5   Outranking Methods

As mentioned by Vincke (1989), outranking methods make use of pairwise comparisons of all criteria when evaluating alternatives against each other, which means that one alternative outranks another alternative if the former is better or equal to the latter on most of the criteria, and there is no evidence indicating the contrary on the remaining criteria. The most popular outranking methods that have been used in GIS-MCDA are PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) and ELECTRE (ESTYLF).

2.3.6   Method Selection

According to Guarini et al. (2018), there is a lack of guidance for selecting the most appropriate MCDA method for a specific decision-making problem and it seems that this is a stumbling block against adopting MCDA for complex spatial problems. Ishizaka & Nemery (2013) also stated, at the time, that there were no existing procedures for deciding which method to use in a specific decision-making situation, and that made the task of selecting an appropriate decision-making method rather difficult.

Since there are many MCDA methods available there is a risk that a method is selected that is not optimally suited to the problem at hand, which can affect the outcome of the decision-making process (Guarini et al., 2018; Ishizaka & Nemery, 2013).

Because of this problem, Guarini et al. (2018) created a procedure for selecting a suitable MCDA method, which compares the properties that represent each MCDA

method against the qualification of variables that are expected for the method to have. The outcome also depends upon both endogenous and exogenous variables as well as the decision-making problem at hand. This is illustrated in Table 1 and 2 below.

Table 1: Properties of MCDA Methods Compared to Exogenous Variables. Adapted from Guarini et al. (2018)

Exogenous Variables	Variable Options	ELECTRE	MAUT	ANP	MACBETH	AHP	TOPSIS	PROMETHEE
Number of evaluation elements	Limited criteria and limited alternatives	x						
	Limited criteria and many alternatives		x					
	Many criteria but limited alternatives			x		x		
	Many criteria and many alternatives				x		x	x
Typology of Indicators	Quantitative	x	x	x	x	x	x	x
	Qualitative	x		x	x	x	x	x
	Mixed	x		x	x	x	x	x
Stakeholders in Decision Process	None	x	x	x	x	x	x	x
	Limited number of Stakeholders	x	x	x	x	x	x	x
	Many Stakeholders	x	x	x	x	x	x	x
Expected solution	Better overall alternative	x	x	x	x	x		x
	Ideal alternative closest to the lens						x	

	Required	x	x	x	x			
Technical support of a Decision Aid Specialist	Not required					x	x	x

Table 2: Properties of MCDA Methods Compared to Endogenous Variables. Adapted from Guarini et al. (2018)

Endogenous Variables	Variable Options	ELECTRE	MAUT	ANP	MACBETH	AHP	TOPSIS	PROMETHEE
Type of decision-making problem	Sorting	x						
	Descriptive	x						
	Preference or ranking	x	x	x	x	x	x	x
Solution approach	Outranking	x						x
	Full aggregation		x	x	x	x		
	Goal or aspiration						x	
Implementation procedure	Preference thresholds, indifference thresholds, veto thresholds	x						
	Preference thresholds, indifference thresholds							x
	Utility function		x					
	Pairwise comparison on rational scale and interdependencies			x				
	Pairwise comparison on interval scale				x			
	Pairwise comparison on rational scale					x		
	Ideal option and anti-ideal option						x	
Input level	High		x	x	x	x		
	Medium	x						x
	Low						x	

Output typology	Ordering obtained by expressing pairwise preferences degrees	x						x
	Ordering obtained considering scores		x	x	x	x		
	Ordering with score closest to the aim assumed						x	
Decision problem solution	n categories of alternatives of equal score but different behaviour	x						x
	Alternative with the higher global score		x	x	x	x		
	Alternative with the closest score to the ideal solution						x	

Guarini et al. (2018) refer to exogenous and endogenous variables in the context of selecting a suitable MCDA method. Exogenous variables relate to decision problems and the context surrounding them. These include variables such as the stakeholders in the decision process, the number of evaluation elements, and the expected solution, amongst others. Endogenous variables, on the other hand, relate to properties of the MCDA methods, such as type of decision-making problem, solution approach, implementation procedure, and output typology, to name a few.

The procedure for selecting a suitable MCDA method, created by Guarini et al. (2018), has 4 steps defined as follows:

1. *"The weighting of variables (optional action)":* The variables defined in Table 1 and 2 above can be defined as having equal importance or a different importance in relation to one another, in which case a weight can be assigned to each variable.

2. *"Determining the framework of expected properties"*: This step requires identifying which properties of each variable are present or absent for each of the MCDA methods.

3. *"Calculation of the overall index of suitability"*: The suitability of a MCDA method is calculated by comparing the properties of each MCDA method with their expected properties, against each variable option, and then an

overall index of suitability can be calculated for each MCDA method being considered.

4. ***"The Identification of the method best suited to resolving the decision-making problem"***: This step results in a ranking of the MCDA methods, determined by listing each method in descending order of suitability, with the highest overall index of suitability first.

Even with a procedure in place for selecting an appropriate MCDA method for a decision-making problem, it can be noted that it is quite a complex and involved process. In most cases an MCDA selection procedure or expertise that understand how to select an appropriate MCDA method is absent. This could be prohibitive for organizations or people considering the use of MCDA methods for their decision-making problem.

2.4 Mobile Decision Support Systems

2.4.1 Advantages

Advances in mobile computing and wireless telecommunication technology have revolutionized the way we access information and has subsequently created the environment for a new category of decision support systems to emerge. Spatially-enabled MDSS have a unified software and hardware architecture that enables the remote access of spatial data and services through wireless networks (Tsou, 2006; Haghighi, 2013).

Field-based personnel could use spatially-enabled MDSS to provide real-time geospatial information and GPS coordinates from the field to office-based decision makers. Similarly, decision makers can provide immediate feedback to personnel in the field. (Tsou, 2006; Haghighi, 2013) suggest that this immediate two-way communication between in-field personnel and office-based decision makers allows for a more cost-effective and efficient decision-making process.

MDSS, in general, are effective in a wide range of applications such as mobile banking, emergency management, mobile healthcare or any application that requires a high degree of mobility and the ability to support rapid decision making in real-time. Since the field of MDSS is relatively new, additional research is required to determine appropriate guidelines, methodologies, and principles, so that the capabilities of MDSS are used more efficiently and effectively to provide a solid platform for more timely and successful decision making (Tsou, 2006; Haghighi, 2013; Perez et al, 2008).

2.4.2 Limitations

One of the main considerations when implementing a spatially-enabled MDSS that could potentially be a limiting factor is the interoperability between different systems, platforms, communication protocols and data structure standards. It is important to overcome the challenge of insuring interoperability between mobile GIS and internet GIS interfaces. There are various operating systems for mobile devices and similarly for desktop systems, which means that cross-platform considerations become very important when implementing a spatially-enabled MDSS. Data format independence is also critical when transferring data between different hardware devices, so the use of proprietary data formats should be avoided. A better approach would be to use generic data formats such as JSON, XML, or GML, which is an XML-based geospatial data structure (Tsou, 2006).

Another major limitation to consider when setting up a spatially-enabled MDSS is wireless network availability and coverage. Some rural areas and national parks do not have network coverage, which makes it difficult to use a spatially-enabled MDSS in real-time (Tsou, 2006).

Compared to desktop systems mobile devices have small screen sizes, lack of windows, and basic navigation, which limit the amount of information (text and graphics) that can be displayed to the user (Perez et al, 2008).

2.5 Technical Considerations

The following technical considerations provide some context to the research question "What advances in technology make it possible to a create a spatially-enabled MDSS?".

2.5.1 Cross Platform Development

The cross-platform development process concerns creating mobile applications that function on a variety of different mobile platforms, such as Android and iOS, without having to code for each native platform. Reducing these coding requirements, in turn, reduces the costs, resources, overhead and time necessary to produce the same app on each platform.

According to Manchanda (2021) there is an ongoing debate within the tech community whether cross-platform development is better than native app development. There are many advantages and disadvantages to both approaches.

Budget is usually the biggest issue when businesses decide whether to go the native app route or to embrace cross-platform development (Sheldon, 2021).

Some of the advantages of cross-platform development are reduction of development costs and quicker development process; more efficient maintenance and deployment; reusable code; consistent design on all platforms that provide a uniform user experience; and maximum market exposure. There are however a few disadvantages when going the cross-platform development route. These include performance glitches that are caused by interface issues between native and non-native components, which lead to bad user experience; inferior user interface since not all native components are available for cross-platform development tools; and security concerns. Some factors to consider when selecting cross-platform development tools include platform compatibility, scalability, security, usability, and development workload (Wardynski, 2021).

At the time of writing, these are the leading cross-platform development tools, although there are other development tools available, such as Ionic, Sencha and Appcelerator:

- Xamarin
- Flutter
- React Native
- Adobe PhoneGap

Xamarin has been around since 2011, although since 2016, Xamarin has been owned by Microsoft. Xamarin is an open-source cross-platform framework that boasts some robust features and uses C# .Net for coding, along with the popular Visual Studio development environment. It is backed by a strong open-source community, with more than 60 000 contributors. Over 75% of the code can be shared across platforms, which greatly improves the efficiency of the development process. Although Xamarin is free for individuals and start-ups, it is quite expensive for enterprises. It is also not recommended for graphic-intensive apps.

Flutter is owned by Google and is also an open-source cross-platform framework that is used for developing high-performance, native interfaces for both Android and iOS. Flutter is one of the most popular frameworks within in the development community. It uses the Dart programming language and supports native device features, hot reloading, Minimum Viable Product (MVP) development, and robust creative designs. On the other hand, Flutter offers no TV support and app sizes are larger than native apps.

Adobe PhoneGap is another open-source, cross-platform framework that is useful for creating hybrid mobile web applications and utilizes HTML5, CSS, and JavaScript. These hybrid apps look and behave almost identically to native mobile applications and are robust, flexible, and secure. However, PhoneGap is not recommended for high-performance applications due to performance issues.

React Native is a lightweight and fast open-source cross-platform framework created by Facebook. Some of the advantages are shorter development times, sharing about 80% of code across platforms, highly responsive UI, hot reloading, and it supports access to many native components. Some disadvantages of using React Native include having to use some native components that do not have a cross-platform equivalent, such as the camera or accelerometer. In addition, it lags behind the native platforms with regards to new or updated features (Manchanda, 2021; Wardynski, 2021).

2.5.2 Mapping technologies and APIs

Since the advent of Google Maps in 2005, the popularity of online maps and mapping tools has risen exponentially (Tarvainen, 2021). Although Google is still leading the way with online map technologies, especially in certain areas such as 3D visualization, nowadays there are many other companies providing online mapping solutions in the industry. These include Bing Maps API from Microsoft, TomTom, Here, MapKit from Apple, OpenStreetMap, MapQuest, Mapbox and Yandex Maps, among others.

Most of the mapping API services offer a limited free tier, but for larger enterprises a licence or subscription is required, which adds to the cost of creating and maintaining online maps and these costs can be quite prohibitive.

An alternative option to paid mapping services is OpenStreetMap (OSM), which is a free open-source, community driven mapping platform maintained by a group of volunteers. OSM is managed by a non-profit foundation that obtains funding via membership fees and donations, which are in turn used to further develop the technology platform. OSM also has corporate members with their own mapping services that contribute to the project, for example Facebook contributed to OSM with RapiD – an artificial Intelligence tool that enables the addition or update of map features. Although OSM API and data is free to use, additional hosting costs need to be considered. OSM does not provide hosting services and companies must host their own map data via a tile server (Tarvainen, 2021).

Another consideration is the geographical coverage of the mapping API. It might be worthwhile paying for a commercial mapping API with better geographic coverage of the region considered for a spatially-enabled MDSS.

Google offers a wide selection of different APIs for Google Maps, such as Maps Image API, Web Services API, Embed API, and Places API. These APIs are accompanied with detailed documentation, code samples, SDKs, libraries, and tools.

Microsoft Bing Maps is another popular commercial mapping platform that is constantly improving by adding new features and updates to the platform, such as

Streetside cities. Although not as popular as Google Maps, it provides the latter with stiff competition.

MapQuest was founded in 1967 and has a decent selection of various online mapping solutions on offer, including MapQuest Mobile, MapQuest.com, MapQuest Enterprise, MapQuest Local and MapQuest Developers. The MapQuest platform comes with two versions: Licensed and Open Data. The former is available after purchasing a MapQuest Enterprise Edition license. The latter is available with a Free and Open license and uses OpenStreetMap as the main data source for the MapQuest Open Data Platform. The MapQuest API is well documented, includes a map builder and map wizards, a route planner and various other development tools.

Mapbox is another mapping platform that was founded in 2010 and offers various payment plans, starting from a free starter plan and on the other end – a high-volume enterprise plan. Mapbox is an open-source platform that enables the quick creation of custom maps using the Mapbox editor. It provides a robust API and development tools that are well documented.

An important technological advancement when it comes to online mapping technologies is the availability of spatial data structures that enable the transfer of spatial data via online web mapping services. Examples of spatial data structures that are available are KML, GML GeoJSON, TopoJSON, to name a few (Wagner, 2021).

2.6 Network analysis

In order to understand the routing algorithms required to implement the Route Optimizer SDSS prototype, it is necessary to have a basic understanding of network analysis and graphs.

Routing algorithms, such as Dijkstra's Shortest Path algorithm, use graphs as a data structure that represents a network. Graphs are made up of nodes that represent physical spatial objects in the real-world, and edges, which are the connections between nodes. Nodes are usually represented on a graph as a circle, whilst edges are represented as lines that connect the circles. Graphs usually represent a real-world network. For example, a transportation network or a communication network, such as the internet, can be represented as a graph (Tyagi, 2020; Comber et al, 2008).

Graphs can be of two types, either directed or undirected. Undirected graphs allow movement between nodes in both directions, whereas directed graphs allow movement from one node to another in one direction only. In the case of directed graphs, arrows are used to indicate directed edges, as opposed to the simple lines that are employed in undirected graphs (Joshi, 2021).

In addition, graphs can also be weighted. Weighted graphs have edges with a value that can represent a distance or cost between one node and another. Weighted graphs can be represented by an adjacency list that has an extra field to store the cost of each edge in the graph. It is important to note that the weights must be a positive number (Navone, 2021).

Fischer (2004) differentiates between a pure network and a flow network, with the former considered pure if only topology and connectivity are examined. In addition to topology, flow networks are characterised by flow properties, which could include capacity constraints and cost functions.

An incidence matrix is a useful representation of a network, in network analysis. It consists of columns for each edge (arc) and rows that represent each vertex (node), and it is used to indicate the presence or absence of a relationship between the nodes and arcs in directed and undirected graphs (Szabo, 2015).

Many networks represented within a GIS environment are planar networks, which are defined by the requirement that all arcs intersect at a node and this model guarantees topological consistency of the network (Kanyari, 2011).

Fischer (2004) suggests that a major disadvantage of achieving topological consistency within a planar network is that complex intersections, such as an overpass or underpass, cannot be distinguished in such a model and this can lead to unexpected results when running routing algorithms. A solution to this problem is the use of non-planar network models that allow some arcs to cross without having a node at the intersection.

2.7 Routing algorithms

Routing algorithms are used to determine optimum paths between a start location and a destination. This could be the shortest path or the path with the least cost. Cost could indicate a property such as the least amount of traffic or the least amount of time taken to get to the destination. Routing algorithms are an integral part of network analysis (Kanyari, 2011).

In the context of this research paper and for the purpose of implementing the Route Optimizer SDSS prototype, Dijkstra's Shortest Path algorithm and the A* Search algorithm were the routing algorithms that were considered.

In the end, Dijkstra's algorithm was preferred since it calculates the shortest path for every node in the graph and the destination node is 'unknown'. In addition, the network graph is relatively small so any gains in performance by other routing algorithms, such as A*, were irrelevant.

The purpose of Dijkstra's Shortest Path algorithm is to find the shortest path between a source node and every other node in the graph that can be reached from the source node. The algorithm only finishes once all the nodes in the graph have been visited. Dijkstra's algorithm only needs to be run once and the shortest distances can be accessed from the resulting graph whenever needed (Abiy et al, 2021).

According to Joshi (2021) and Navone (2021) the basic flow of Dijkstra's Shortest Path algorithm is:

1. The node with the smallest cost is visited first (in the beginning this is the source node, which has a cost of 0).
2. Once a node is visited, the neighbouring reachable nodes are assessed.
3. The cost for each neighbouring node is calculated by summing the cost of all edges that lead to the node in question, from the starting node.
4. If the cost is less than a previously known distance, then the cost is updated for that node.
5. Once the node's shortest path to the start node has been determined, it is marked as visited and added to the path.
6. The process repeats until all nodes have been visited.

It is important to note that Dijkstra's Shortest Path algorithm uses breadth-first graph traversal, which means that neighbouring nodes are visited before child nodes (Joshi, 2021).
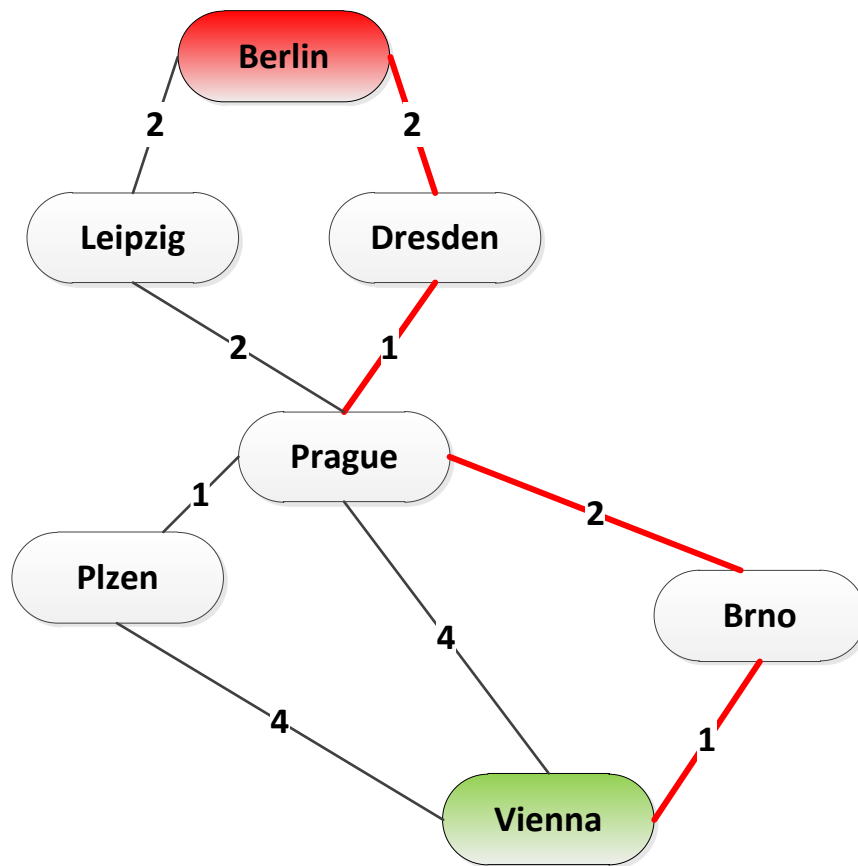
Figure 2: An Example of Dijkstra's Shortest Path. Adapted from Navone (2021).

In the above graph, we can see that the cost of the shortest path between Vienna and Berlin is 6, by following the shortest path (marked in red) back from Berlin to Vienna and summing the costs along the path.

The costs between nodes are tracked during the execution of the algorithm. Initially, the distances from each node to the source node is set to infinity since the distances have not been calculated yet. The distance to the source node to itself is naturally 0 (Tyagi, 2020).

3. Methodology

To answer the established research questions, the following methods were used (See Figure 3):

- A questionnaire was used to determine any gaps that a spatially-enabled MDSS prototype could demonstrably fulfil in terms of improving current decision-making processes.
- Before implementation of the spatially-enabled MDSS prototype, the functional requirements were specified that determine the scope of the functionality of the prototype.
- The next step involved the architectural system design, which determines the components of the system that are needed to fulfil the functional requirements and illustrates how all the different components of the system interact.
- Once the design was completed, the implementation of the prototype involved:
  - Database design and implementation – gathering and processing of spatial data, design of the database, and importing the data to the database.
  - Formulating the different MCDA and routing algorithms.
  - Implementing the client user-interfaces for mobile and desktop systems.
  - Implementing the web services that provide an interface between the various clients, and the backend logic and databases.
- The final step was to test the prototype and determine whether it answers any of the research questions.
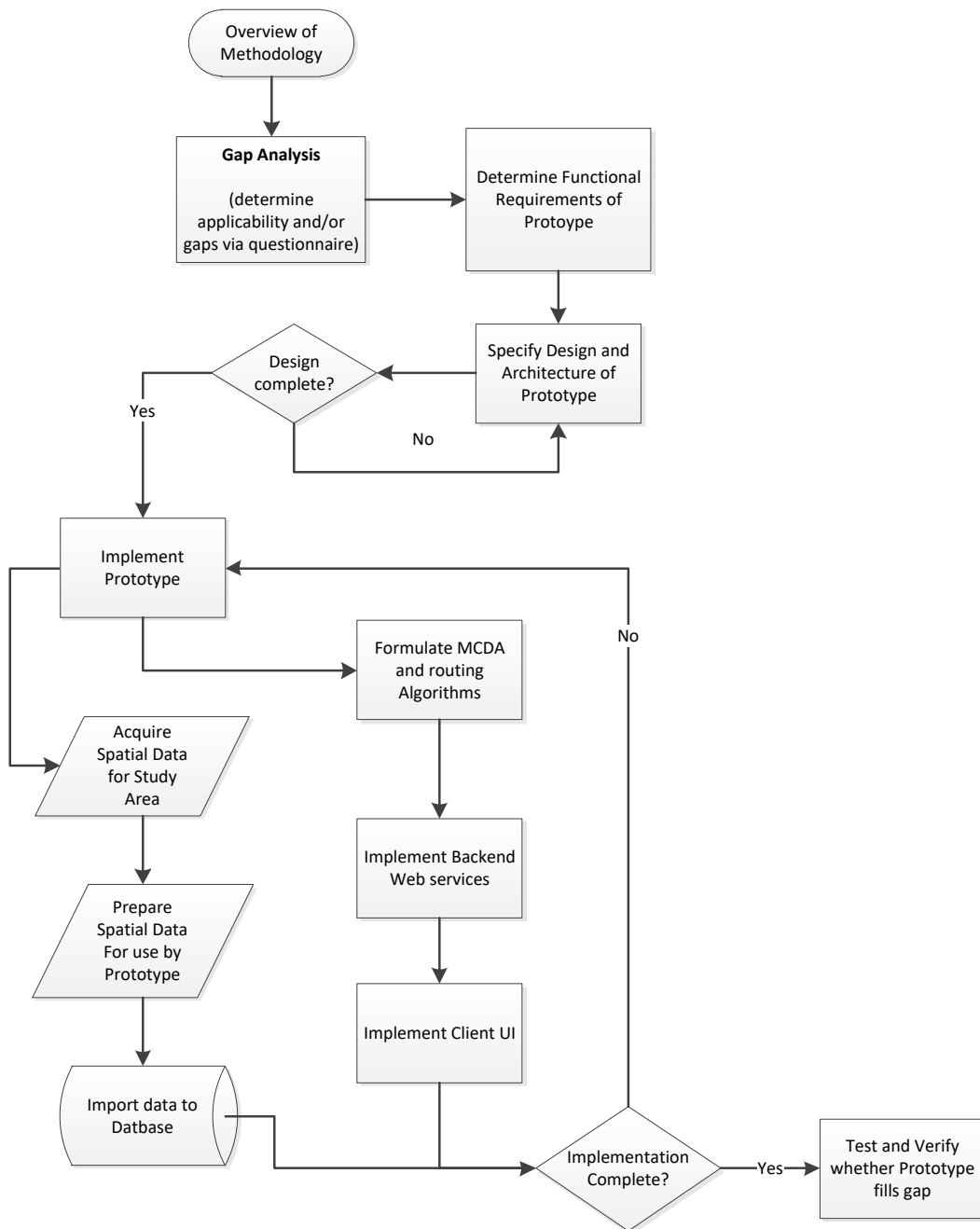
Figure 3: An Overview of the Methodology

3.1 Gap Analysis - Questionnaire

The gap analysis consisted of a questionnaire (See Appendix 1) that was designed and sent out to 50 marathon event organizations. The questionnaire was designed with the intention of understanding how marathon event organizations currently make decisions when designing a race route and see whether the number of people that are usually involved in the decision-making process are enough to constitute a collaborative decision-making environment. In addition, it was important to

ascertain whether there are any gaps within current decision-making processes and whether a spatially-enabled MDSS might be able to fill these gaps to some degree. I identified various physical criteria that might be important to event organizations to consider while designing a race route and hoped to get feedback on the overall preferability of the criteria. This was then used to see whether the testing of the prototype could satisfy these preferences.

