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# Finding Routes for Hyperloop Transportation Infrastructure in the Netherlands Using a GIS-MCDA Approach

by

Niek Bebelaar

n.bebelaar@student.rug.nl
s2206056

Faculty of Spatial Sciences
University of Groningen

Supervisor: Dr. T. Busscher
Second reader: Drs. A.M. Hilbers

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# ABSTRACT

Plans exist for a Hyperloop (test) track in the Netherlands. Hyperloop is an innovative transportation technology with a dedicated tube-infrastructure.

Currently there is no suitable institutional framework for the implementation of Hyperloop in the Netherlands. Therefore, the GIS-MCDA approach is chosen because this location problem can be defined as a multi-criteria decision problem, whereby a variety of spatial criteria have to be taken into account and various stakeholders are involved. The research question is defined as follows: *where to place the route of Hyperloop infrastructure in the Netherlands taken into account an origin and destination location, using a GIS-MCDA approach?*

The area-oriented planning approach is used, whereby interaction of infrastructure with its surrounding is considered. From the current configuration of the study area, expressed in 17 criteria, are routes calculated. With a Pairwise Comparison questionnaire (n=16) consulting experts were importance values assigned to criteria. Five response groups were defined, each with different sets of weights.

The result is 10 possible routes of which most routes covered the same area, had similar scores for evaluation statistics (accumulated cost, length, sinuosity) and they crossed four identified bottlenecks at the same location. Integration of the method with the Dutch Tracéwet infrastructure planning procedure is also discussed.

Suggestions for future work include an analysis of the effect of buffer sizes around specific features, the use of a (non-spatial) MCA for choosing a "best" route, and the automation of parts of the methodology in order to make it an iterative process for a workshop setting.

**Keywords:** *Hyperloop, GIS-MCDA, least cost path analysis, infrastructure route design, transportation infrastructure, area-oriented planning*

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# ACRONYMS

# 1 | INTRODUCTION

## 1.1 MOTIVATION

In contemporary transportation planning, sustainable mobility is an 'alternative paradigm within which to investigate the complexity of cities, and to strengthen the link between land use and transport' [Banister, 2008]. Encouraging modal shift (i.e. from the use of cars for transportation to sustainable modes for transportation) and greater efficiency of the transportation system are both actions that contribute to sustainable mobility [Banister, 2008]. Maglev trains, biofuel powered vehicles, battery electric vehicles, hydrogen fuel cell vehicles, and e-bikes are exemplar sustainable forms of mobility [Leibowicz, 2018].

The *Hyperloop* is a proposed technology for the transportation of people and goods [Arup et al., 2017]. It is proposed by the founder of SpaceX, Elon Musk, and introduced as a fifth mode of transport, next to cars, trains, planes, and boats. The Hyperloop technology uses fast (in theory up to 1220 km/hour) vehicles floating on a magnetic cushion in tubes with low air pressure, so that resistance to movement of the vehicles is reduced [Dudnikov, 2017; SpaceX, 2013].

With regard to sustainable mobility, Hyperloop could be an interesting development. Hyperloop could encourage passengers to shift modality if it is well integrated with other forms of public transportation, such as train stations or bus stations. Moreover, Hyperloop could encourage greater efficiency in the transport system if vehicles can leave the stations as regularly as planned (every 2 minutes) [SpaceX, 2013].
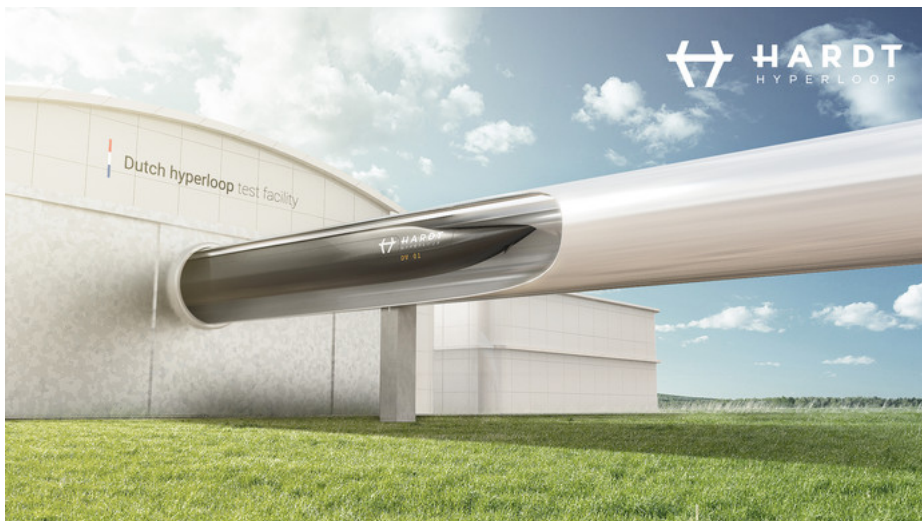


**Figure 1.1**: Impression of a Hyperloop station. Image created by Hardt Hyperloop.

The Dutch Ministry of Infrastructure and Water stated the ambition to "pioneer public transport innovation", as mentioned in the report "Public Transport in 2014 - Outlines of a vision for the future" [Ministry of Infrastructure and Water, 2019]. Besides, as "one of the leading countries in the development and implementation of new and innovative mobility concepts" [Arup et al., 2017], the ambition of the

Dutch Ministry of Infrastructure and Water is to "further strengthen and broaden this position" [Arup et al., 2017].

In that regard, the Dutch government conducted a study to the suitability of the construction of a test track for the Hyperloop in the Netherlands [Arup et al., 2017]. The study by Arup et al. [2017] resulted in an advice to create a test track of three kilometers in the province of Flevoland. More recently, the Dutch company Hardt Hyperloop announced their plans for building the "European Hyperloop Center" near the city of Groningen, which includes a three kilometer test track [Hardt Hyperloop, 2019].

The main reason for Arup et al. [2017] for choosing the location in Flevoland was that it might become part of a future commercial route between Schiphol Airport and Lelystad Airport. If the tests with the three kilometers track succeeds, the Hyperloop will be tested on a 40 kilometers track before it can be used to transport people and goods. It is, however, unclear where in the Netherlands this 40 kilometer track should be located. Where in the Netherlands, between Schiphol Airport and Lelystad Airport, should the track (or *route* or *corridor*) of this infrastructure be located?

## 1.2 INFRASTRUCTURE DEVELOPMENTS

In general, the planning of any (public) transportation project starts with the recognition of a current or future need to meet the demand for transportation [Farkas, 2009]. In the Netherlands, for highways and rail infrastructure, the long-term forecasts regarding the need for new infrastructure is covered in a national vision on infrastructure and the environment: the Structuurvisie Infrastructuur en Ruimte (SVIR) [Ministry of Infrastructure and the Environment, 2012]. In the SVIR, the Amsterdam region is depicted as one of the *key-regions*, which is of national significance because it comprises for example business district Zuidas, Schiphol Airport, the Amsterdam seaports, and an large expected growth of the housing market [Ministry of Infrastructure and the Environment, 2012].