With this in mind, the questionnaire was designed to identify:

- **The numbers of decision makers involved in the organization of the race event**. The options given were: 1; 2 – 4; 5 – 9; and 10 or more.

- **The current methods used by the respondent's event organization to design a marathon course**. The options were: GIS software; In-field surveying of roads (using GPS or other methods); Spatial Decision Support System; Physical maps; and Google or Bing Maps.

- **The importance of various physical criteria used to determine a potential race route**. The options were: course capacity (the width of the roads on the race route - sufficient for number of runners); surface of the course (asphalt, concrete, cobble stones, gravel, dirt); aesthetics of the course (greenery - parks, natural scenery, cultural sights); average difference in elevation; maximum slope; and the number of turns in the route. These criteria were used in the design of the prototype.

- **The importance of various accessibility criteria used to determine a potential route**. The options were: start / finish area layout and capacity; parking areas in vicinity; location of refreshment stations; location of medical services; and public transport to start / finish area.

The questionnaire was also used to get feedback from respondents on the applicability of a collaborative Spatial Decision Support System (SDSS) to complement or potentially to replace current techniques used to design a new, or adjust an existing, race route.

The results of the questionnaire are discussed further in the Discussion and Results sections of the thesis.

3.2 Functional Requirements Specification

The cross-platform SDSS prototype, used for route-optimization, should meet the following minimum functional requirements:

- The SDSS prototype should be interoperable across both mobile and desktop platforms. In this case the prototype will only operate on Windows desktop and Android mobile platforms.
- The prototype should be integrated as much as possible across both desktop and mobile platforms and should have a common user interface to simplify usage of the prototype.
- The mobile devices and desktops that use the prototype should be able to communicate via the Internet.
- The prototype should calculate optimum routes based on the user's selection of criteria weights.
- The prototype should be able to store relevant data in a database, such as the following spatial data: Road network features that are used as input in the route calculation and proposed routes that result as output from the route optimization calculation should be stored. In addition, criteria weights resulting from user input should also be stored in the database.
- The user interface should be simple to use and provide the following functionality to the user:
  - o The route selection criteria should be displayed to the user and consists of aesthetics of the course, maximum slope, average slope, course capacity, surface of the course, and the number of turns in the course.
  - o The user should be able to assign weights or priorities to each specific route selection criteria.
  - o The prototype should display the output of the potential route to the user via an integrated map. This can be achieved using either the Google Maps API or Bing Maps API.
  - o The prototype should show one or two alternative potential routes to the user.
  - o The prototype should allow the user to modify selection criteria weights and recalculate a proposed route.

3.3 Prototype Design and Architectural Specification

The core functionality, which includes the route optimization algorithm and spatial database, will be hosted on Microsoft Azure and made available to various clients (desktop and mobile) via web API services.

Since the mobile phone clients will mostly serve the purpose of verification in the field, only a limited set of the functionality was made available to these clients. Such limited functionality includes verification of routes that are calculated by the SDSS, and the ability to add notes to each calculated route.

Spatial Decision Support System Architecture
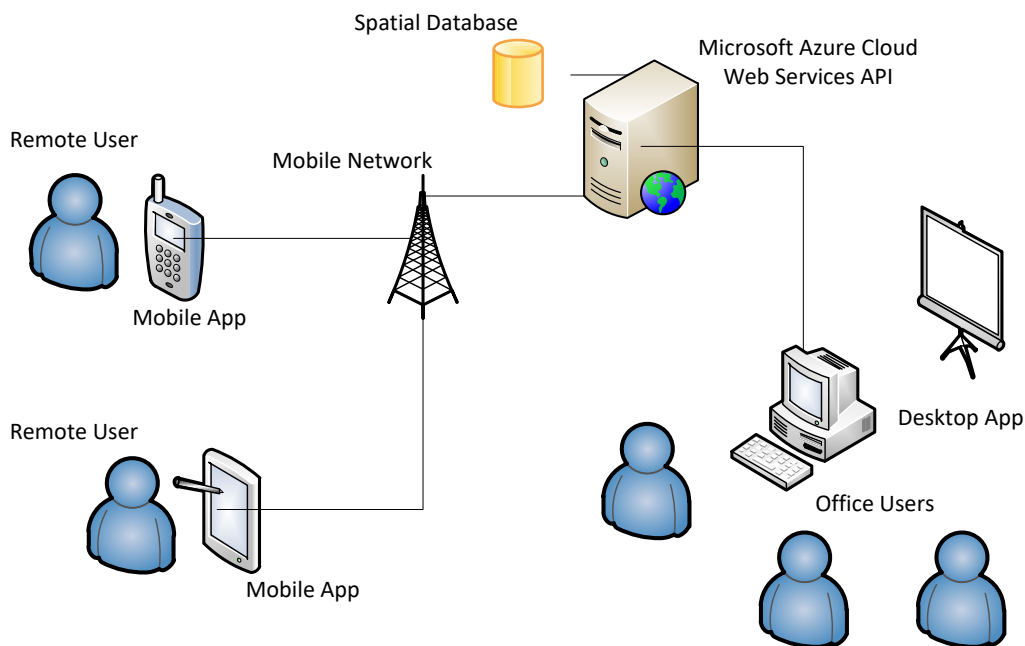
Figure 4: Architectural Design of the Route Optimizer Prototype

3.4 Implementation of the Route Optimizer Prototype

For the purposes of this study, only a prototype for the Route Optimizer application was implemented. The main reason for this is that the purpose of building the Route Optimizer prototype is to provide a demonstration of the application of the fundamental principles that this study investigates. Another reason is the obvious lack of resources and time to implement a fully operational production-quality system. Considering this, only the functionality listed in the functional requirements specification was implemented to completion. In addition, the real-time decision-making capability of the prototype was limited to the basic manual verification of the route in-field but does not include the capability to dynamically change route parameters, such as the removal of any undesired road segments while in-field.

3.4.1 Database Design

An SQL Server spatial database was used for the implementation of the SDSS. The database consists of tables to store data for roads, criteria weights, and calculated routes. The road spatial data is stored as both geometry and WKT (Well-known Text)

types within the database. WKT is an industry standard markup language that represents vector geometry data types in text format.

3.4.2 Acquisition of Spatial Data

The datasets used in this study were acquired from the following spatial data service providers, with the original data sources in paranthesis:

Table 3: Description of Sourced Spatial Data

Service Provider (Original Source)	Layer Description	Type	Coordinate System
Geofabrik (OpenStreetMap)*	Roads	Line	WGS 1984
	Water bodies	Polygon	WGS 1984
	Land use	Polygon	WGS 1984
	Points-of-interest	Polygon	WGS 1984
GADM (national governments, NGO, and/or from maps and lists of names available on the Internet.) **	Administrative boundaries	Polygon	WGS 1984
Gisat (Shuttle Radar Topography Mission (SRTM)) ***	DEM	Raster (Resolution – 100, 100)	Krovak

* Roads, water bodies, land use, and point-of-interest shapefiles downloaded from http://download.geofabrik.de/europe/czech-republic.html

** Administrative boundaries shapefile downloaded from http://www.gadm.org

*** DEM raster downloaded from http://www.gisat.cz/content/en/products/digital-elevation-model/srtm-dem

3.4.3 Preparation of Spatial Data

The following modifications were made to the spatial datasets:

3.4.3.1 Projection

The datasets were projected into the Krovak coordinate system. The Krovak projection is used by the Czech Office for Surveying, Mapping and Cadastre (ČÚZK) and is suitable for use in GIS applications. It was designed for the Czech and Slovak Republics by Josef Krovak in 1922, and it is limited for use in these two countries. The Krovak projection is an oblique version of the Lambert conformal conic projection. I chose this projection because it has minimal distortion of distance within the boundary of the Czech Republic, which is important for the accuracy of distance calculations performed by algorithms used within the prototype SDSS. It also maintains accurate local angles because of conformality and has minimal distortion of area within the country's boundaries.

3.4.3.2 Clipping

The Prague boundary was extracted from the CZE_adm1 shapefile into its own shapefile and projected into the Krovak projection, as described in Section 3.1. The Prague shapefile was then used to clip the roads, point-of-interest, land-use and water bodies shapefiles. The DEM was also clipped and projected and resampled accordingly.

3.4.3.3 Removal of Redundant Data

As discussed in Section 4.5, roads in the vicinity of emergency services, such as police stations, fire stations and hospitals, were removed from the dataset, since this was defined as a hard criterion.

In order to achieve this, features of the type police, fire stations, and hospitals were selected and exported into a new feature class containing emergency features. Roads within a buffered region of 200 meters from any emergency service feature were removed.

In addition to this, roads of a certain class were also deemed redundant for the use of race route selection by the prototype. Data of the following road classes were removed: 'motorway', 'motorway_link', 'steps', 'service', and 'bridleway'. Motorway and motorway linking roads, such as onramps and offramps, were removed because

of difficulty in having these roads closed for the duration of the race. Service roads, which provide access to parking lots and buildings, steps and bridleway paths were removed because of the unsuitability for running on such road types.

3.4.3.4   Addition of Slope Data

Slope data attributes were added to the roads feature class, using a surface information tool. Input layers were roads feature class and the DEM model sourced from Gisat, which had a 100m spatial resolution.

Table 4: New Fields Added to Roads Feature Class After Running Surface Information Tool

Field	Description
Z MIN	lowest surface elevation (Z value) present along the length of a line
Z MAX	highest surface elevation (Z value) present along the length of a line
Z MEAN	average surface elevation (Z value) present along the length of a line
SURFACE LENGTH	3D distance of the line along the surface
MIN SLOPE	minimum slope value along the line
MAX SLOPE	maximum slope value along the line
AVG SLOPE	average slope value along the line

3.4.3.5   Addition of Proximity to Aesthetic Features

The proximity to aesthetic features, such as attractions, greenery, and water features, is one of the criteria used in the SDSS to calculate a race route.

To incorporate this criterion, two layers - attractions and greenery - were derived from the points-of-interest and land-use shapefiles respectively, that were provided by Geofabrik. The water features layer was already provided by Geofabrik.

The attractions feature layer was created by extracting features from the points-of-interest shapefile belonging to one of the following classes: attraction, castle, fountain, memorial, monument and townhall. Similarly, the greenery feature layer was created by extracting features from the land-use shapefile belonging to one of the following classes: farm, forest, grass, heath, meadow, nature reserve, orchard, park, recreation ground and vineyard.

The roads layer was then updated using a proximity analysis tool to establish the proximity of each road to one of the aesthetic features (attractions, greenery, and water features). The distance (proximity) to one of the aesthetic features layers is one of the criteria used by the prototype.

3.4.3.6   Normalization of Criteria Data

Before weights can be applied to criteria data by the algorithm, the criteria data must be normalized (Malczewski & Rinner, 2015; Catrinu-Renström et al., 2013). The following steps were taken to normalize the criteria data – maximum slope, average slope, distance to aesthetic features, number of turns, road surface and road capacity:

- Prior to normalization of criteria data, some of the criteria were categorized into classes to prevent extremely small or large values (outliers) from affecting the algorithm in an unexpected manner.

    Maximum slope and average slope were categorized into the following classes:

    - 1 where slope less than 2°
    - 2 where slope greater than 2° and less than 5°
    - 3 where slope greater than 5° and less than 10°
    - 4 where slope greater than 10° and less than 20°
    - 5 where slope greater than 20°

    Distance to aesthetic features was categorized into the following classes:

    - 1 where distance less than 25m
    - 2 where distance greater than 25m and less than 50m
    - 3 where distance greater than 50m and less than 100m
    - 4 where distance greater than 100m and less than 200m
    - 5 where distance greater than 200m

    Road length (number of turns) was categorized into the following classes:

    - 1 where distance less than 50m
    - 2 where distance greater than 50m and less than 100m
    - 3 where distance greater than 100m and less than 250m
    - 4 where distance greater than 250m and less than 500m
    - 5 where distance greater than 500m

- Maximum slope, average slope and distance to aesthetic features are non-beneficial criteria, which means that smaller values are considered

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better. A path with less hills is better and a path closer to aesthetic features is better. To normalize non-beneficial data the following equation was applied: Min(x) / x, where x is the criterion in question.

- Road length (which inversely affects number of turns), road surface and road capacity are beneficial criteria – in other words larger values are better. Since number of turns cannot be measured ahead of time, before the route selection algorithm has run, this criterion is derived from the premise that a route of a fixed distance that consists of fewer longer road segments usually has less turns than a route consisting of more shorter road segments. As a result of this, road length was normalized, and this value was used while applying the weight of the number of turns criterion. Road surface and road capacity were also derived, this time from the road class types. These class types were given a value using a conversion scale between 1 and 5, with 1 being less favourable and 5 being more favourable. For example, in relation to capacity, a footpath was given the value of 1 and a primary road, the value of 5. In the same way, with regards to road surface an unsealed track was given the value of 1 and a primary road, the value of 5. Normalization was then applied to these numerically scaled class types. To normalize beneficial data the following equation was applied: Min(x) / x, where x is the criterion in question.

3.4.4 Data Import into the Database

The tool Shape2SQL downloaded from https://www.sharpgis.net/page/shape2sql was used to import the final road shapefile to the SQL Server database. It is a simple tool to use. The user can select the shapefile as input and the target SQL Server database; which attributes to import; whether to import as a geometry or geography type; the spatial reference identifier (SRID); whether to replace the existing table or not; and whether to create a spatial index.

After importing the road shapefile into the database, I ran a script to change the attribute names to more meaningful column names in the database. Since the algorithm in the code used a WKT value of the geometry, I also ran a script to save the WKT value in the database. This saved processing time converting the geometry to WKT within the algorithm.

3.4.5 Identification of MCDA Method and Formulation of Route Optimization Algorithm

Since there is only a single objective – to design a race route that fulfils certain design criteria – the problem of alternative route selections will be addressed using the multi-attribute decision making (MADM) framework (Hochmair & Rinner, 2005). The analytic hierarchy process (AHP) was selected as the appropriate MCDA method for the route selection SDSS because the problem is a preference or ranking problem, and it consists of many criteria but limited alternatives, with the preferred alternative being the one with the highest global score.

A greedy algorithm was selected for the route optimization calculation. A greedy algorithm attempts to find the optimal solution by selecting the best alternative during each step of the calculation with the goal of eventually leading to a globally optimal solution, although this is not always the case. It could lead to a locally optimal solution because not all options are considered. This limitation of greedy algorithms was accepted, with the view that it is sufficient to demonstrate the purpose of the thesis, which is to analyse the advantages and potential pitfalls of establishing a spatially-enabled MDSS.

To determine the best route, as opposed to the shortest route, a modification was made to the Dijkstra algorithm. Instead of selecting the shortest route between two points, the modified algorithm selects routes with the best total preferability score that meet the required distance hard constraint.

The overall process for the route optimizer algorithm consists of the following steps (see figure 5):

- Initially the user would enter the weights for each of the criteria and then the criteria weights are applied to each road segment to generate an overall preferability score for each road segment and the database is then updated with the new scores.
- Once the weights have been calculated, the user can generate a route. The first step in this part of the process is to read all the road segments from the database and create an adjacency graph, using the modified Dijkstra algorithm. The modified algorithm uses total preferability score instead of shortest distance to determine the best route. Once the graph has been created, with each segment containing a total preferability score from the starting point, the graph is ready to be traversed by the route optimizer algorithm, in order to find the optimal route.
- To start traversing the graph, the algorithm selects adjacent segments from the starting point. The algorithm selects the segment with the best performance score and checks whether it is a dead-end i.e., the segment has no adjacent segments. If it is a dead-end it discards the segment, otherwise it is added to the route.

- The algorithm then checks whether the route is the required distance. If not the process repeats, otherwise the route with the best performance score is returned.
- When the optimal route has been calculated, the route is returned by the web service API to the desktop client in JSON format (See Appendix 2). JSON stands for JavaScript Object Notation and is a format used for data-interchange. It is lightweight and it can be easily parsed and generated by programming languages. In addition, it is an easy format for people to understand.

Algorithm Design
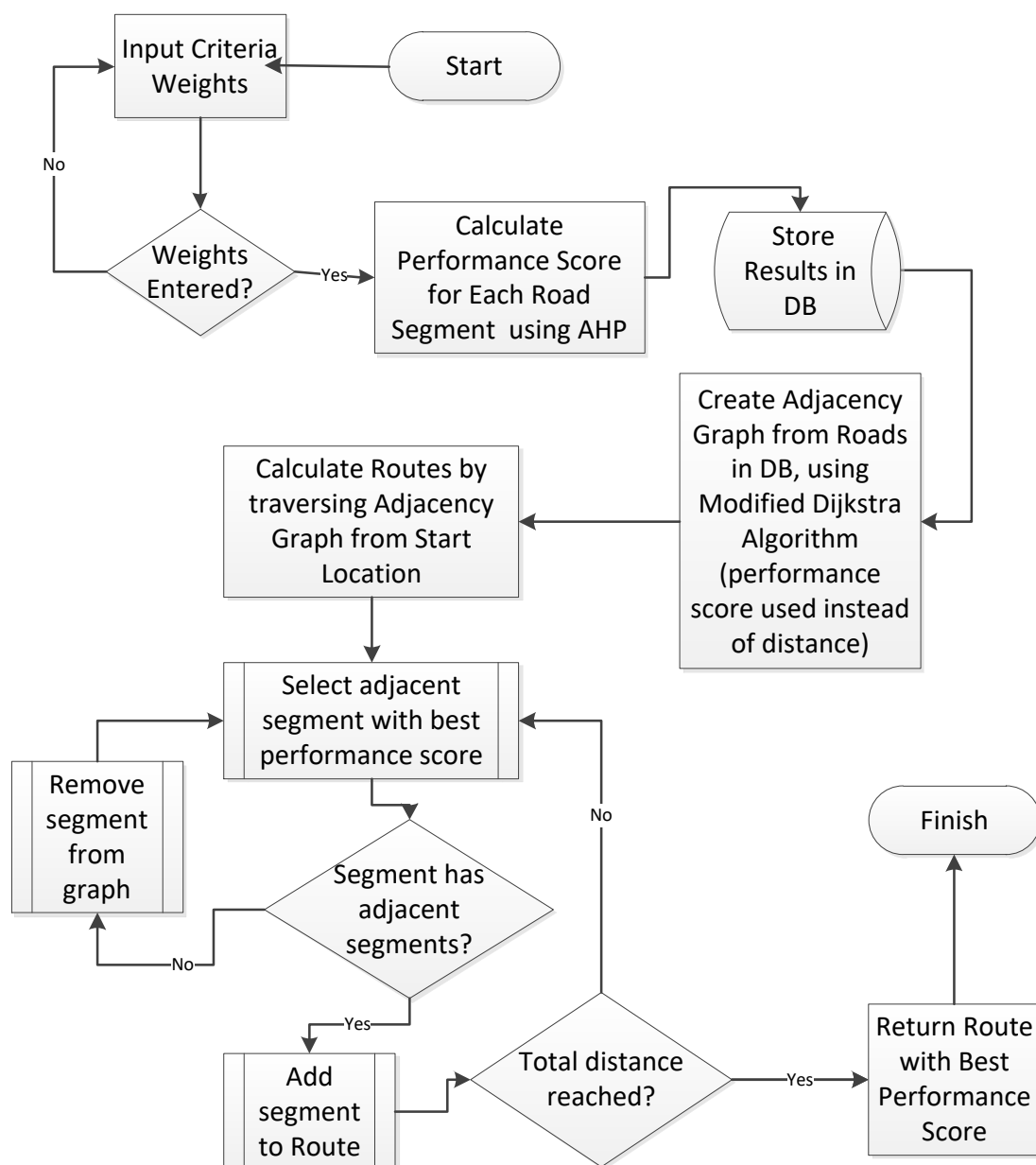
Figure 5: Design of Route Optimizer Algorithm

3.4.6 Identification of Hard and Soft Constraints

Hard constraints are constraints that cannot be altered. Some hard constraints to be considered in the context of route selection by the prototype are obvious, whilst other constraints require more thought and examination. An example of the former is race distance. This is a constant value and cannot be changed: 42.195 km for a marathon; 21.0975km for a half marathon and so on. An example of the latter might be exclusion of roads within a certain distance from hospitals, police stations and other emergency services.

The following is a list of hard constraints that were used in the prototype SDSS:

- **Race distance:** During calculation of a race route, the prototype will stop selecting roads or paths, as part of the race route, when the race distance has been met.

- **Buffer zone around emergency service buildings:** The prototype will not select roads within 200 meters from emergency service buildings

Soft constraints are constraints that can be modified by decision makers that make use of the SDSS.

The following is a list of soft constraints that were used as criteria in the prototype SDSS:

- aesthetics of the course
- maximum slope
- average slope
- course capacity
- surface of the course
- number of turns in the course.

3.4.7 Client UI – Mobile and Desktop Cross-platform Implementation

For the purposes of this study, a prototype SDSS was developed with only limited cross-platform ability. The prototype was developed to run on Windows desktop and Android mobile platforms.

As, previously discussed, there are many cross-platform app development frameworks available in the market today, such as Ionic, Xamarin, React Native, Flutter and Adobe PhoneGap.

For the implementation of the prototype, I decided to go with Xamarin, together with Universal Windows Platform (UWP) for the desktop user-interface. The reason for my choice was simply because I have more experience programming with C# and

the .Net framework, using the Visual Studio IDE, than I do with JavaScript, HTML, and CSS, which are technologies used by the other frameworks.

3.4.8 Back-end Implementation

The prototype SDSS was implemented using Web API restful services that provide an interface between the desktop and mobile clients, on one hand, and the business logic and database on the other.

In order to speed up development time, a database-first approach was followed, using Entity Framework 6. This approach facilitated the automatic generation of the data models in the code from the database tables. In addition, scaffolding was used to automatically generate the Web API service controllers that provide an external interface to the client UI. The Web API service controllers enable the user to retrieve, add, delete, or update data that is stored in the database via the data models.

3.4.9 Map Technologies

I decided to use the Xamarin.Forms Map control to implement mapping functionality in the SDSS prototype. This map control is provided by the cross-platform app development framework Xamarin. Xamarin.Forms Map uses the power of both Google Maps API and Bing Maps API technologies to provide mapping functionality. The Universal Windows Platform (UWP) desktop platform uses the Bing Maps API and Android mobile platform uses Google Maps API. However, it is one map control that is needed for the implementation and all that is required is to have two keys, one for Google Maps API and one for Bing Maps API.

3.5 Testing and Verification of the Prototype

3.5.1 Internal Testing of the Prototype

Unit tests were implemented to test both the AHP MCDA algorithm, and the greedy algorithm needed for selecting the best performing race route.

3.5.2 In-Field Testing of the Prototype

Using the desktop app, I created five use-cases, each of which emphasise a specific criterion, such as average slope or road capacity. A selection of three use-cases were tested in the field, on the mobile-app.

The strategy behind the in-field testing of the prototype was to see whether the route optimizer prototype could be beneficial to the decision-making process, by:

- Satisfying user preferences indicated by criteria weights set prior to route generation.
- Comparing the routes of the three use-cases in-field to see how they differ to each other with respect to the criteria.
- Analysing the routes of the three use-cases in-field to see whether there are any problems along the route generated by the prototype and to suggest how, in theory, a production MDSS system would be able to deal with such problems in a decision-making environment.

In addition to using the route optimizer mobile app, a Garmin Forerunner 245 GPS watch was used to measure the route in-field, so that the actual in-field measurement of the route could be compared to the one generated by the app.

3.5.3 Verification of Results Using Spatial Analysis Tools

The use-cases described above were verified in ArcGIS and through other means, to investigate whether the AHP criteria weighting functioned as expected.

4. Results and Discussion

The following section looks at the feedback from the questionnaire, gives an overview of the prototype and the setup of various use-cases to be used in in-field testing. This is followed by the results of in-field testing of the use-cases and verification of the results of in-field testing, using spatial analysis and other means. The goal of which, is to illustrate the potential of the prototype to satisfy various design preferences, as obtained from the feedback from the questionnaire, and highlight any potential shortcomings of such a prototype.

4.1 Feedback from Questionnaire

This section presents the results of the questionnaire (see Appendix 1) that was used to get feedback from respondents on the applicability of a collaborative Spatial Decision Support System (SDSS) to complement or potentially to replace current techniques used to design a new, or adjust an existing, race route. Of the 50 questionnaires that were sent out, a total of 33 respondents responded.

4.1.1 Number of People in the Decision-making Process

The first question is as follows:

"How many people are involved in your organisation's decision-making process when designing a new marathon course or adjusting an existing marathon course?"

The results from the respondents show that 48% of the participating organisations have between 2 and 4 people involved in the decision-making process, and 30% of the organisations have between 5 and 9 people involved in the decision-making process. Only 6% of the organisations had 1 person making autonomous decisions regarding the route design process (see Table 5).

These results indicate that this could be an appropriate situation for collaborative decision-making, using a spatially-enabled MDSS for route design.

Table 5: Number of People in Decision-making Process

Number of people in decision-making process	Results
1	2 (6%)
2 - 4	16 (49%)
5 - 9	10 (30%)
> 10	5 (15%)

4.1.2   Race Route Design Methods

The second question was focussed on race route design methods and was stated as follows:

"Please indicate which of the following methods your organisation uses to support the design of a new or existing marathon course?"

The results from the respondents show that 38% of the organisations use Google or Bing Maps to support the design of the race route, while 33% use In-field surveying of roads and a further 26% make use of physical maps. A mere 3% of respondents used GIS software for this purpose, and perhaps unsurprisingly there was not a single organisation that used a Spatial Decision Support System (see Table 6).

Table 6: Race Route Design Methods

Design Method	Results
GIS software	2 (3%)
In-field surveying of roads (using GPS or other methods)	22 (33%)
Spatial Decision Support System	0 (0%)
Physical maps	17 (26%)
Google or Bing Maps	25 (38%)

4.1.3   Feedback on Race Route Criteria

The third question focussed on race route criteria and was stated as follows:

"In terms of the actual route, what are the most important considerations that are considered when designing a new or adjusting an existing course? Please rank in order of importance."

In Table 7 the criteria are ordered in terms of importance according to the respondents' selections, with 1 being the most important and 6 being the least important. Course capacity had 12 respondents deeming it the most important criterion and has a score of 4.7. Next are surface and aesthetics with scores of 4.61 and 4.18 respectively. Slope (average and maximum) along with number of turns are less important to the respondents.

Table 7: Race Route Criteria

	1	2	3	4	5	6	Score
Course capacity (the width of the race course sufficient for number of runners)	12	9	6	3	2	1	4.7
Surface of the course (asphalt, concrete, cobble stones, gravel, dirt)	10	11	5	4	2	1	4.61
Aesthetics of the course (Greenery - parks, natural scenery, cultural sights)	8	7	10	2	3	3	4.18
Average difference in elevation	2	2	6	6	12	5	2.82
Maximum slope	1	1	3	11	6	11	2.39
The number of turns	0	3	3	7	8	12	2.3

4.1.4 Feedback on Accessibility Criteria

Although accessibility criteria were not used in the design of the prototype, I have included the results from this question below:

"In terms of the accessibility, what are the most important considerations that are considered when designing a new or adjusting an existing course? Please rank in order of importance."

It is unsurprising that the criterion with the highest score (4.55) is "Start / finish area layout and capacity". However, it was interesting to note that "Parking areas in vicinity" was more important to the respondents than "Public transport to start / finish area", considering the drive for a greener environment (see Table 8).

Table 8: Accessibility Criteria

	1	2	3	4	5	Score
Start / finish area layout and capacity	26	3	1	2	1	4.55
Parking areas in vicinity	2	12	7	8	4	3
Location of refreshment stations	2	6	10	8	7	2.64
Location of medical services	1	9	3	11	9	2.45
Public transport to start / finish area	2	3	12	4	12	2.36

4.1.5 Feedback on Applicability of a Spatially-enabled MDSS

The most interesting and fundamental feedback in terms of this paper comes from the following, rather more subjective, question:

"The objective of this project thesis is to illustrate the applicability of a collaborative Spatial Decision Support System (SDSS) that can be used by various people involved in the decision-making process, across both desktop and mobile platforms. A Spatial Decision Support System (SDSS) merges technologies and methodologies from GIS and MCDA. Geographic Information Systems (GIS) consist of an integrated set of components capable of analysing and visualising spatial data, which can assist in decision making. Multi-criteria decision analysis (MCDA) consists of a framework and various algorithms used for the prioritisation and evaluation of various alternative decisions that assists in the decision-making process. During the process of a marathon course design, various people involved in the decision-making process might need to be able to analyse the proposed route alternatives in a boardroom meeting projected from a desktop PC. On the other hand, people in the field could be verifying and providing 'real-time' feedback on potential route alternatives using mobile devices. In your view would such a SDSS system complement or have the potential to replace your current techniques used when designing a new or adjusting an existing course? Please elaborate."

The responses from the 33 respondents were very mixed (see Appendix 7), with 11 (33%) of the 33 responding quite negatively and only 4 (12%) of the 33 respondents giving a definite positive response. The rest of the responses were more neutral, with 11 (33%) of the 33 stating that a spatially-enabled MDSS could possibly compliment their current methods, and 7 (21%) of the 33 seemed rather unsure of the benefit of a spatially-enabled MDSS.

A few of the respondents, such as the responses given by respondents 5, 13, 23, and 24, seemed to misunderstand the full value of the spatially-enabled MDSS, which was not only to generate routes but also to verify the generated routes in-field and provide feedback, which is part of the decision-making process.

Some of the respondents indicated that cost might be a factor, which is understandable.

4.2 Overview of Route Optimizer Prototype

The route optimizer prototype consists of a desktop application - Universal Windows Platform (UWP) - and a mobile application that runs on Android. The Windows desktop application is useful for selecting desirable criteria weights, generating routes, and viewing the resulting maps, since it has a larger screen size and has a good internet connection. This enables a collaborative decision-making environment where the desktop application can be viewed on a projector in a conference room. The mobile application, on the other hand, is suitable for verifying a generated route in the field.

4.2.1 Criteria Selection

The first step in creating a new route is to select appropriate preferences. Weights are calculated by assigning preferences to criteria with regards to other criteria in a matrix (See Figure 6). It is necessary to fill in only half of the matrix, since the other half of the matrix, below the diagonal line consisting of ones, is the inverse of the top half of the matrix and is calculated within the algorithm.

Criteria Setup Generate Map

Criteria	Capacity	Surface	Aesthetics	Ave Slope	Max Slope	Num Turns
Capacity	1	1	7	9	9	7
Surface		1	7	9	9	7
Aesthetics			1	3	3	1
Ave Slope				1	1	1/3
Max Slope					1	1/3
Num Turns						1

Criteria weights calculated successfully   Calculate Weights
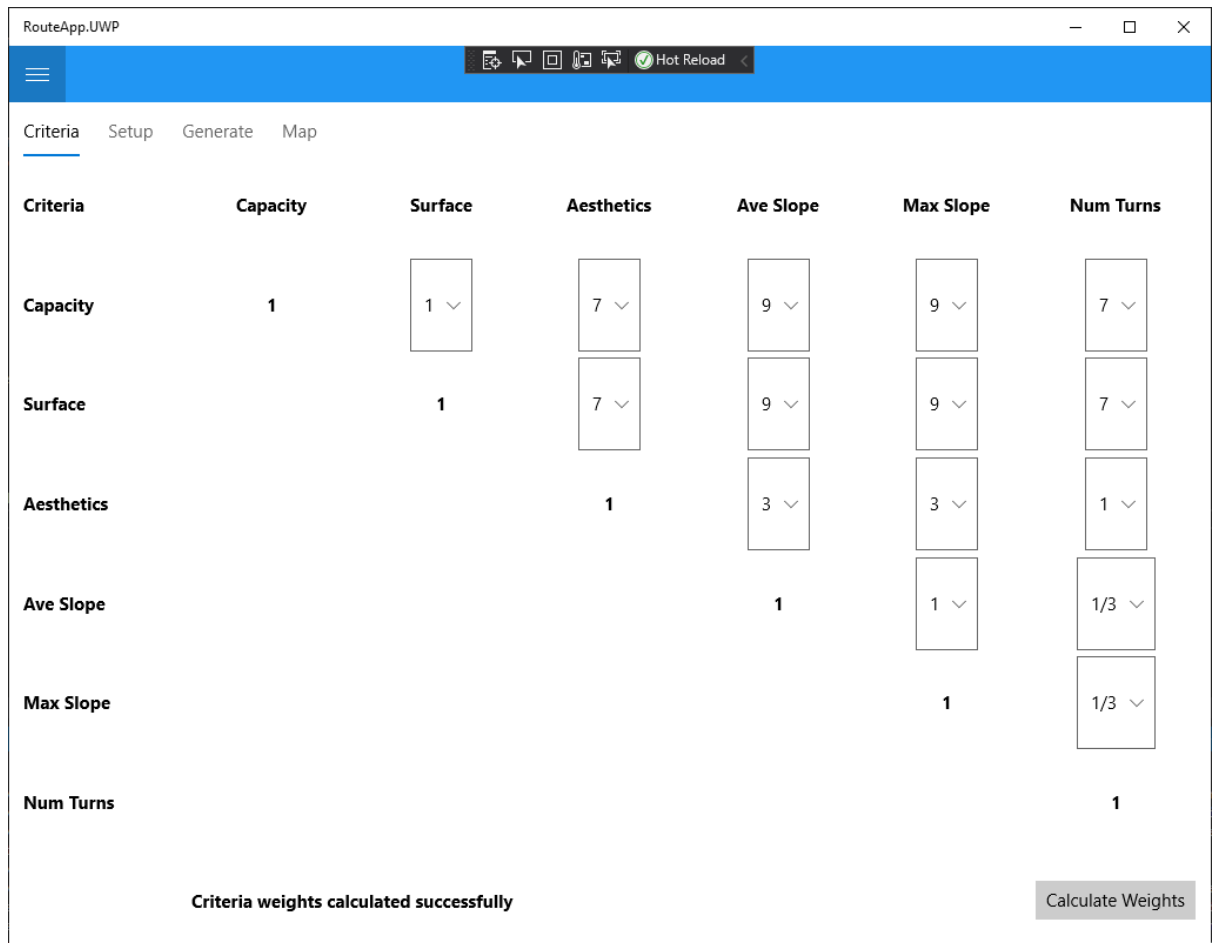
Figure 6: Criteria Weighting User-interface Displaying a AHP Matrix

4.2.2 Route Generation

Once the weights have been calculated, the user can generate a route. Initially the criteria weights are applied to each road segment to generate an overall preferability score for each road segment. Then all the road segments are added to an adjacency graph, which consists of the edges and vertexes of each road segment. The graph is then ready to be traversed by the route optimizer algorithm, to find the optimal route.

For the purposes of the route optimizer prototype, the starting point of the route is fixed, and the length of the route is fixed to 5km, which made in-field testing more manageable.

4.2.3 Calculated Route Displayed on Output Map

The route is displayed on an embedded map within the desktop and mobile clients. In the case of the desktop application Microsoft Bing Maps is used to display the route to the user (See Figure 7).

In the desktop application the start and end points are indicated by green and red pins respectively. The blue pins indicate kilometre markers along the route.
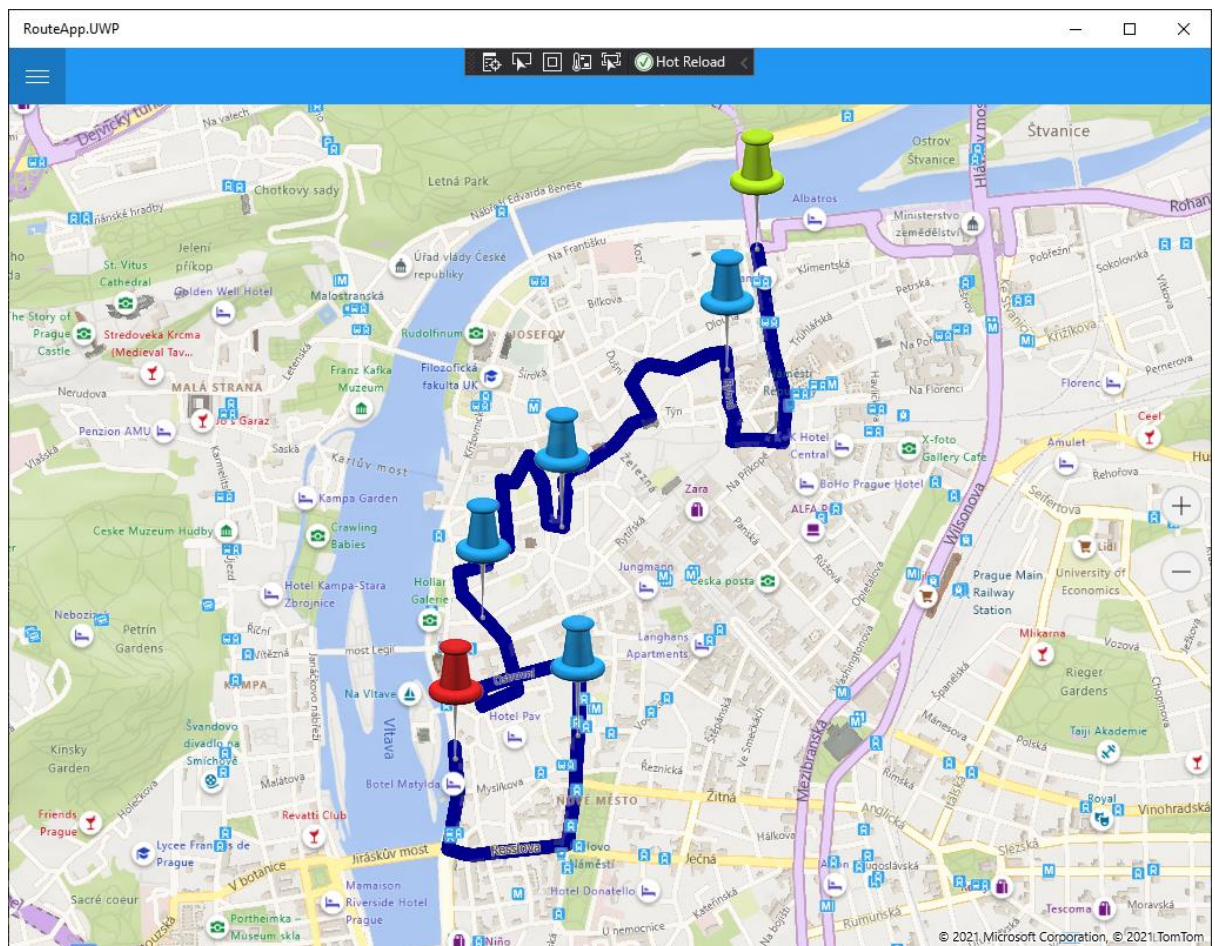
Figure 7: Route Displayed in the Desktop Application, Using Bing Maps

In the mobile application, Google Maps is used to display the route to the user (See Figure 8). On Google Maps the start and end points and kilometre markers are all rendered as red pins by default. When a user clicks on the pins in either the desktop or mobile applications, the number of kilometres is displayed.
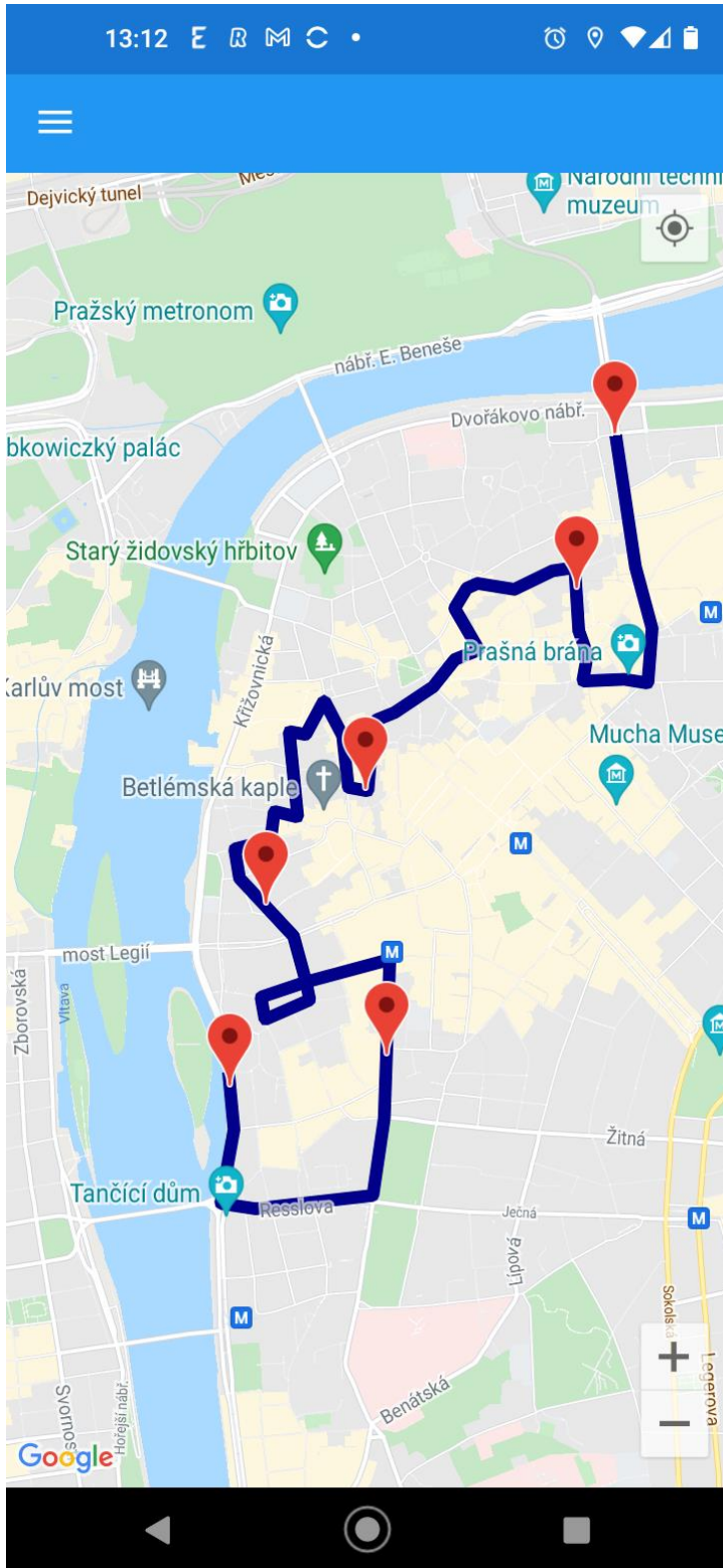
Figure 8: Route Displayed in the Mobile Application, Using Google Maps

4.3 Use-case Setup for Testing

4.3.1 Overview

Five use-cases were setup for general application testing. Three of these were selected to be additionally tested in the field on the mobile application. The five use-cases each emphasize a different criterion, namely capacity, surface, slope, aesthetics, and number of turns of the route.

4.3.2 Use-case 1: Capacity Prioritized

The first use-case prioritizes capacity of the race route. This should emphasize larger roads that have a capacity for more people. In this case the criterion Capacity was given a high value of 9 when compared to the other criteria (See Figure 9).

Figure 9: Selecting the Criteria Weighting to Prioritize the "Capacity" Criterion

After calculating the weights (Table 9), the weights were saved in the database. Here it is obvious that the capacity criterion has a much higher weight of 0.64, compared to the other criteria which have a weight of 0.07.

Table 9: AHP Calculated Weights Emphasizing the Criterion – "Capacity"

Aesthetics	AverageSlope	Capacity	MaxSlope	NumTurns	Surface
0.07	0.07	**0.64**	0.07	0.07	0.07

When the route optimizer algorithm was executed, using the weights emphasizing capacity, the route depicted in Figure 10 was generated.
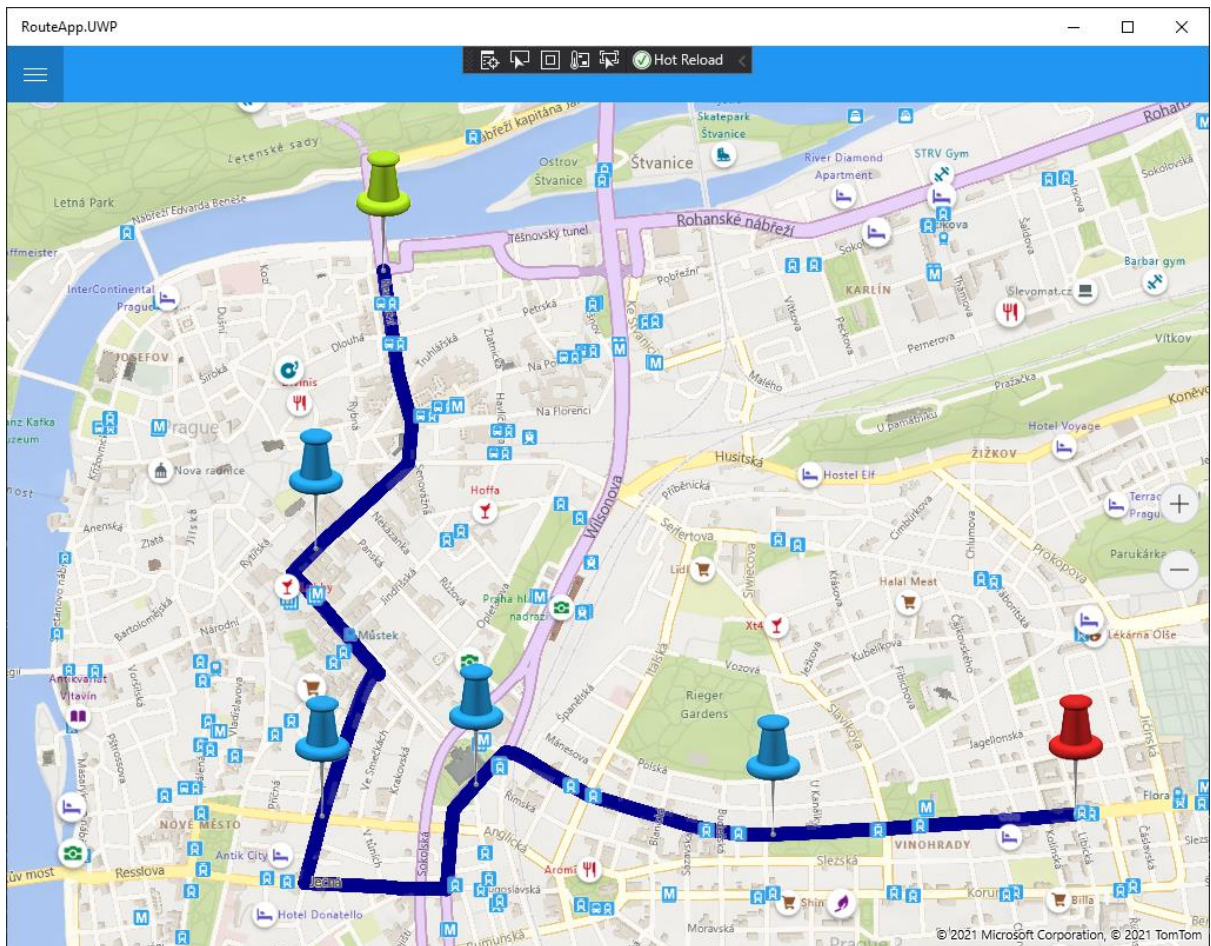
Figure 10: Route Generated with the Criterion "Capacity" Prioritized

4.3.3 Use-case 2: Slope Prioritized

The second use-case prioritizes the slope of the race route. Roads with a smaller slope i.e., flatter roads, should be prioritized above hillier roads. In this case the criteria *Average Slope* and *Maximum Slope* were given higher values when compared to the other criteria (See Figure 11).

Figure 11: Selecting the Criteria Weighting to Prioritize "Average Slope" & "Max Slope"

The weights described in Table 10 were calculated using the AHP algorithm and saved in the database. The average slope and max slope criteria both have a weight of 0.35, which is higher than the weights of the other criteria.

Table 10: AHP Calculated Weights Emphasizing the Criteria – "Average Slope" & "Max Slope"

Aesthetics	AverageSlope	Capacity	MaxSlope	NumTurns	Surface
0.13	**0.35**	0.04	**0.35**	0.10	0.04

After executing the route optimizer algorithm, using the new weights in Table 10, the route depicted in Figure 12 was generated. It is immediately obvious that a completely different route has been generated compared to the route generated in Use-case 1.
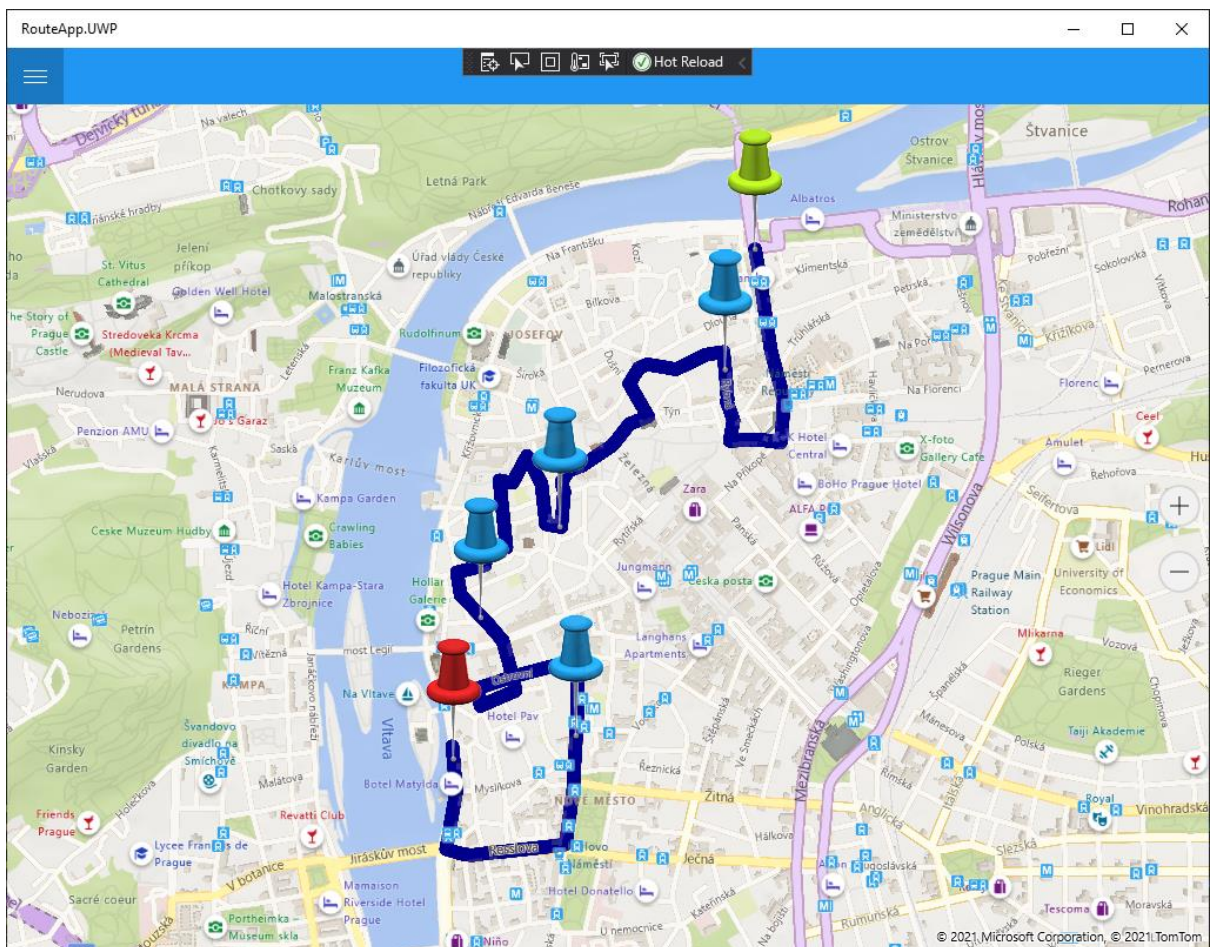
Figure 12: Route Generated with the Criteria "Average Slope" & "Max Slope" Prioritized.

4.3.4 Use-case 3: Aesthetics Prioritized

The third use-case prioritizes the aesthetics of the race route. Roads closer to aesthetic features are preferred. Aesthetic features include man-made features such

as historical buildings and bridges. In Prague, Charles Bridge and Prague Castle are examples of man-made aesthetic features. Aesthetic features can also include natural features such as parks, rivers, and forests. In this case the criterion *Aesthetics* was given a higher value compared to the other criteria (See Figure 13).
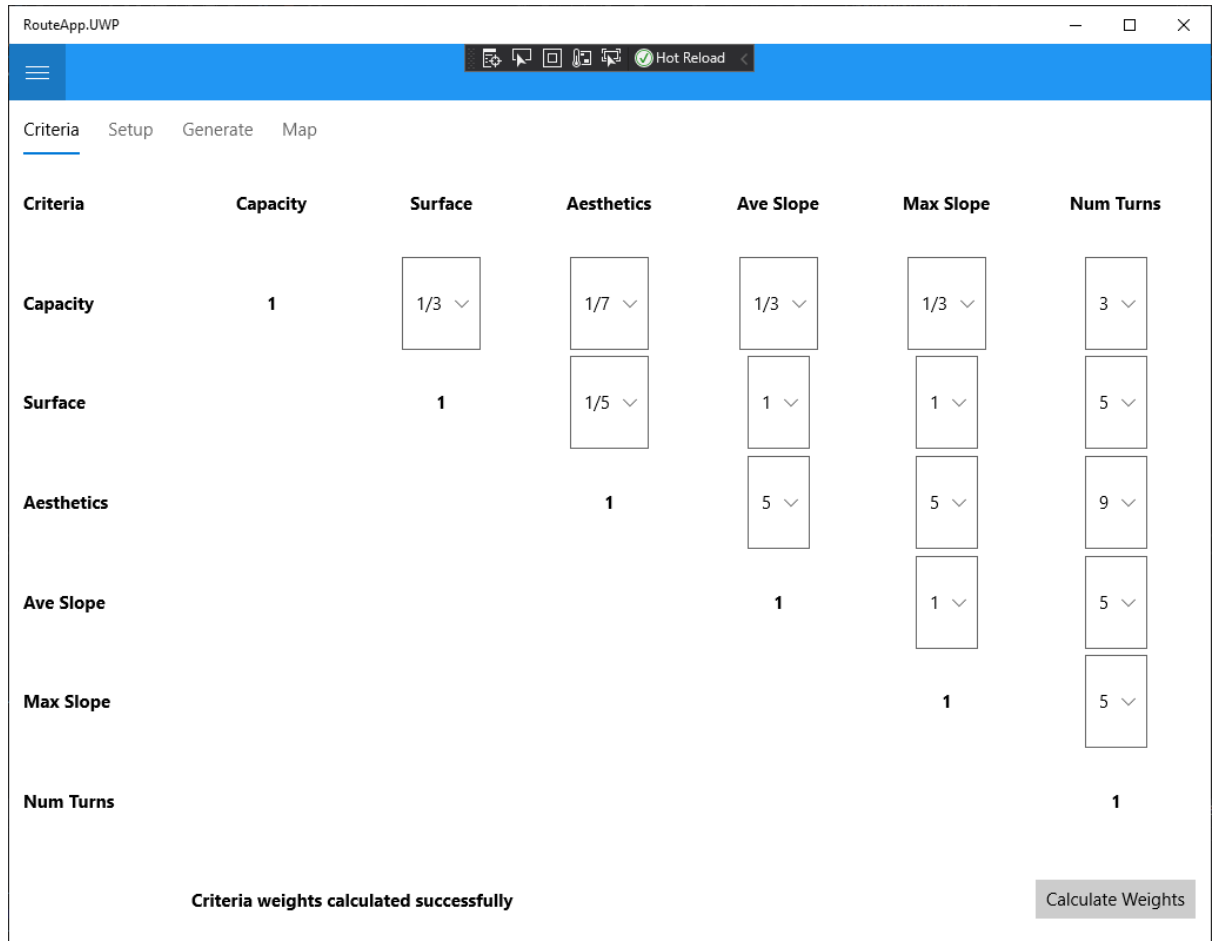
Figure 13: Selecting the Criteria Weighting to Prioritize the "Aesthetics" Criterion

The weights depicted in Table 11 were calculated using the AHP algorithm and saved in the database. The *Aesthetics* criterion has a weight of 0.50, which is higher than the weights of the other criteria.

Table 11: AHP Calculated Weights Emphasizing the Criterion – "Aesthetics"

Aesthetics	AverageSlope	Capacity	MaxSlope	NumTurns	Surface
0.50	0.14	0.06	0.14	0.03	0.14

When the route optimizer algorithm was executed, using the weights emphasizing *Aesthetics*, the route depicted in Figure 14 was generated.

55
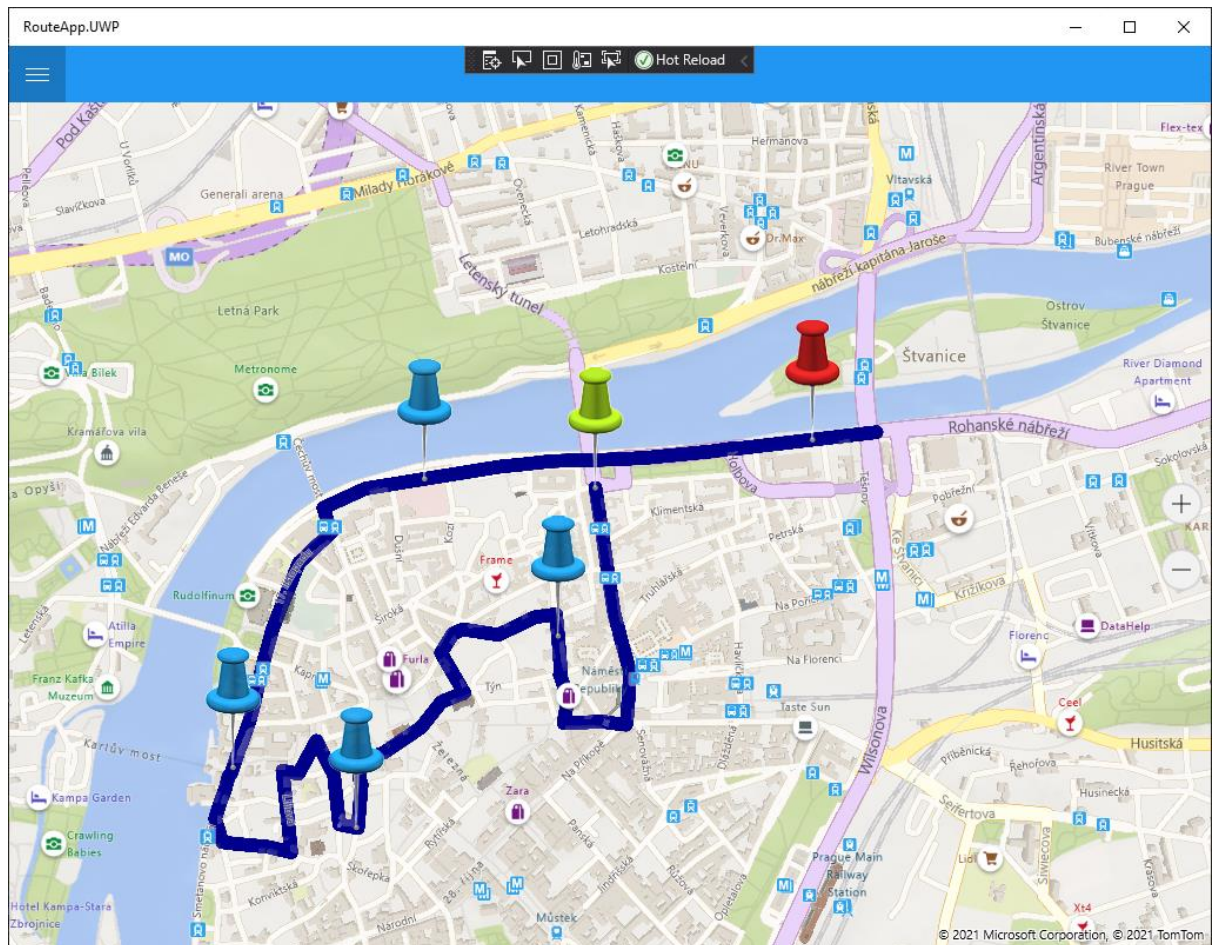
Figure 14: Route Generated with the Criterion "Aesthetics" Prioritized.

4.3.5 Use-case 4: Surface Prioritized

Road surface was prioritized in the fourth use-case of the race route. Roads with a smoother surface are preferred. In this case the *Surface* criterion was given a higher value compared to the other criteria (See Figure 15).
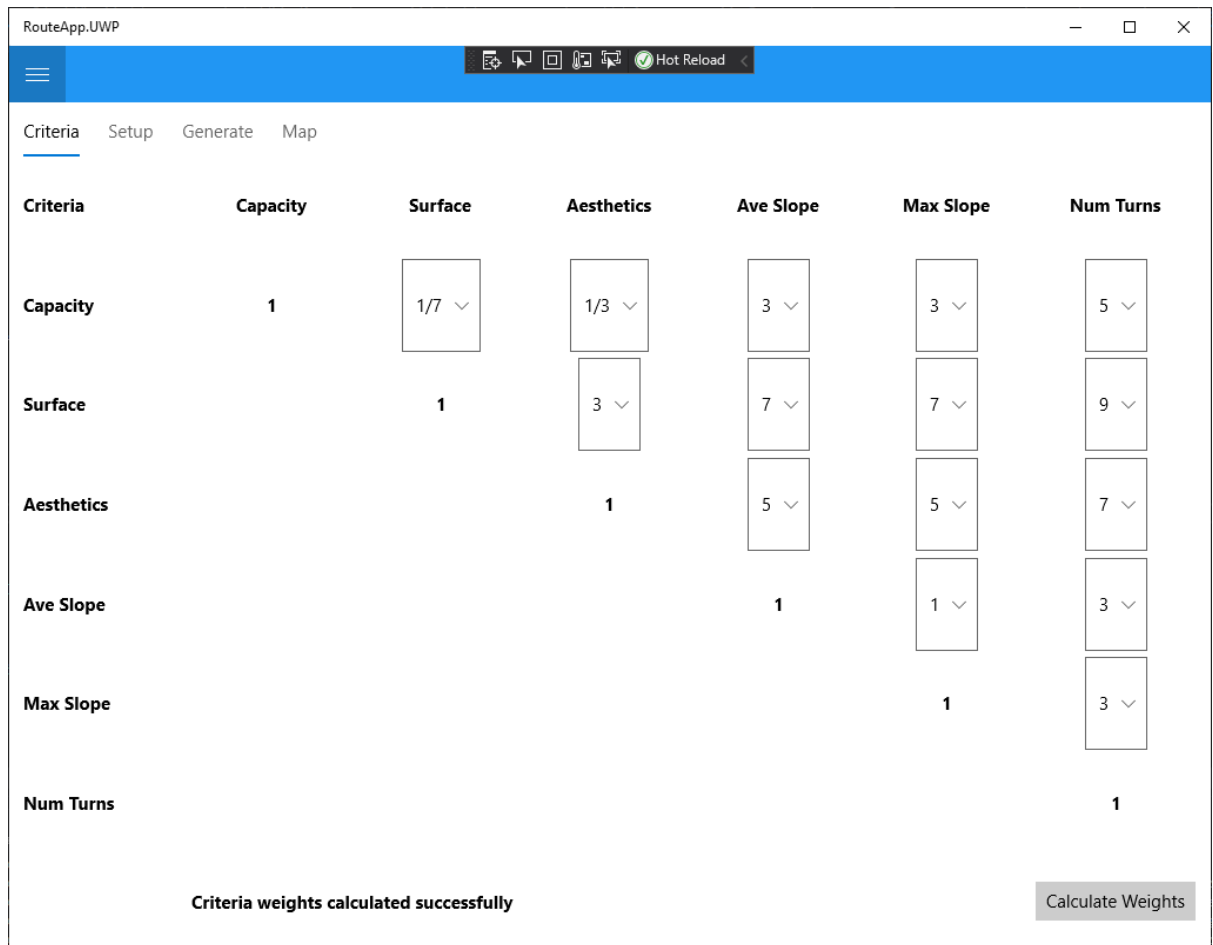
Figure 15: Selecting the Criteria Weighting to Prioritize the "Surface" Criterion

The weights shown in Table 12 were calculated using the AHP algorithm and saved in the database. The *Surface* criterion has a weight of 0.48, which is higher than the weights of the other criteria. *Aesthetics* has the next highest weight of 0.24, so it should also be quite an influential criterion when selecting a route.

Table 12: AHP Calculated Weights Emphasizing the Criterion – "Surface"

Aesthetics	AverageSlope	Capacity	MaxSlope	NumTurns	Surface
0.24	0.06	0.13	0.06	0.03	**0.48**

After executing the route optimizer algorithm, using the weights emphasizing *Surface*, the route shown in Figure 16 was generated. It is quite similar to the route generated in Use-case 3, where aesthetics is prioritized. This is expected, since aesthetic had the second highest weight in the matrix.
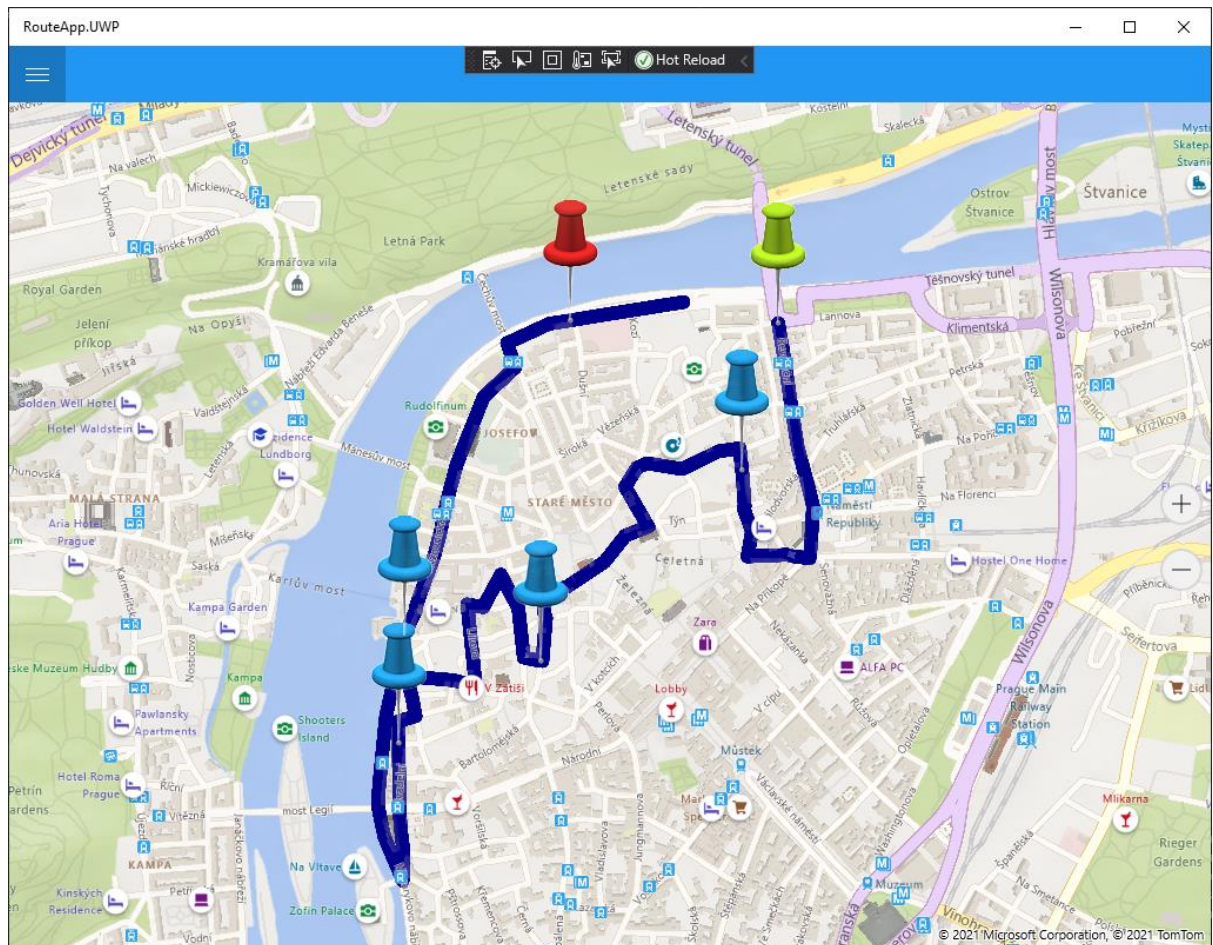
Figure 16: Route Generated with the Criterion "Surface" Prioritized.

4.3.6 Use-case 5: Number of Turns Prioritized

The last use-case prioritizes the number of turns of the race route. Longer roads are prioritized, with the hypothesis that there will be less turns in the route compared to a route with a lot of shorter road segments. In this use-case the *Number of Turns* criterion was given a higher value when compared to the other criteria (See Figure 17).
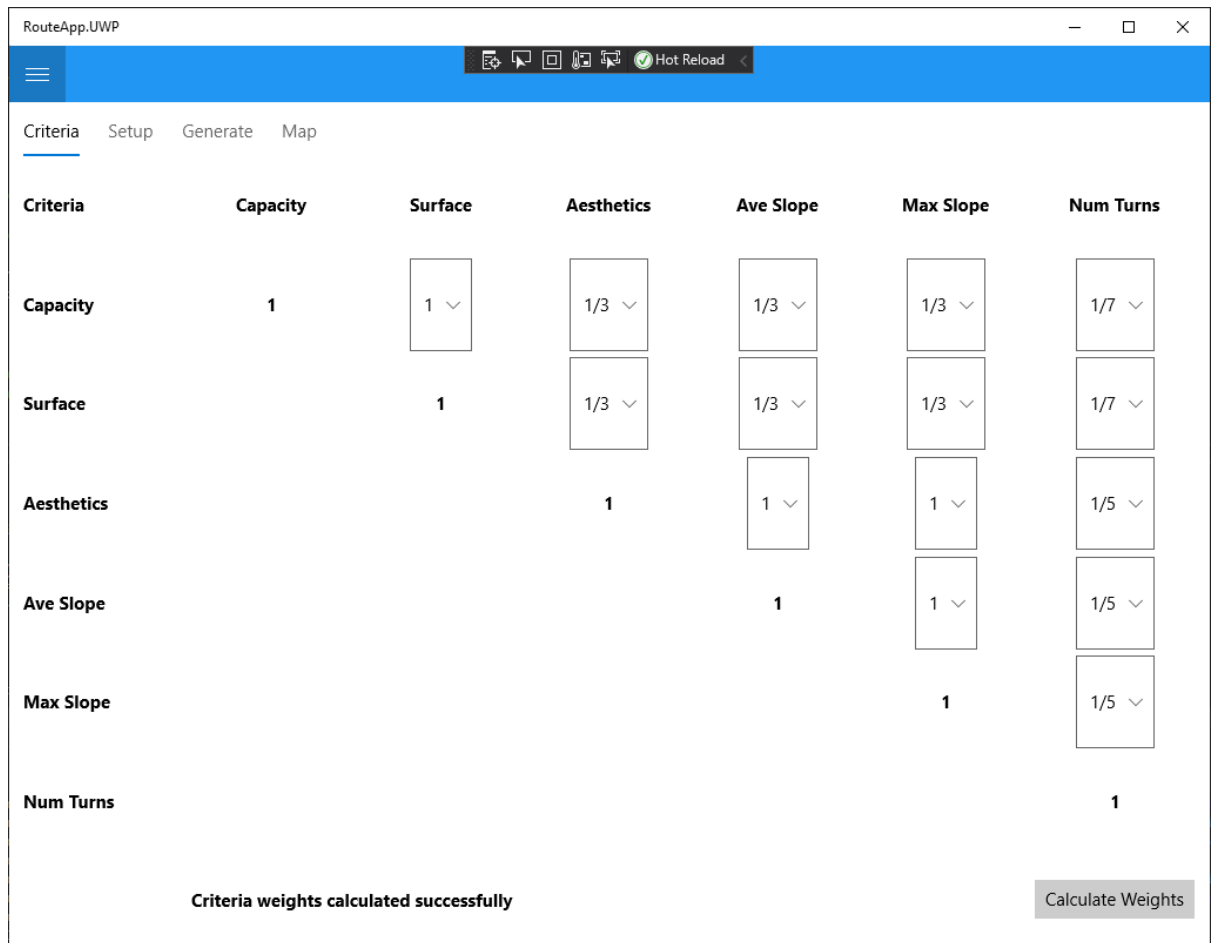
Figure 17: Selecting the Criteria Weighting to Prioritize the "Number of Turns" Criterion

The AHP algorithm calculated the weights, which were then saved in the database (See Table 13). The *Number of Turns* criterion has a weight of 0.51, which is a higher value than that of the other criteria.

Table 13: AHP Calculated Weights Emphasizing the Criterion – "Number of Turns"

Aesthetics	AverageSlope	Capacity	MaxSlope	NumTurns	Surface
0.13	0.13	0.05	0.13	**0.51**	0.05

Using the weights in Table 13, the route optimizer algorithm generated the route shown in Figure 18. Here it is noticeable that the route has less turns compared to the routes generated in Use-cases 2, 3 and 4.
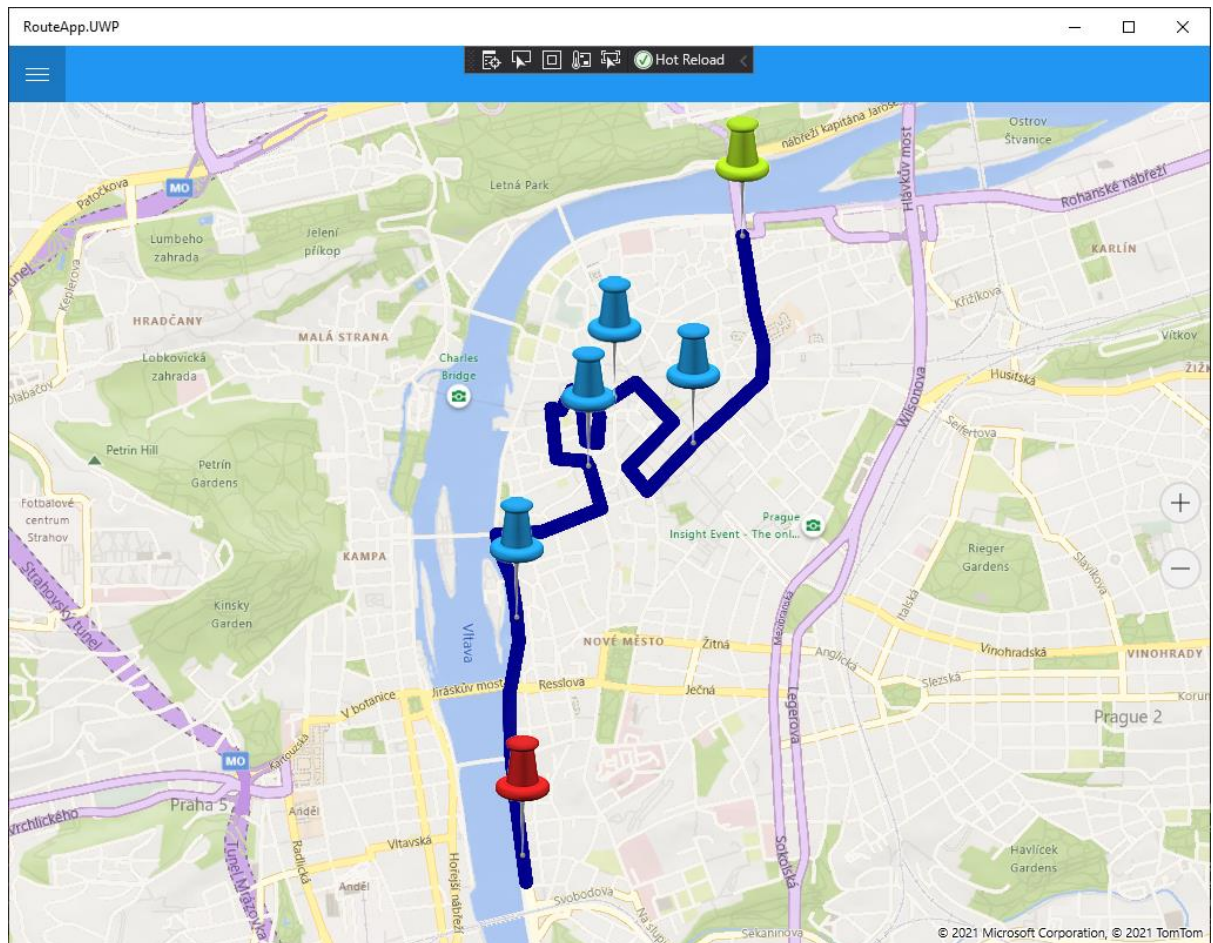
Figure 18: Route Generated with the Criterion "Number of Turns" Prioritized.

4.4 Analysis of Results of In-field Testing

Due to time-constraints only three of the five use-cases were tested in the field. The following use-cases were selected: Use-case 1 (Capacity), Use-case 2 (Slope) and Use-case 3 (Aesthetics).

4.4.1 Results of Use-case 1: Capacity Prioritized

In the first use-case, road capacity is prioritized, which means the expected result is a route that has bigger roads that can handle a larger number of runners.

As mentioned previously, the route length used for testing purposes was fixed to 5km, and the road Revoluční, near the Old Town of Prague, was used as the starting point. The start point is the top-most marker on the route (See Figure 19)
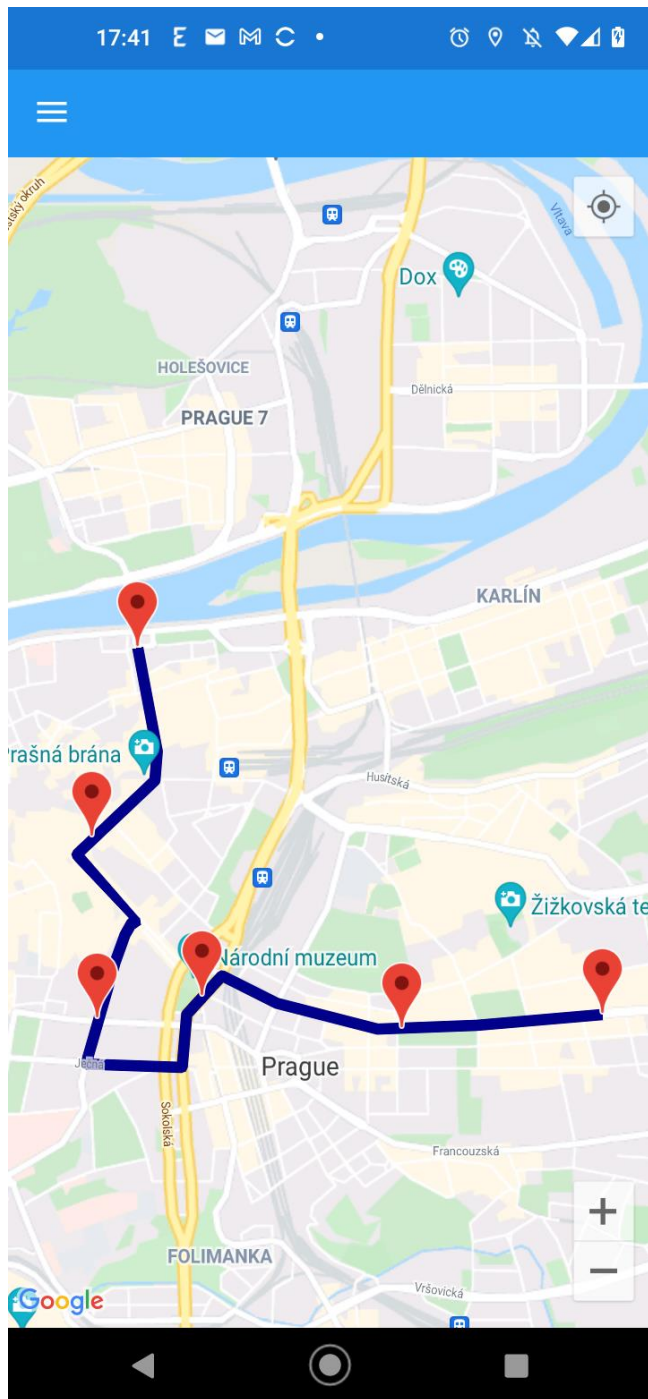
Figure 19: "Capacity" Prioritized Route on Mobile App.

I started walking from the start at Revoluční to the end, indicated on the map by the
last red marker. To navigate along the route, I was guided by a blue icon with an
arrow, which indicated my current position and direction. In addition, the red
markers indicated how far along the course I was. An example is shown in Figure 20
below.
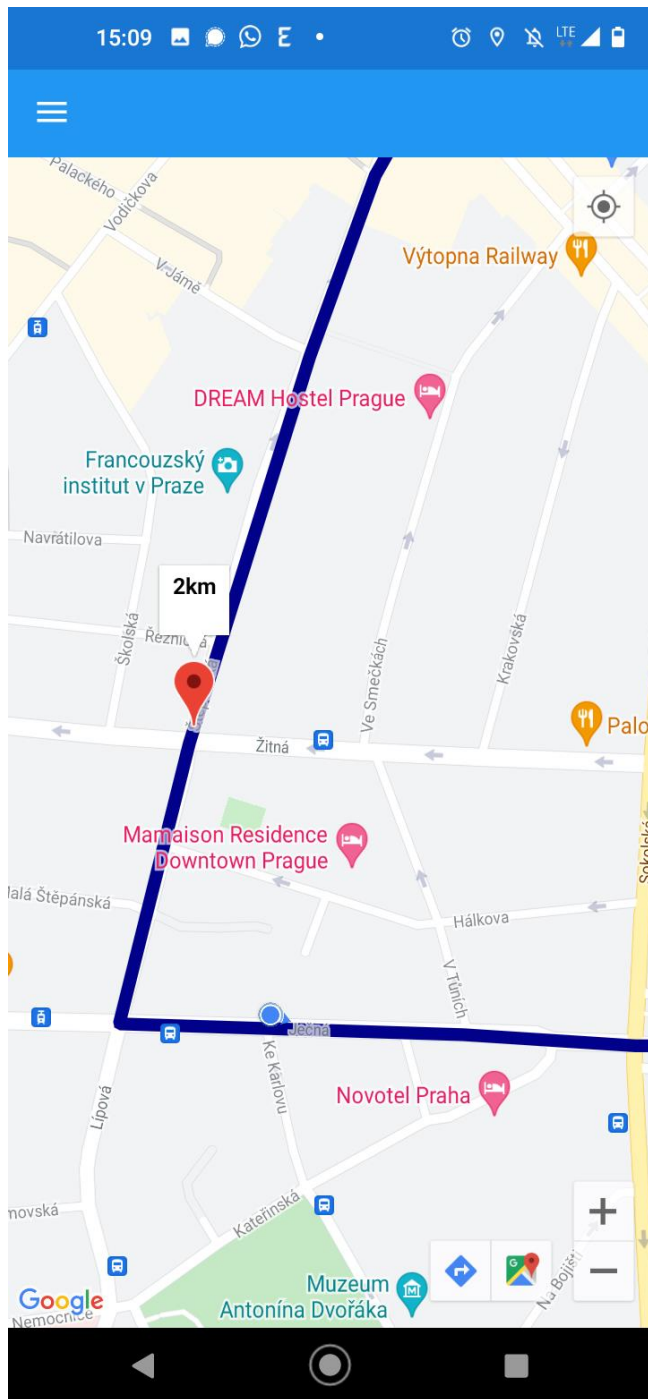
Figure 20: Navigating Along the Route

To verify the route length and elevation gain, I used my Garmin Forerunner 245 GPS watch to measure the route while following the route on the mobile app.

By testing the route in the field, I noticed the following:

- The route itself seemed to be at an almost constant incline, although not very steep. This is also verified in Section 4.4.1 Verification of Use-case 1

- As expected, the route consisted of mostly main roads, consisting of one or more lanes, since road capacity is prioritized for this use-case. In Appendix 3 there are photographs taken along the route that illustrate this.
- I came across some road works along the route, which highlights the potential advantage of in-field verification of the route. Although the prototype is limited in its ability to provide real-time decision support, a production MDSS could potentially enable an in-field operator to decide whether to reject the route. For example, if the operator came across something that obstructs the route, such as road works in this case, the operator could exclude the road segment with the obstruction and then generate a new route.

4.4.2 Results of Use-case 2: Slope Prioritized

In this use-case, slope is prioritized, so the expected result is a relatively flat route.

As in the previous use-case, the route length is 5km and the starting point is the road Revoluční, however it is immediately visible in Figure 21 that the route generated for this use-case is entirely different.
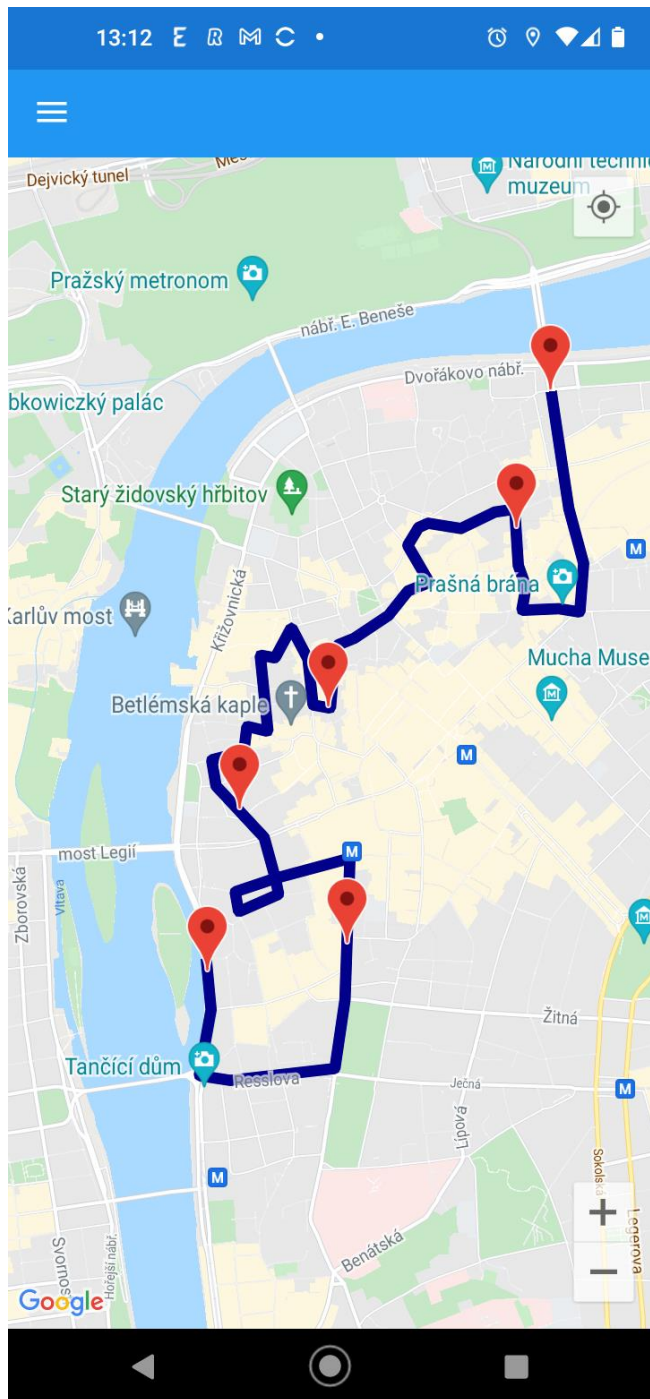
Figure 21: "Slope" Prioritized Route on Mobile App.

While verifying this route in the field the following points became apparent, which can be seen in the photographs in Appendix 4:

- The route was much flatter than the route generated for Use-case 1. It also consisted of quite a few downhill sections.

- The route passed through the Old Town, which was not that surprising since Aesthetics was the criterion with the second highest weighting and there are a lot of interesting historical buildings in the area.
- The route had a lot more turns, compared to the route generated for use-case 1. Logic tells me that larger roads, with higher capacity are generally longer than smaller streets. In this use-case the *Capacity* criterion has the lowest weight, which is why I think this route had more turns in it than the previous one.
- Since the route passed through the old town it was quickly noticeable that most roads were paved with cobblestones. This is not an ideal situation for runners. Unfortunately, the surface classifications derived from the Road Class in the original dataset do not consider cobblestones. In hindsight it would make sense to reclassify all roads in the old town to a surface category with a lower value. Again, the value of in-field verification on a mobile device was highlighted.

4.4.3 Results of Use-case 3: Aesthetics Prioritized

Use-case 3 prioritizes the criterion Aesthetics, which means that it is expected that the route will go through some picturesque areas.

This use-case has the same starting point at Revoluční and route length (5km) as the previous two use cases. The route generated for this use-case is similar to the one in Use-case 2, with the first half being the same, however the second half runs along the river which adds to the overall attractiveness of the route (See Figure 22).

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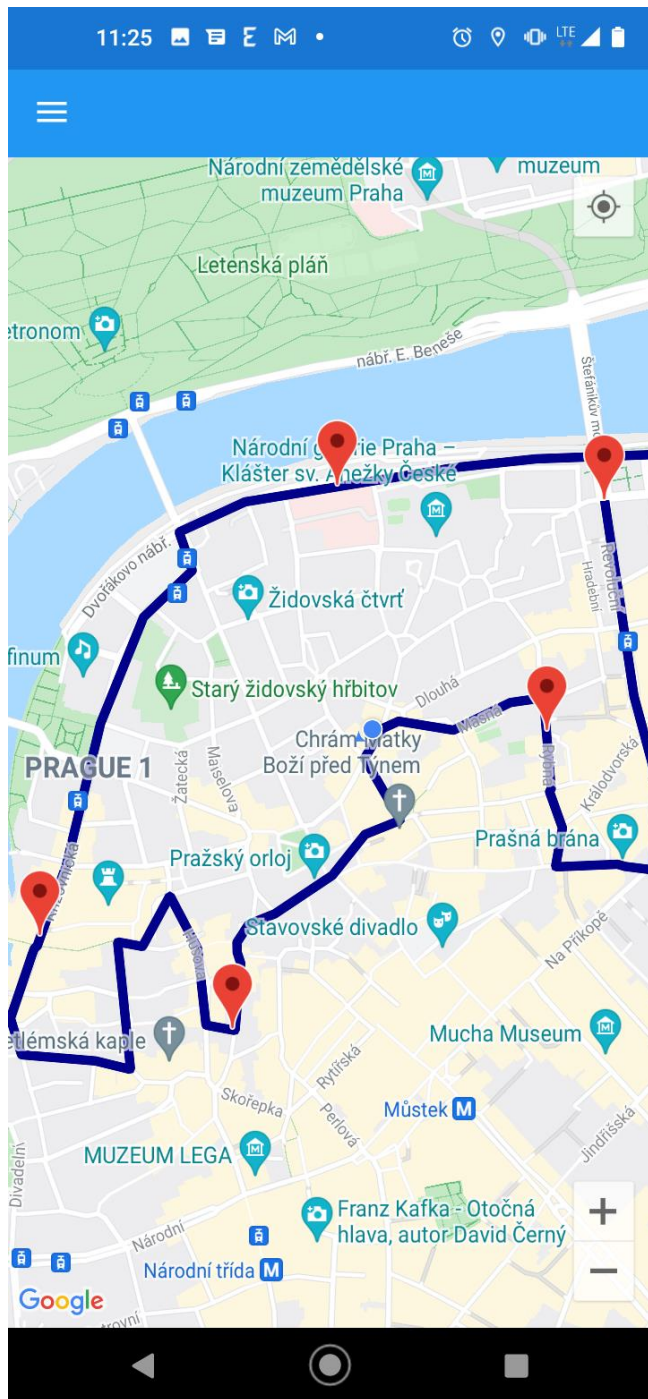
Figure 22: "Aesthetics" Prioritized Route on Mobile App.

During the verifying of this route in the field, I noticed the following points, which are illustrated in the photographs in <u>Appendix 5</u>:

- The first half of the course runs through the old town of Prague, which has many beautiful historical buildings and squares.
- The second half of the course ran along or nearby the river, with historical monuments such as Charles Bridge, Prague Castle, and Rudolfinum all visible

from the race route. The overall aesthetics of the course was higher than that of Use-case 2 and much higher than that of Use-case 1.

- This use-case had the same problem as Use-case 2 with regards to cobblestones and would need to be resolved if this prototype ever evolved into a commercial SDSS application.
- The route was also much flatter than the route in Use-case 1.

4.5 Verification of Test Results

To verify the test results of each use-case, the geometry of each route was exported from the SQL Spatial Database and converted into shapefiles, using FME Desktop (a data transformation tool). The resulting shapefiles were then imported into ArcMap for verification.

4.5.1 Verification of Use-cases: Comparing Capacity of Routes

In this section the capacity of the routes for each use-case are compared and verified.

To verify the capacity, the shapefiles for each route were intersected with the original Roads shapefile. In the resulting attribute tables, the results were then summarized by the *Road Class* field, which generated tables 15 - 19.

The road classes are illustrated in Table 14 below and are scaled from 1 to 5 according to the capacity of the road, with 1 having the least capacity and 5 the largest capacity.

Table 14: Road Capacity Scale for Road Classes

Road Capacity Scale	Class
1	footway
1	path
1	unknown
2	track grade3
2	track grade4
2	cycleway
2	track grade5
2	track
2	track grade2
2	track grade1
3	residential

3	pedestrian
3	unclassified
3	living street
4	tertiary link
4	tertiary
5	secondary
5	trunk
5	trunk link
5	secondary link
5	primary
5	primary_link

4.5.1.1   Use-case 1: Capacity Prioritized

In Use-case 1 (capacity prioritized), roads with the largest capacity scale of 5 amounted to 50% of roads in the calculated route (see Table 15). The weight used for capacity in this use-case was 0.64 and was much higher than the weights used for capacity in the other use-cases, where capacity was not prioritized.

Table 15: Count of Road Classes in "Capacity" Prioritized Route

Road Class	Scale	Count
secondary	5	21
primary	5	17
secondary link	5	1
tertiary	4	5
residential	3	20
pedestrian	3	14
living street	3	1

4.5.1.2   Use-case 2: Slope Prioritized

In Use-case 2 (slope prioritized), roads with the biggest capacity scale of 5 came to only 25% of roads in the calculated route (see Table 16). This is half the percentage of the capacity prioritised use-case. The weight used for capacity in this use-case was only 0.04 and is the lowest weight used for capacity of all the use-cases.

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Table 16: Count of Road Classes in "Slope" Prioritized Route

Road Class	Scale	Count
primary	5	20
secondary	5	8
tertiary	4	1
residential	3	66
pedestrian	3	11
living street	3	3

4.5.1.3   Use-case 3: Aesthetics Prioritized

In Use-case 3 (aesthetics prioritized), roads with the largest capacity scale of 5 totalled 45% of roads in the calculated route (see Table 17). The result is 5% less than that of the capacity prioritised use-case. The weight used for capacity in this use-case was 0.06.

Table 17: Count of Road Classes in "Aesthetics" Prioritized Route

Road Class	Scale	Count
secondary	5	41
primary	5	10
residential	3	49
pedestrian	3	11
living street	3	3

4.5.1.4   Use-case 4: Surface Prioritized

In Use-case 4 (surface prioritized), roads with the largest capacity scale of 5 came to 43% of roads in the calculated route (see Table 18). The result is 7% less than that of the capacity prioritised use-case and similar to the aesthetics prioritized use-case. The weight used for capacity in this use-case was 0.13, which is the second highest weighting from all the use-cases.

Table 18: Count of Road Classes in "Surface" Prioritized Route

Road Class	Scale	Count
secondary	5	46
residential	3	48
pedestrian	3	11
living street	3	3

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4.5.1.5   Use-case 5: Number of Turns Prioritized

In Use-case 5 (number of turns prioritized), roads with the largest capacity scale of 5 came to 35% of roads in the calculated route (see Table 19). The result is 15% less than that of the capacity prioritised use-case. The weight used for capacity in this use-case was 0.05.

Table 19: Count of Road Classes in "Number of Turns" Prioritized Route

Road Class	Scale	Count
secondary	5	33
primary link	5	1
residential	3	44
pedestrian	3	19
living street	3	1

4.5.1.6   Conclusion of Verification: Capacity of Routes

The capacity-prioritized use-case resulted in the route with the most roads with the highest capacity scale of 5, which seems to indicate that the weighting of capacity functions as expected. The other use-cases had 5% to 25% less roads with the highest capacity scale of 5 in their calculated routes. The results of each use-case were of course influenced by the weights of the other criteria used, so there is not a strict correlation between the weight of capacity and the percentage of high-capacity roads in the calculated route. The overall performance of each road, that is calculated using all the criteria weights and the actual normalized criteria values, ultimately determines whether the road in question gets selected.

4.5.2 Verification of Use-cases: Comparing Slope of Routes

In this section the slope of the routes for each use-case are compared and verified.

In order verify the slope, the line of each route was interpolated against the digital elevation model (DEM) layer. An elevation profile was then generated for each use-case route.

4.5.2.1   Use-case 1: Capacity Prioritized

In Use-case 1 (capacity prioritized), the generated route had quite a significant slope and elevation gain of 133m, which was measured on my Garmin Forerunner 245 GPS watch (Figure 24) during in-field testing of the route. The elevation profile generated by ArcMap is also illustrated in Figure 23 and looks similar to the elevation profile in Figure 24. In this use-case, average and maximum slope had a weight of 0.07, which was the second lowest of all the use-cases. The slope was perhaps unsurprisingly quite large, since it was given a low weighting value.
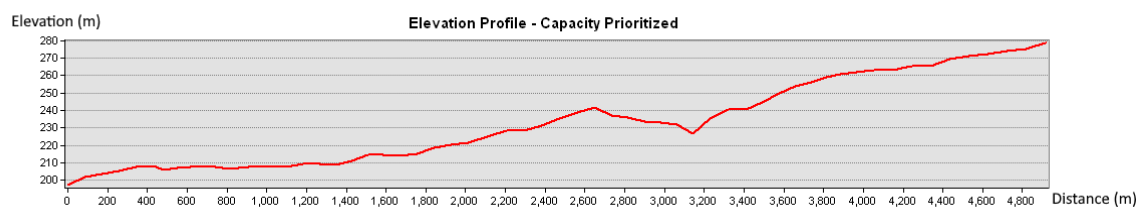
Figure 23: Elevation Profile of "Capacity" Prioritized Route - ArcMap
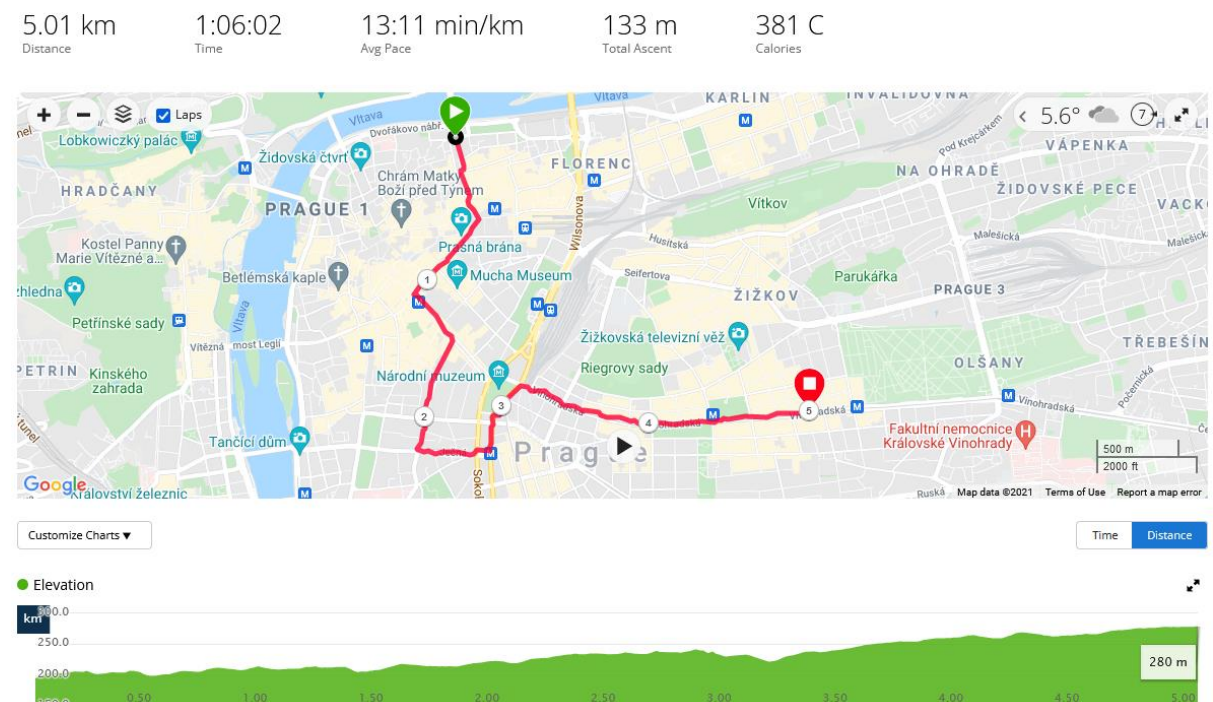
Figure 24: Elevation Profile and Gain of "Capacity" Prioritized Route – Garmin GPS

4.5.2.2 Use-case 2: Slope Prioritized

In Use-case 2 (slope prioritized), the generated route had a significantly flatter slope than the previous use-case and has an elevation gain of only 41m, which was measured on my Garmin Forerunner 245 GPS watch (Figure 26) during in-field testing. This can be seen in the elevation profile generated by ArcMap (Figure 25). In this use-case average and maximum slope had a weight of 0.35, which was the highest of all the use-cases. Since the weighting of slope was very high the resulting route was, as expected, quite flat and included several downhill sections.
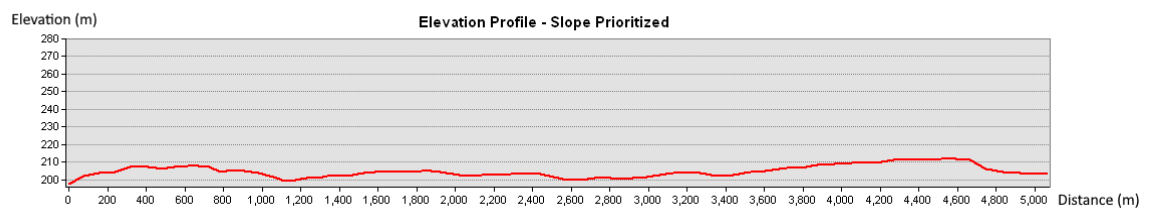
Figure 25: Elevation Profile of "Slope" Prioritized Route - ArcMap
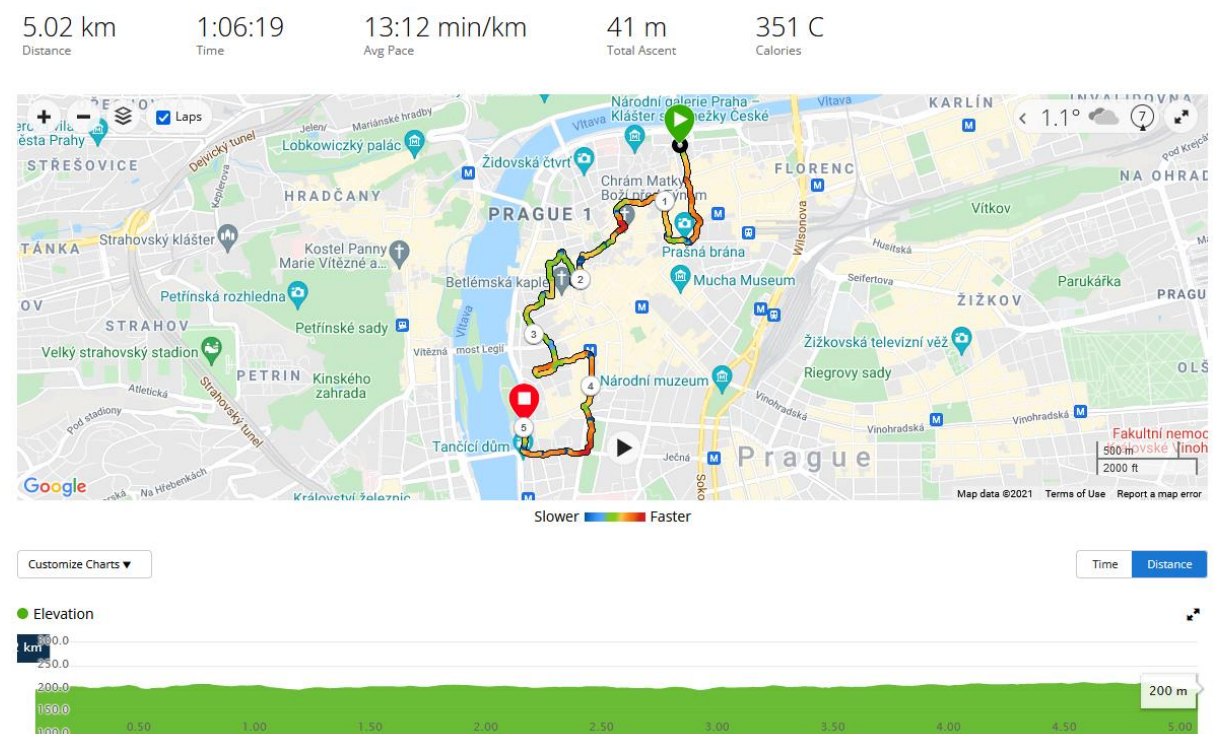
Figure 26: Elevation Profile and Gain of "Slope" Prioritized Route – Garmin GPS

4.5.2.3 Use-case 3: Aesthetics Prioritized

In Use-case 3 (aesthetics prioritized), the generated route also had a significantly flatter slope than the capacity-prioritized use-case and elevation gain of only 59m, which was measured by my Garmin Forerunner 245 GPS watch (Figure 26) during in-field testing. This can be seen in the elevation profile generated by ArcMap (Figure 27). In this use-case, average and maximum slope had a weight of 0.14, which was the second highest of all the use-cases. Since the weighting of slope was quite high the resulting route was quite flat and included several downhill sections, similar to that of Use-case 2.
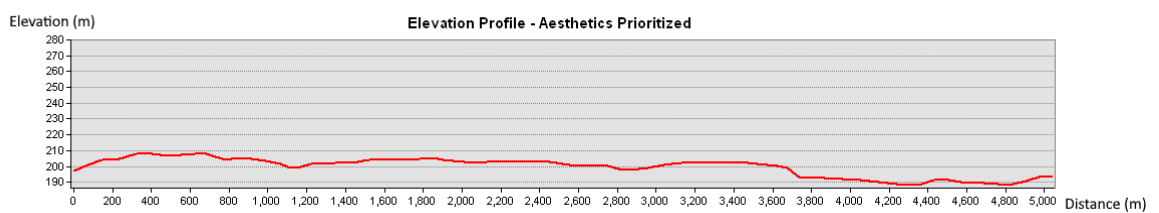
Figure 27: Elevation Profile of "Aesthetics" Prioritized Route - ArcMap
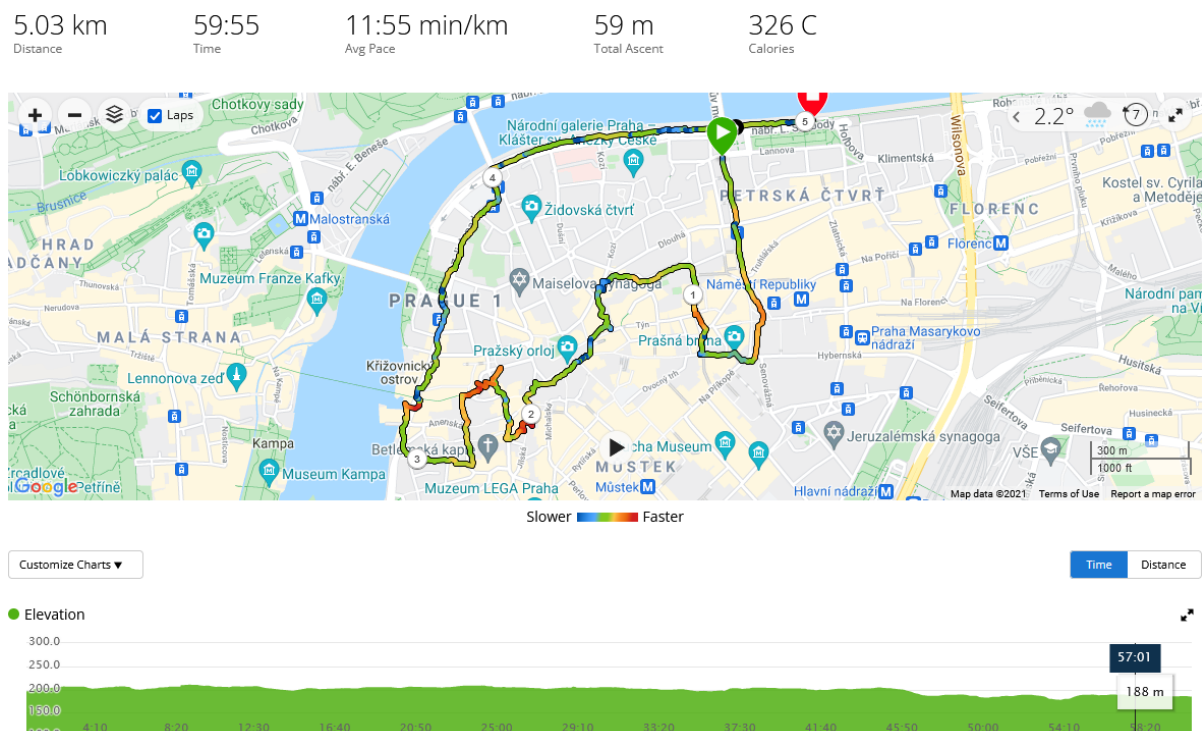
Figure 28: Elevation Profile and Gain of "Aesthetics" Prioritized Route – Garmin GPS

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4.5.2.4 Use-case 4: Surface Prioritized

In this use-case (surface prioritized), average and maximum slope had a weight of 0.06, which was the lowest of all the use-cases. Unexpectedly, the generated route had a rather flat slope. This can be seen in the elevation profile generated by ArcMap (Figure 29). This could be due to other prevailing criteria, which had a greater influence on the route calculation. Aesthetics had quite a high weight of 0.24, while capacity was also quite influential with a weight of 0.13. No in-field testing was done for this use-case.
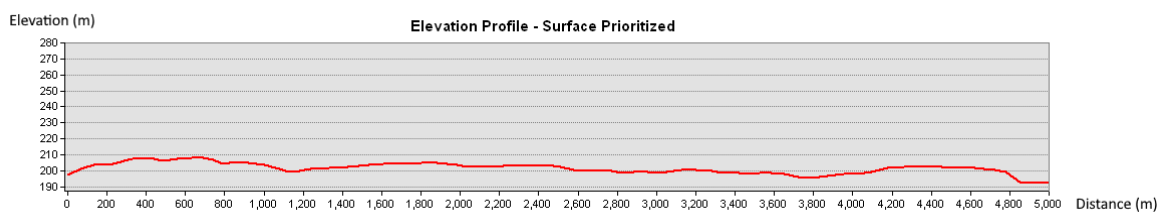
Figure 29: Elevation Profile of "Surface" Prioritized Route - ArcMap

4.5.2.5 Use-case 5: Number of Turns Prioritized

In Use-case 5 (number of turns prioritized), average and maximum slope had quite a high weight of 0.13, which was a similar weight compared to the weight for slope used in Use-case 3 (aesthetics prioritized). As expected, the generated route had quite a flat slope. This can be seen in the elevation profile generated by ArcMap (Figure 30). Like the previous use-case, no in-field testing was done for this use-case.
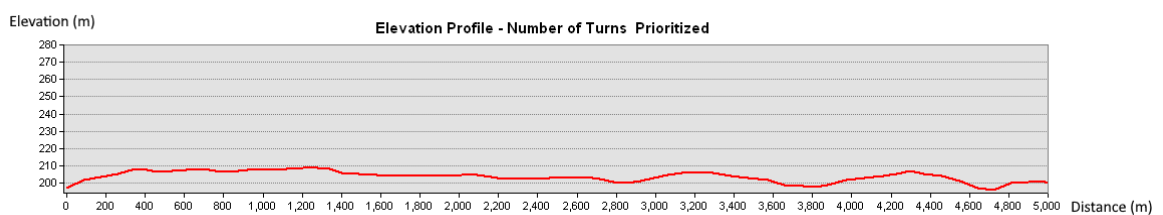
Figure 30: Elevation Profile of "Number of Turns" Prioritized Route – ArcMap

4.5.2.6   Conclusion of Verification: Slope of Routes

Except for Use-case 4, where surface was prioritized, all the other use-cases produced results that seemed to correspond to the weight of the slope criteria. The capacity-prioritized use-case resulted in the route with the steepest incline and highest elevation gain and it had the second lowest weighting. The slope prioritized route had the lowest elevation gain from the use-cases tested in field. With regards to Use-case 4, one must consider other criteria with high weights to put the result into context. In general, I think the results are as expected.

4.5.3   Verification of Use-cases: Comparing Aesthetics of Routes

The verification of aesthetics was performed by doing a proximity analysis. The output was proximity information between the route and aesthetic features contained in the layers Greenery, Attractions and Water. The data used for the maps depicted in figures 31 to 35 were provided and processed by © GISAT (2007), GADM, and Geofabrik (OpenStreetMap).

4.5.3.1   Use-case 1: Capacity Prioritized

In Use-case 1 there were only 12 aesthetic features within 50m of the route. This is visually apparent in Figure 31. Since the *Aesthetics* criterion had a weight of only 0.07 it can be expected that there might only be a few aesthetic features in proximity of the route. Table 20 lists all the aesthetic features that are within 50m proximity of the route.

Figure 31: Proximity of Aesthetic Features to "Capacity" Prioritized Route

Table 20: Proximity of Aesthetic Features to "Capacity" Prioritized Route

Number of Aesthetic Features within 50m of Route	Aesthetic Feature Class
10	Greenery
2	Attractions

4.5.3.2   Use-case 2: Slope Prioritized

The results of the verification for Use-case 2, slope prioritized, indicated that there were 20 aesthetic features within 50m of the route (see Figure 32). Here the *Aesthetics* criterion had a higher weight of 0.13, which resulted in more aesthetic features in proximity of the route. Table 21 lists all the aesthetic features within 50m proximity of the route.

Route Proximity to Aesthetic Features

Legend
— Route - Slope
▢ Attractions
▢ Greenery
▢ Water body
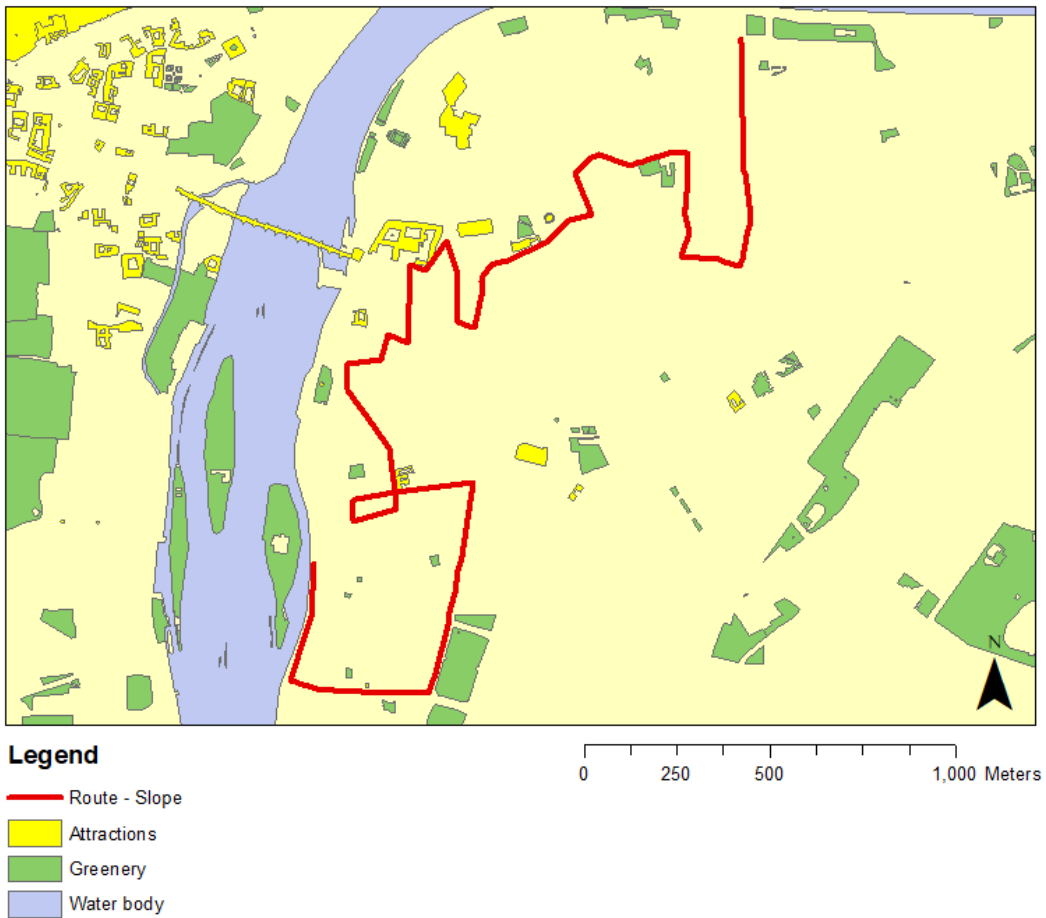
Figure 32: Proximity of Aesthetic Features to "Slope" Prioritized Route

Table 21: Proximity of Aesthetic Features to "Slope" Prioritized Route

Number of Aesthetic Features within 50m of Route	Aesthetic Feature Class
9	Attractions
10	Greenery
1	Water body

4.5.3.3   Use-case 3: Aesthetics Prioritized

The verification of Use-case 3, aesthetics prioritized, indicated that there were 27 aesthetic features within 50m of the route (see Figure 33). In this use-case the *Aesthetics* criterion had the highest weight of 0.50 and this resulted in the second highest number of aesthetic features in proximity of the route. The list of all the aesthetic features within 50m proximity of the route are shown in Table 22.
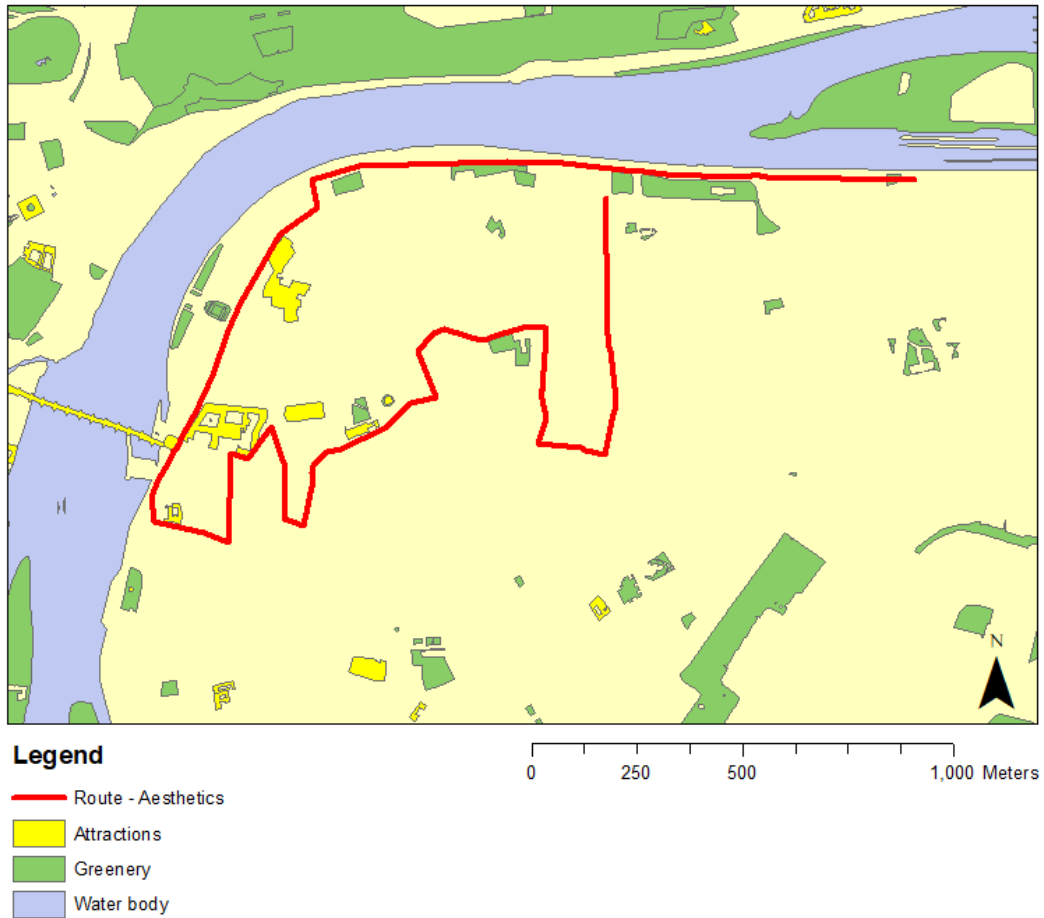
Figure 33: Proximity of Aesthetic Features to "Aesthetics" Prioritized Route

Table 22: Proximity of Aesthetic Features to "Aesthetics" Prioritized Route

Number of Aesthetic Features within 50m of Route	Aesthetic Feature Class
11	Attractions
15	Greenery
1	Water body

4.5.3.4   Use-case 4: Surface Prioritized

When Use-case 4 (surface prioritized) was verified, the verification indicated that there were 30 aesthetic features within 50m of the route (see Figure 34). This was the highest number of aesthetic features in proximity of the route, even though the *Aesthetics* criterion had the second highest weight of 0.24. The list of all the aesthetic features within 50m proximity of the route are shown in Table 23.

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Route Proximity to Aesthetic Features
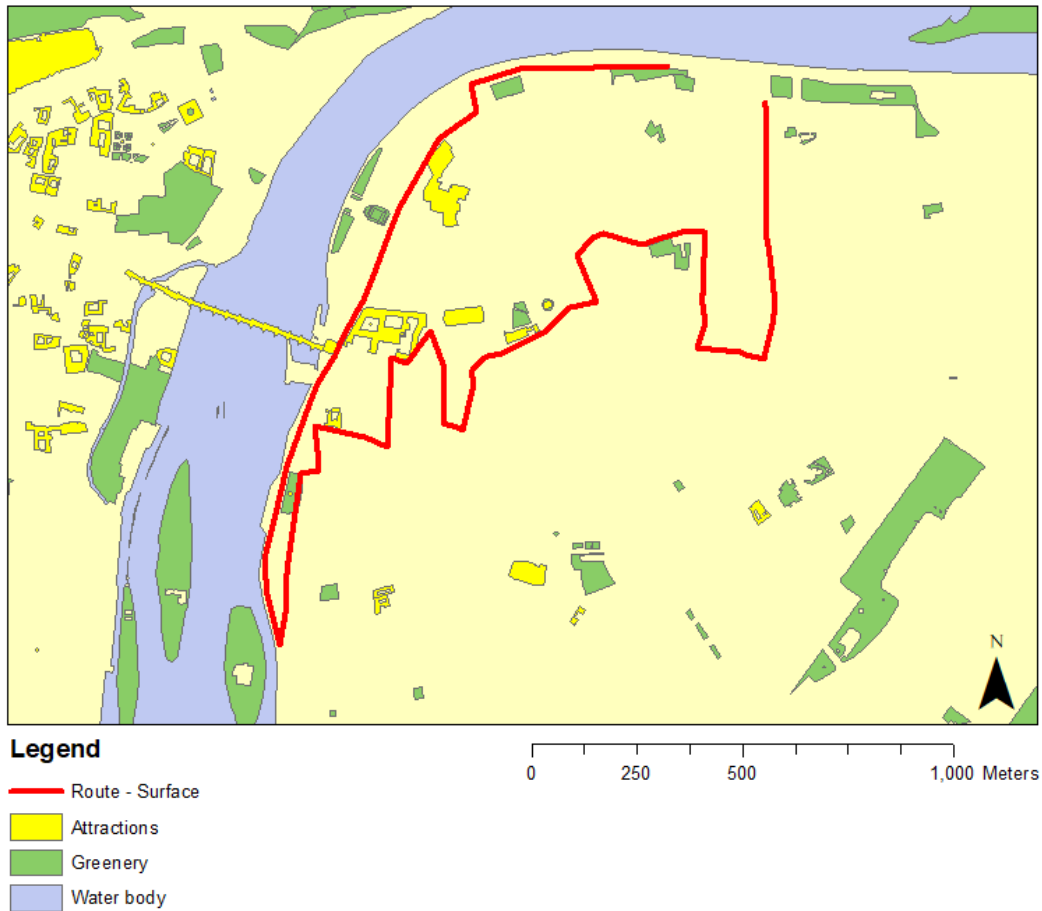
Figure 34: Proximity of Aesthetic Features to "Surface" Prioritized Route

Table 23: Proximity of Aesthetic Features to "Surface" Prioritized Route

Number of Aesthetic Features within 50m of Route	Aesthetic Feature Class
14	Attractions
15	Greenery
1	Water body

4.5.3.5   Use-case 5: Number of Turns Prioritized

The verification of Use-case 5, Number of Turns prioritized, resulted in 13 aesthetic features within 50m of the route (see Figure 35). In this use-case the *Aesthetics* criterion had a weight of 0.13, which was similar to the weight used in the slope prioritized use-case. The list of all the aesthetic features within 50m proximity of the route are shown in Table 24.
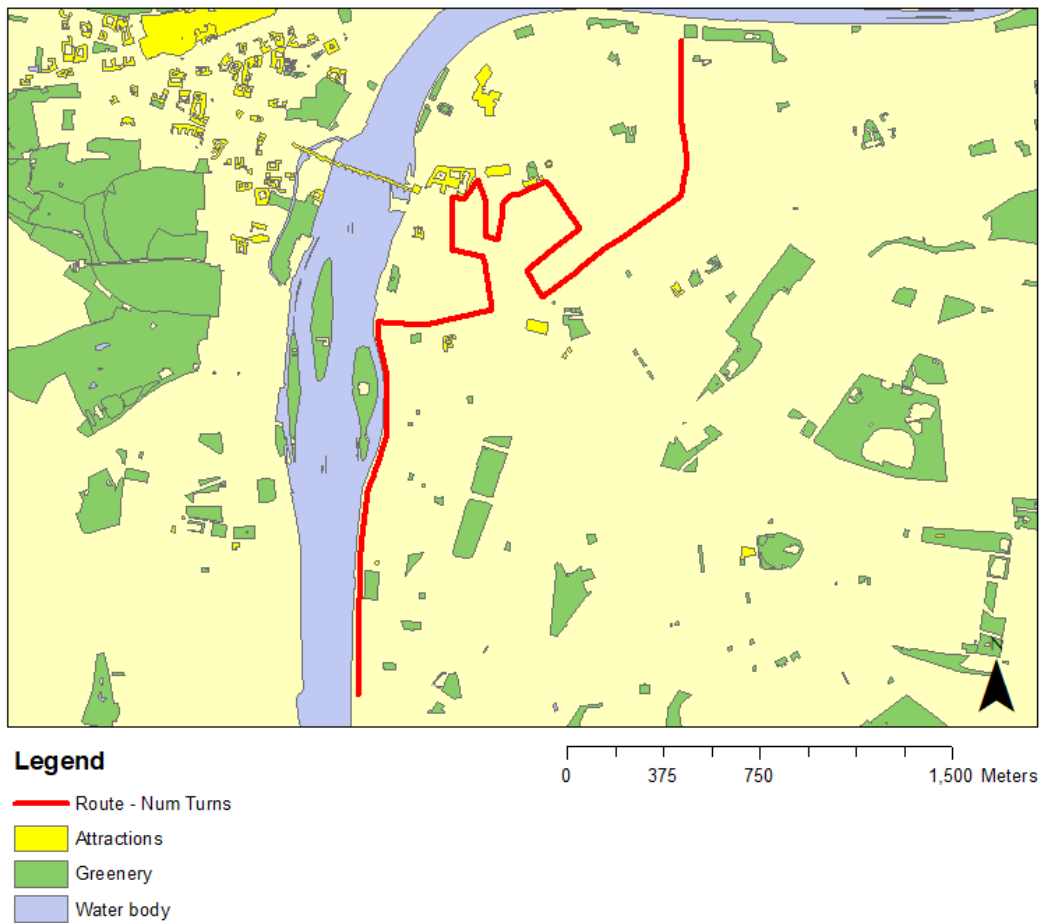
Figure 35: Proximity of Aesthetic Features to "Number of Turns" Prioritized Route

Table 24: Proximity of Aesthetic Features to "Number of Turns" Prioritized Route

Number of Aesthetic Features within 50m of Route	Aesthetic Feature Class
5	Attractions
7	Greenery
1	Water body

4.5.3.6 Conclusion of Verification: Aesthetics of Routes

Although Use-case 3 (aesthetics-prioritized) only had the second highest number of aesthetic features in proximity of the route, the results showed a general correlation between the weighting of the aesthetics criterion and the number of aesthetic features in proximity to the route.

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4.5.4 Verification of Use-cases: Comparing Number of Turns of Routes

Verification of number of turns consisted only of a manual count of the number of turns in each route, for all the use-cases. The number of turns prioritized route had the second lowest number of turns out of all the use-cases, with only the capacity prioritized use-case having a lower count of 7 (see Table 25).

Table 25: Number of Turns Measured Per Use-case

Use-case	Number of Turns
Use-case 1: Capacity Prioritized	7
Use-case 2: Slope Prioritized	25
Use-case 3: Aesthetics Prioritized	19
Use-case 4: Surface Prioritized	20
Use-case 5: Number of Turns Prioritized	14

In general, there seems to be a correlation between the weighting of the *Number of Turns* criterion and the number of turns in each route. Of course, there are other criteria that have an influence over the selection of routes – no criterion works in isolation.

4.5.5 Verification of Use-cases: Comparing Surface of Routes

Unfortunately, during the field testing of some of the use-cases, it came to light that the surface classifications derived from the Road Class in the original dataset did not include roads with a cobblestone surface. Although it proved the value of in-field testing on mobile devices, it also showed that the system is only as good as the data it uses.

Since the classifications didn't include cobblestones and this would have to be manually added because the original road classifications did not contain this information, I decided that it would not make sense to verify the road surface use-case.

4.6 Reflections on How Results Answer Research Questions

The following discussion elaborates on the findings that came to light during the research project and testing of the prototype and attempts to provide some answers to the research questions that were established during the introduction to this research project.

4.6.1 Is a spatially-enabled MDSS applicable to remote decision making?

A spatially-enabled MDSS takes out much of the guesswork that occurs when using online or physical maps to create a race route and, in addition, such a system could expedite the creation of a race route, since it is automatically generated, while accurately reflecting the preferences of the decision-makers. In addition, the testing of the prototype highlighted its usefulness for in-field verification of a generated route and at the very least it could add value to in-field surveying of roads.

Using MCDA methods in the decision-making process encourages the decision-makers to be more aware of their preferences and gives more structure to the decision-making process, as opposed to decision-making in a more ad-hoc manner. This can only result in a solution that is more aligned with the preferences of decision-makers.

During the testing of the prototype via the 5 use-cases, it became evident that the preferences of potential users could be accommodated by assigning appropriate weights to the criteria and then generating routes based on these preferences. The results of the use-case tests showed that the generated routes generally reflected the user preferences for the use-case in question. The capacity prioritized use-case generated a route with bigger roads that can handle many runners; the aesthetics prioritized use-case generated a route that passed through picturesque areas, through the old town and alongside the river front; and the slope prioritized use-case generated a route that was flat. The exception was the use-case that prioritized road surfaces, which was due to the dataset containing inaccurate and incomplete road surface classifications, although this does not detract from the successful fulfilment of user preferences, since it could be rectified by properly reclassifying road surfaces.

Overall, the prototype showcased the potential of a spatially-enabled MDSS to support decision-making in various environments, such as in the boardroom or providing rapid feedback in the field, and in this sense, it was a success.

4.6.2 What advances in technology make it possible to a create a spatially-enabled MDSS?

Technological advances such as the availability of cross-platform APIs, increased mobile networks coverage and availability, MCDA algorithms, and GIS analysis techniques make it possible to implement spatially enabled MDSS.

Cross-platform development alleviates the need to code for each native platform, which helps reduce the costs, resources, overhead and time necessary to implement a spatially-enabled MDSS. It also addresses the issue of interoperability.

GIS and MCDA combine perfectly to provide the decision-making algorithms and spatial analysis techniques required to implement a spatially-enabled MDSS.

The greater mobile networks coverage and availability enable the use of spatially-enabled MDSS in increasingly remote locations.

4.6.3 What are the practical limitations of a spatially-enabled MDSS in real word scenarios?

The research confirmed that factors such as cost, high expertise requirements, interoperability, accuracy of spatial data and network coverage are limitations to adopting spatially-enabled MDSS.

The personal experience gathered during the creation of a spatially-enabled MDSS further verified the fact that it requires substantial expertise to understand all the technical considerations needed to develop such a system, such as: the selection of an appropriate MCDA method for the problem; the skills required for cross-platform development; and the understanding of various mapping technologies and APIs. Such expertise costs money and the complexity of a spatially-enabled MDSS means that it would potentially take some time to implement, which translates into further costs.

The high cost of implementing a spatially-enabled MDSS indicates that the potential commercial value of such a system should be high enough to provide value and cover the high costs, otherwise decision-makers would likely select cheaper tools to assist in decision making.

Network coverage was not a problem while testing the prototype in the city of Prague, but it might be a problem while using a spatially-enabled MDSS in more remote regions and is a limitation to consider when designing a commercial spatially-enabled MDSS product.

Another limitation discovered during in-field testing was the inaccuracy of spatial data, specifically the issue discovered regarding cobblestone road surfaces. A spatially-enabled MDSS that uses inaccurate data will provide inaccurate results

during decision support. Another consideration is geometric accuracy, which can affect calculations, such as slope, distance or proximity. A DEM with a 10m resolution will have higher accuracy than a DEM with 100m resolution. On the positive side, the issue regarding inaccurate road surface classifications highlighted the advantage of being able to verify output from a spatially-enabled MDSS and make further decisions in the field.

4.6.4 Why is there slow adoption of spatially-enabled MDSS in the industry?

The feedback from the questionnaire indicated that only 3% of respondents used GIS software during the design of a race route, and there was not a single organisation that used a Spatial Decision Support System. This illustrates that the potential of a spatially-enabled MDSS has not really been explored by organizations for the purpose of designing a race event.

On the other hand, the feedback from the questionnaire showed that 38% of organisations use Google or Bing Maps to support the design of the race route, 26% use physical maps, while 33% use In-field surveying of roads. Here an argument could be made that a spatially-enabled MDSS could be used to supplement or replace both the use of online or physical maps and in-field surveying of roads, for the purpose of designing a race event.

The research shows that some of the reasons why there is a slow adoption to using spatially-enabled MDSS include:

- User satisfaction with traditional decision-making techniques.
- Some lack of knowledge or trust of new technologies.
- Cost restrictions when it comes to adopting new technologies.
- Lack of personnel with expertise to implement the new technologies.
- Commercial value of a spatially-enabled MDSS does not exceed the substantial costs to implement.

5. Conclusion and Recommendations

This thesis aimed at analysing the value of establishing a spatially-enabled MDSS in a collaborative decision-making environment. Furthermore, the limitations of a spatially-enabled MDSS were outlined, along with the probable obstacles that could be encountered during development and usage of such a system.

To highlight these advantages and limitations of a spatially-enabled MDSS, a prototype was developed that could calculate optimal routes for running races.

During the in-field testing of the various use-cases, the full potential of spatially-enabled MDSS became apparent. Being able to make instant decisions in-field, or to provide rapid feedback to other decision-makers located elsewhere, has immense value in many different applications, from event design to emergency management.

Despite the advances in technology that make the creation of a spatially-enabled MDSS possible, there are quite a few limitations and obstacles that hinder the prevalence of such useful decision support tools.

In addition to the limitations of a spatially-enabled MDSS, as introduced in Chapter 2 (such as interoperability, network coverage, and hardware limitations), the feedback from respondents indicated that some major drawbacks are costs, and resistance to, or simply not understanding new technologies.

From a development perspective, costs can be reduced a bit with the advances in cross-platform development, however, the complexity of MCDA algorithms and, as suggested by (Guarini et al., 2018), the lack of guidance for selecting the most appropriate MCDA method for a specific decision-making problem, seems to be a major stumbling block against adopting MCDA for complex spatial problems. Employing a person with the skills and understanding necessary to select and implement an appropriate MCDA for a MDSS could add to the development costs significantly.

Recommendations and future study could include further research into simplifying MCDA method selection and identifying applications of a spatially-enabled MDSS where the high cost is mitigated by high commercial value.

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7. Appendices

7.1 Appendix 1: Questionnaire

I created a questionnaire hosted on Survey Monkey at the following link:
https://www.surveymonkey.com/r/P6W6SLS

The questionnaire was sent to approximately 50 different marathon event organizations around the world, in order to collect feedback regarding the number of people involved in the decision-making process, current methods used during the design of a marathon course, route criteria, accessibility criteria, potential of a SDSS system to complement or replace current design techniques.

The questionnaire was designed as follows:

Marathon Event Organisation

Questions

* 1. How many people are involved in your organisation's decision making process when designing a new marathon course or making adjustments to an existing marathon course?

○ 1

○ 2 - 4

○ 5 - 9

○ > 10

* 2. Please indicate which of the following methods your organisation uses to support the design of a new or existing marathon course?

☐ In-field surveying of roads (using GPS or other methods)

☐ Google or Bing Maps

☐ GIS software

☐ Spatial Decision Support System

☐ Physical maps

Other (please specify)

[   ]

* 3. In terms of the actual route, what are the most important considerations that are taken into account when designing a new or making adjustments to an existing course? Please rank in order of importance.

::	▲▼	Aesthetics of the course (Greenery - parks, natural scenery, cultural sights)
::	▲▼	Average difference in elevation
::	1	The number of turns
::	2 3	Maximum slope
::	4 5	Course capacity (the width of the race course sufficient for number of runners)
::	6	Surface of the course (asphalt, concrete, cobble stones, gravel, dirt)

* 4. In terms of the accessibility, what are the most important considerations that are taken into account when designing a new or making adjustments to an existing course? Please rank in order of importance.

::	▲▼	Location of medical services
::	▲▼	Start / finish area layout and capacity
::	1	Parking areas in vicinity
::	2 3	Public transport to start / finish area
::	4 5	Location of refreshment stations

* 5. The objective of this project thesis is to illustrate the applicability of a collaborative Spatial Decision Support System (SDSS) that can be used by various people involved in the decision-making process, across both desktop and mobile platforms.

A Spatial Decision Support System (SDSS) merges technologies and methodologies from GIS and MCDA. Geographic Information Systems (GIS) consist of an integrated set of components capable of analysing and visualising spatial data, which can assist in decision making. Multi-criteria decision analysis (MCDA) consists of a framework and various algorithms used for the prioritisation and evaluation of various alternative decisions that assists in the decision making process.

During the process of a marathon course design, various people involved in the decision-making process might need to be able to analyze the proposed route alternatives in a boardroom meeting projected from a desktop PC. On the other hand, people in the field could be verifying and providing 'real-time' feedback on potential route alternatives using mobile devices. In your view would such a SDSS system complement or have the potential to replace your current techniques used when designing a new or making adjustments to an existing course? Please elaborate.

[Next]

7.2 Appendix 2: JSON Data Structure Returned from Web Service

[

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    "RouteId": 243,

    "CriteriaId": 80,

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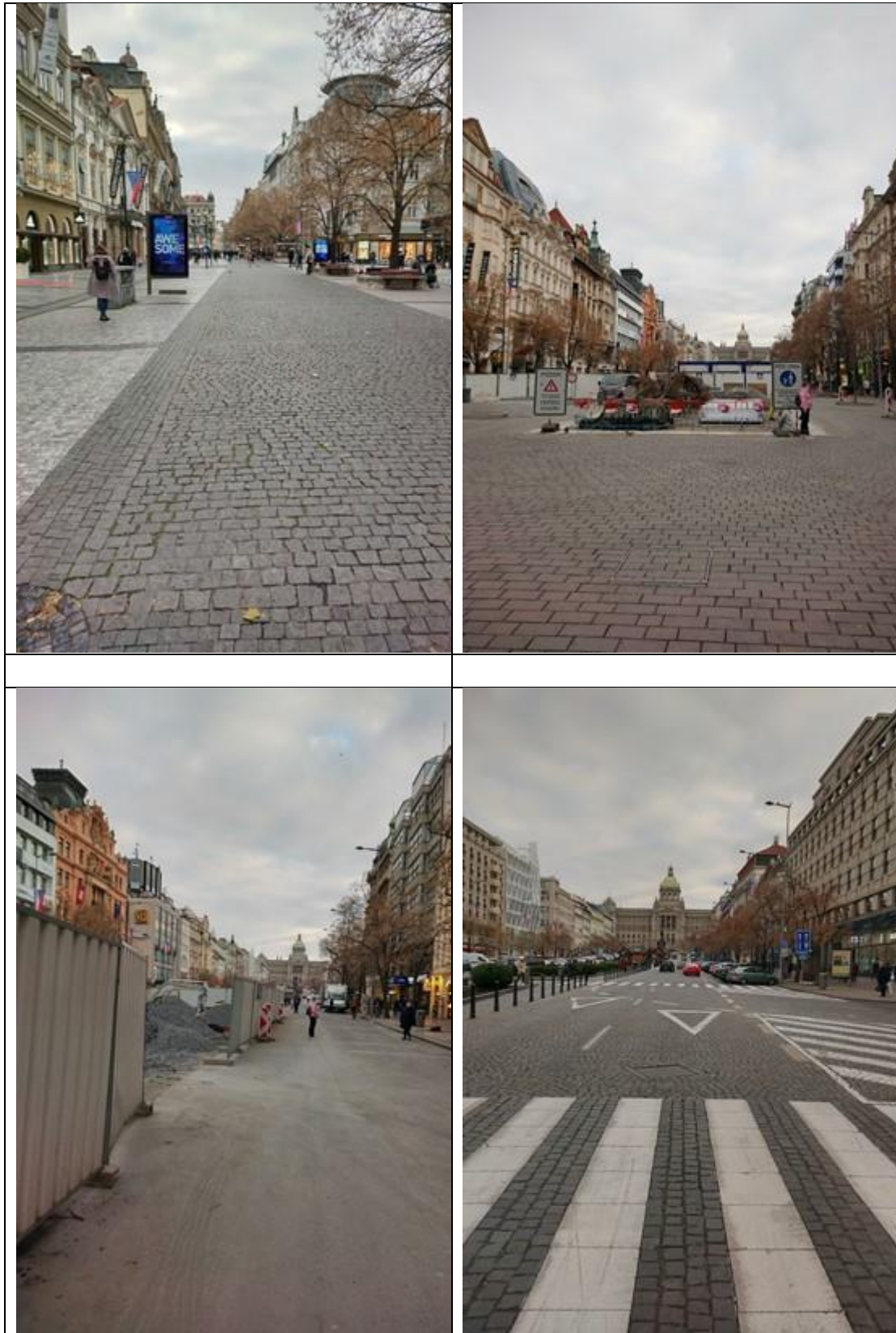
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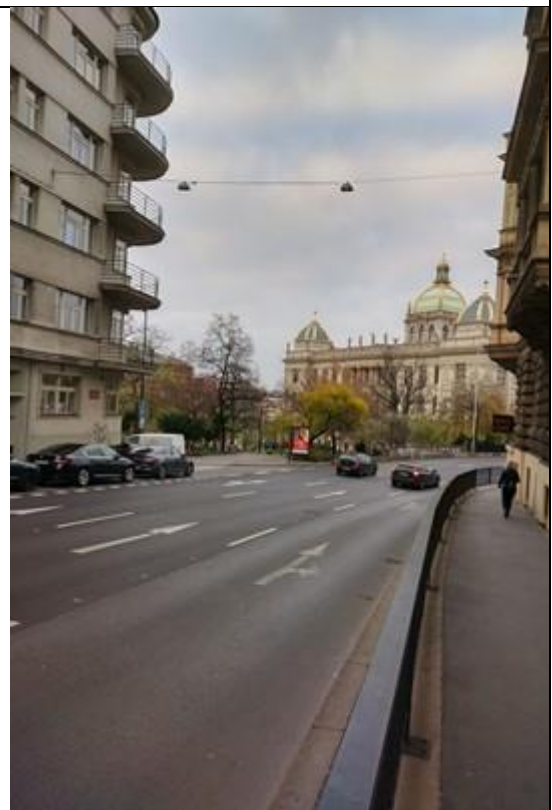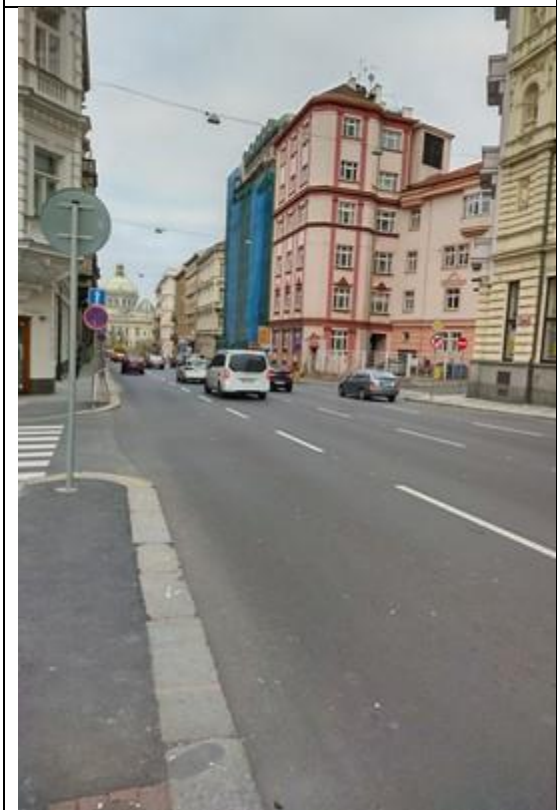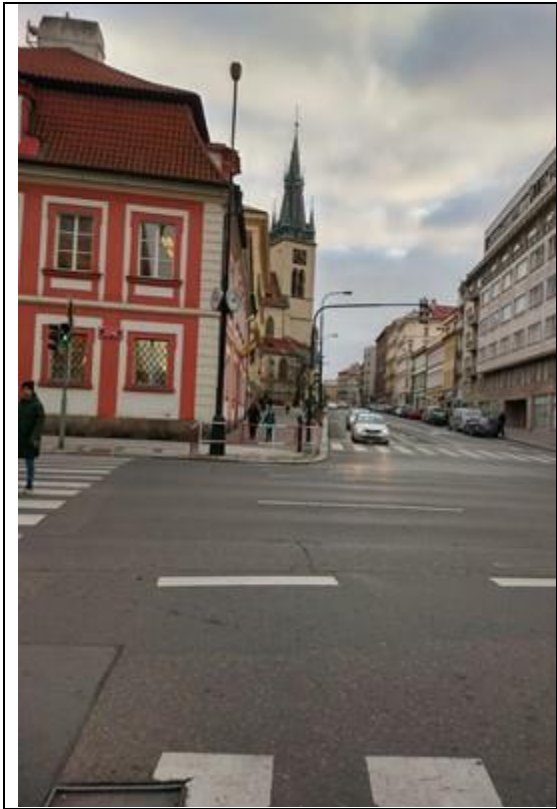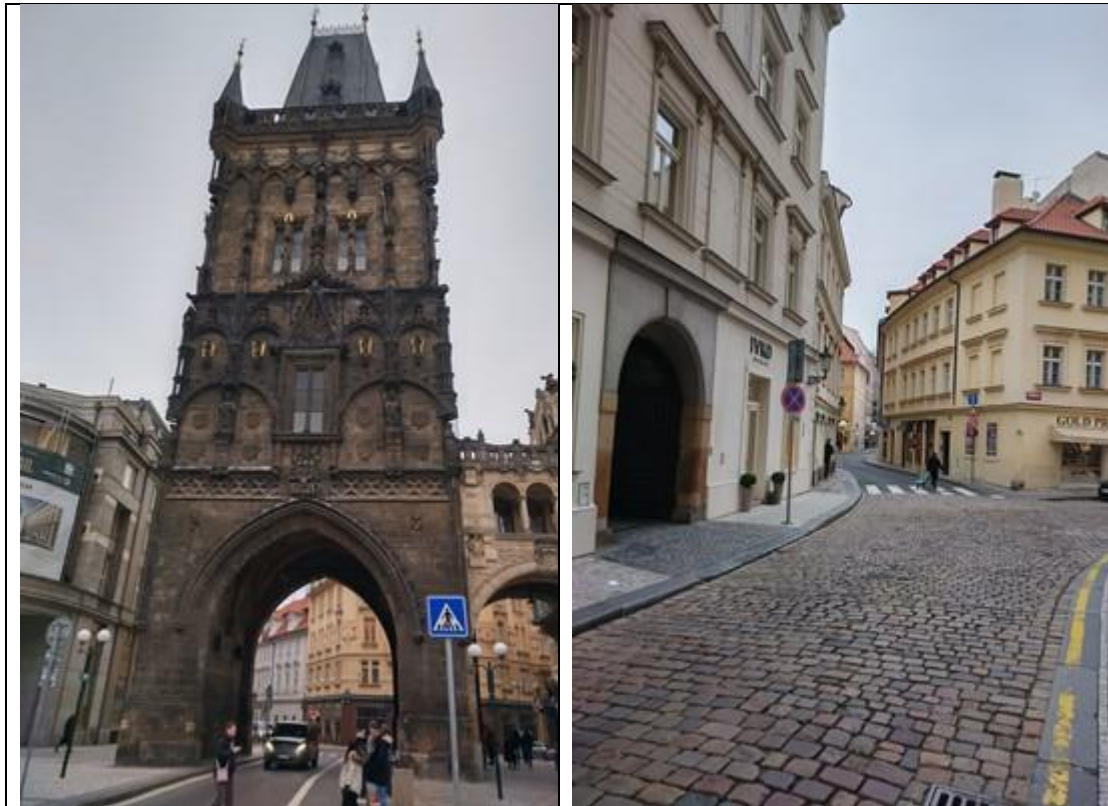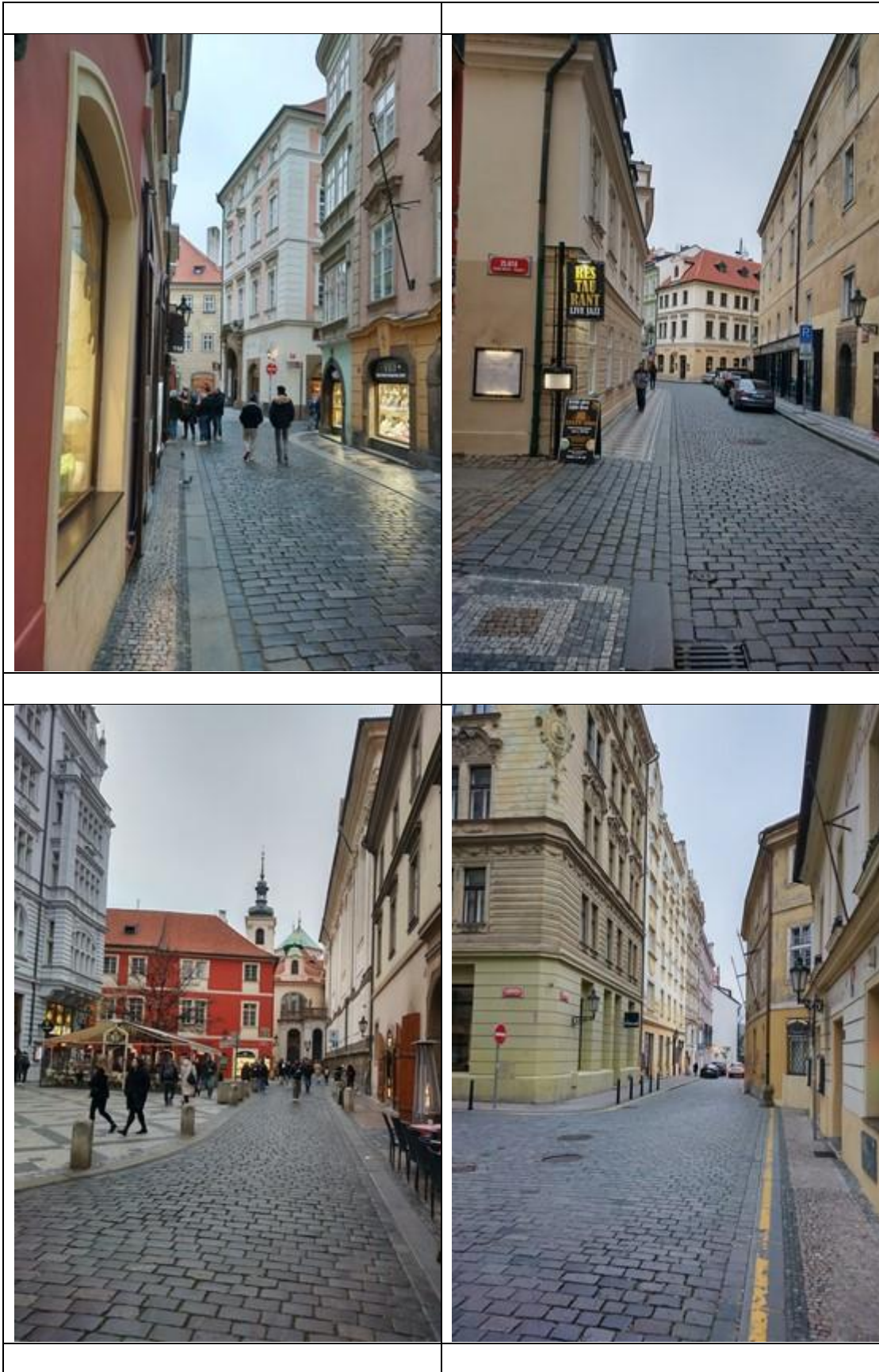
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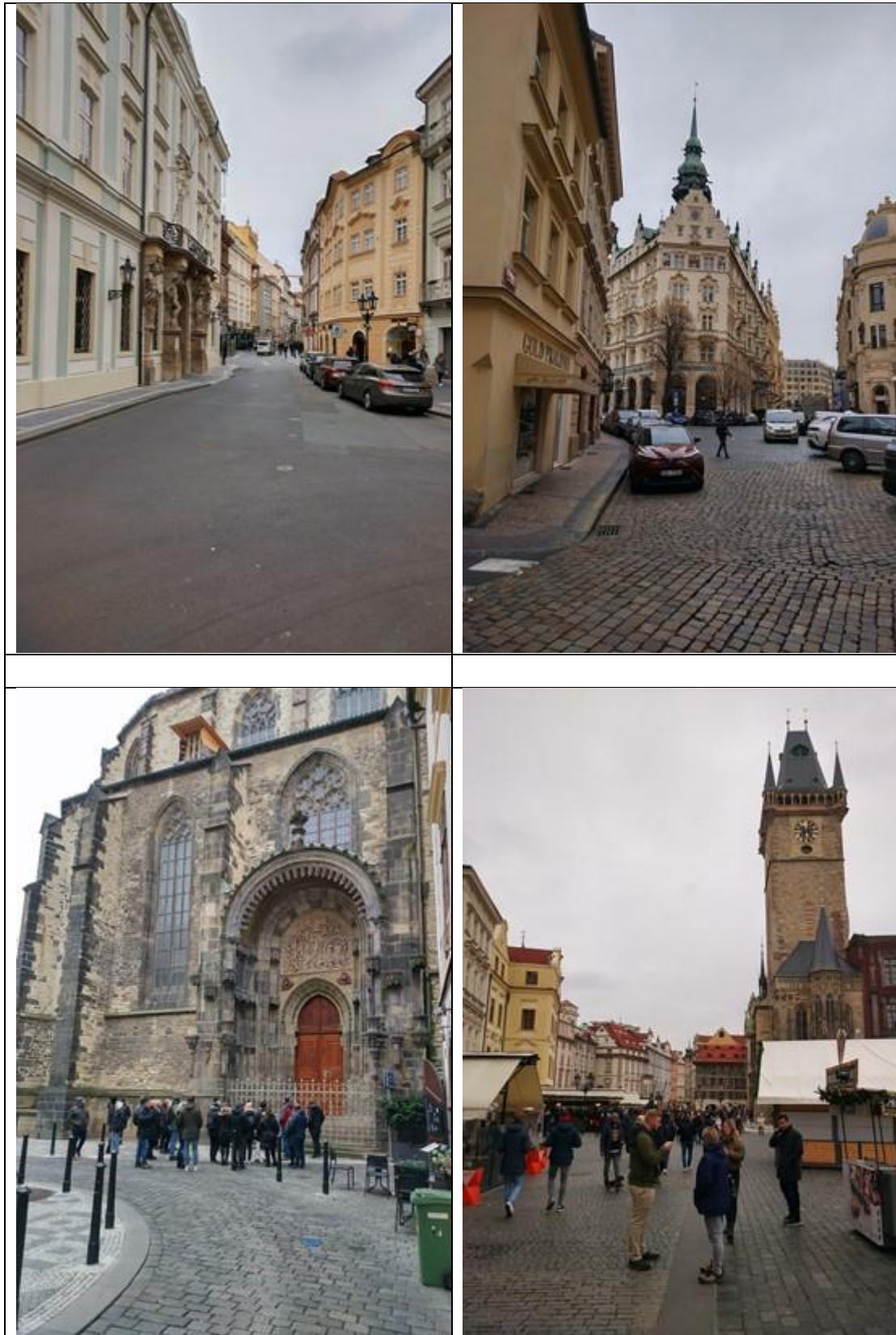## 7.3 Appendix 3: Photos from In-Field Testing of Use-Case 1: Capacity

7.4 Appendix 4: Photos from In-Field Testing of Use-Case 2: Slope

7.5 Appendix 5: Photos from In-Field Testing of Use-Case 3: Aesthetics
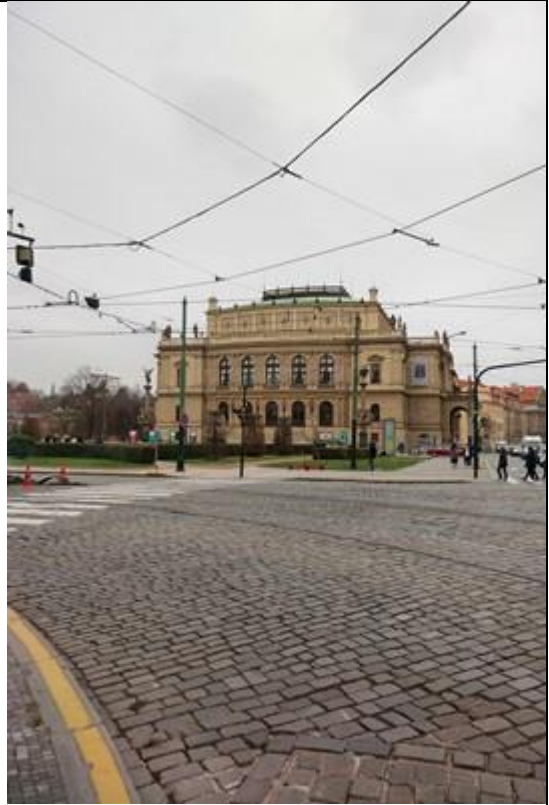
7.6 Appendix 6: Research Articles on Spatially-enabled Mobile Decision Support Systems Since 2013

1. Ivajnsic, D., Pintarič, D., Grujić, V. & Žiberna, I. (2021) A spatial decision support system for traffic accident prevention in different weather conditions. Acta geographica Slovenica. 61. 10.3986/AGS.9415.
2. Kadhim, D. & Rihab, F. (2019) The Intelligent SDSS Mobile Application to Find the Closest Hospital Using the Improved Dijkstra Algorithm with GIS and GPS.
3. Keenan, P. (2013) Cloud computing and DSS: the case of spatial DSS. International Journal of Information and Decision Sciences. 5. 283-294.
4. Erskine, M.A, Khojah, M., & McDaniel, A.E. (2019) Location selection using heat maps: Relative advantage, task-technology fit, and decision-making performance. Computers in Human Behavior.
5. Vitale, A., Guido, G., & Rogano, D. (2016). A smartphone based DSS platform for assessing transit service attributes.

7.7 Appendix 7: Feedback on Applicability of a Spatially-enabled MDSS

The answers from the respondents are listed below:

1. *"No."*
2. *"It would most likely add to the existing techniques. Our Marathon course has been established for 10 years so we have set course."*
3. *"The system would possibly complement current techniques, but small events would typically not have the infrastructure or expertise to support anything too complex. Trail events typically have course sections with little or no coverage for mobile devices."*
4. *"Potentially, although it's a rare event, thus spending a lot of money may be a difficult decision. Several of your questions above need equal ranking so don't reflect my view very well"*
5. *"No, the most important aspect for us is to visit the venue and complete a full visual recce."*
6. *"I believe it could complement our current techniques"*
7. *"Yes. Obviously depends on usability / suitability, but such a tool is an interesting idea."*
8. *"No, it's better to talk to people."*
9. *"Yes"*
10. *"yes potentially"*
11. *"There would be some value, but much of the data still needs to be collected manually. One of the most commonly used tools is Google Earth (or equivalent) which has proven to be very accurate in the planning phase."*

12. *"Possibly. It would need to be evaluated and discussed with our committee. Price would be a huge factor as well."*
13. *"We physically went out and biked and ran out course and made a lot of decisions along the way regarding where the water stations would be, where the signage would be the most important, we stopped took notes along the way etc... We did it all on bike first a few times, then did it running, then still did adjustments till we were happy with our route."*
14. *"Don't see any benefit."*
15. *"I think that would an awesome system if you were designing a new course every week or at least 6 x per year. In my experience we make up the course and from then on it is pretty well static. Any changes are relatively minor and if the course is a certified course it would have to get re-certified which keeps the # of changes down."*
16. *"I don't have any knowledge of DSS"*
17. *"We have only changed the course three times in 15 years and see no need to change again unless we can use our Start/Finish area."*
18. *"No. Route is constrained by our geography. Limited options so unlikely to find this app of much use"*
19. *"It might help, but don't think it would be a major tool. I would love software that could simulate 3 different races (full half and 10k) sharing the same route for runner flow and conflicts"*
20. *"We had marathoners run our course. No technology was used to decide on route."*
21. *"Perhaps. I would point out that the single most important criteria is the "exact distance" which was not referenced above."*
22. *"It sounds like it would most certainly assist what is a difficult and time-consuming process."*
23. *"I believe it would complement - you can't beat having someone on the ground trialling new course routes. Google maps/earth do a good job for us. As for my order of importance, I used 1 as the most important"*
24. *"I am not sure if it helps, for any event you still need to visit the location, plan from the ground and really do a health and safety check. It could be great for planning once the course is set, and the event is running after a few trials"*
25. *"I am not up on all that technology as of yet! The Garmin route with elevation gain etc. is about as technical as it gets, and I had a few people do it for me!"*
26. *"Would not replace but would be an additional tool to help in the process"*
27. *"Yes, I think it could definitely change the way that we create new courses. Like everything else, our progresses evolve and can be made easier than the ways it was once done."*
28. *"Don´t think we would use this as it´s more important to have knowledge of the roads and the traffic."*
29. *"For our purposes something like Google Earth, simple measuring and then a full ground check is very adequate"*

30. *"When we measure the course, we cannot use electronic devices as per Athletics Canada. It is done with a counter on a bike that is calibrated before and after the measuring."*
31. *"complement"*
32. *"No, as a Boston qualifier only traditional survey methods are accepted. We rarely make changes to our existing route. Photographic Imagery and GIS's would be ideal if designing a completely new route from scratch in an area that we are unfamiliar with. But that is rarely the case in the marathon world. Most cases decision makers are familiar enough with the route in that a SDSS system would be unnecessary."*
33. *"I believe this would be able to complement the current techniques that we use. The potential to have all of the above information shown through one system would enable us to make better informed decisions"*

Department of Physical Geography and Ecosystem Science

Master Thesis in Geographical Information Science

1. *Anthony Lawther:* The application of GIS-based binary logistic regression for slope failure susceptibility mapping in the Western Grampian Mountains, Scotland (2008).

2. *Rickard Hansen:* Daily mobility in Grenoble Metropolitan Region, France. Applied GIS methods in time geographical research (2008).

3. *Emil Bayramov:* Environmental monitoring of bio-restoration activities using GIS and Remote Sensing (2009).

4. *Rafael Villarreal Pacheco:* Applications of Geographic Information Systems as an analytical and visualization tool for mass real estate valuation: a case study of Fontibon District, Bogota, Columbia (2009).

5. *Siri Oestreich Waage:* a case study of route solving for oversized transport: The use of GIS functionalities in transport of transformers, as part of maintaining a reliable power infrastructure (2010).

6. *Edgar Pimiento:* Shallow landslide susceptibility – Modelling and validation (2010).

7. *Martina Schäfer:* Near real-time mapping of floodwater mosquito breeding sites using aerial photographs (2010).

8. *August Pieter van Waarden-Nagel:* Land use evaluation to assess the outcome of the programme of rehabilitation measures for the river Rhine in the Netherlands (2010).

9. *Samira Muhammad:* Development and implementation of air quality data mart for Ontario, Canada: A case study of air quality in Ontario using OLAP tool. (2010).

10. *Fredros Oketch Okumu*: Using remotely sensed data to explore spatial and temporal relationships between photosynthetic productivity of vegetation and malaria transmission intensities in selected parts of Africa (2011).

11. *Svajunas Plunge:* Advanced decision support methods for solving diffuse water pollution problems (2011).

12. *Jonathan Higgins:* Monitoring urban growth in greater Lagos: A case study using GIS to monitor the urban growth of Lagos 1990 - 2008 and produce future growth prospects for the city (2011).

13. *Mårten Karlberg:* Mobile Map Client API: Design and Implementation for Android (2011).

14. *Jeanette McBride:* Mapping Chicago area urban tree canopy using color infrared imagery (2011).

15. *Andrew Farina:* Exploring the relationship between land surface temperature and vegetation abundance for urban heat island mitigation in Seville, Spain (2011).

16. *David Kanyari*: Nairobi City Journey Planner: An online and a Mobile Application (2011).

17. *Laura V. Drews:* Multi-criteria GIS analysis for siting of small wind power plants - A case study from Berlin (2012).

18. *Qaisar Nadeem:* Best living neighborhood in the city - A GIS based multi criteria evaluation of ArRiyadh City (2012).

19. *Ahmed Mohamed El Saeid Mustafa:* Development of a photo voltaic building rooftop integration analysis tool for GIS for Dokki District, Cairo, Egypt (2012).

20. *Daniel Patrick Taylor*: Eastern Oyster Aquaculture: Estuarine Remediation via Site Suitability and Spatially Explicit Carrying Capacity Modeling in Virginia's Chesapeake Bay (2013).

21. *Angeleta Oveta Wilson:* A Participatory GIS approach to *unearthing* Manchester's Cultural Heritage '*gold mine'* (2013).

22. *Ola Svensson:* Visibility and Tholos Tombs in the Messenian Landscape: A Comparative Case Study of the Pylian Hinterlands and the Soulima Valley (2013).

23. *Monika Ogden:* Land use impact on water quality in two river systems in South Africa (2013).

24. *Stefan Rova:* A GIS based approach assessing phosphorus load impact on Lake Flaten in Salem, Sweden (2013).

25. *Yann Buhot:* Analysis of the history of landscape changes over a period of 200 years. How can we predict past landscape pattern scenario and the impact on habitat diversity? (2013).

26. *Christina Fotiou:* Evaluating habitat suitability and spectral heterogeneity models to predict weed species presence (2014).

27. *Inese Linuza:* Accuracy Assessment in Glacier Change Analysis (2014).

28. *Agnieszka Griffin:* Domestic energy consumption and social living standards: a GIS analysis within the Greater London Authority area (2014).

29. *Brynja Guðmundsdóttir:* Detection of potential arable land with remote sensing and GIS - A Case Study for Kjósarhreppur (2014).

30. *Oleksandr Nekrasov:* Processing of MODIS Vegetation Indices for analysis of agricultural droughts in the southern Ukraine between the years 2000-2012 (2014).

31. *Sarah Tressel:* Recommendations for a polar Earth science portal in the context of Arctic Spatial Data Infrastructure (2014).

32. *Caroline Gevaert:* Combining Hyperspectral UAV and Multispectral Formosat-2 Imagery for Precision Agriculture Applications (2014).

33. *Salem Jamal-Uddeen:* Using GeoTools to implement the multi-criteria evaluation analysis - weighted linear combination model (2014).

34. *Samanah Seyedi-Shandiz:* Schematic representation of geographical railway network at the Swedish Transport Administration (2014).

35. *Kazi Masel Ullah:* Urban Land-use planning using Geographical Information System and analytical hierarchy process: case study Dhaka City (2014).

36. *Alexia Chang-Wailing Spitteler:* Development of a web application based on MCDA and GIS for the decision support of river and floodplain rehabilitation projects (2014).

37. *Alessandro De Martino:* Geographic accessibility analysis and evaluation of potential changes to the public transportation system in the City of Milan (2014).

38. *Alireza Mollasalehi:* GIS Based Modelling for Fuel Reduction Using Controlled Burn in Australia. Case Study: Logan City, QLD (2015).

39. *Negin A. Sanati:* Chronic Kidney Disease Mortality in Costa Rica; Geographical Distribution, Spatial Analysis and Non-traditional Risk Factors (2015).

40. *Karen McIntyre:* Benthic mapping of the Bluefields Bay fish sanctuary, Jamaica (2015).

41. *Kees van Duijvendijk:* Feasibility of a low-cost weather sensor network for agricultural purposes: A preliminary assessment (2015).

42. *Sebastian Andersson Hylander:* Evaluation of cultural ecosystem services using GIS (2015).

43. *Deborah Bowyer:* Measuring Urban Growth, Urban Form and Accessibility as Indicators of Urban Sprawl in Hamilton, New Zealand (2015).

44. *Stefan Arvidsson:* Relationship between tree species composition and phenology extracted from satellite data in Swedish forests (2015).

45. *Damián Giménez Cruz*: GIS-based optimal localisation of beekeeping in rural Kenya (2016).

46. *Alejandra Narváez Vallejo:* Can the introduction of the topographic indices in LPJ-GUESS improve the spatial representation of environmental variables? (2016).

47. *Anna Lundgren:* Development of a method for mapping the highest coastline in Sweden using breaklines extracted from high resolution digital elevation models (2016).

48. *Oluwatomi Esther Adejoro:* Does location also matter? A spatial analysis of social achievements of young South Australians (2016).

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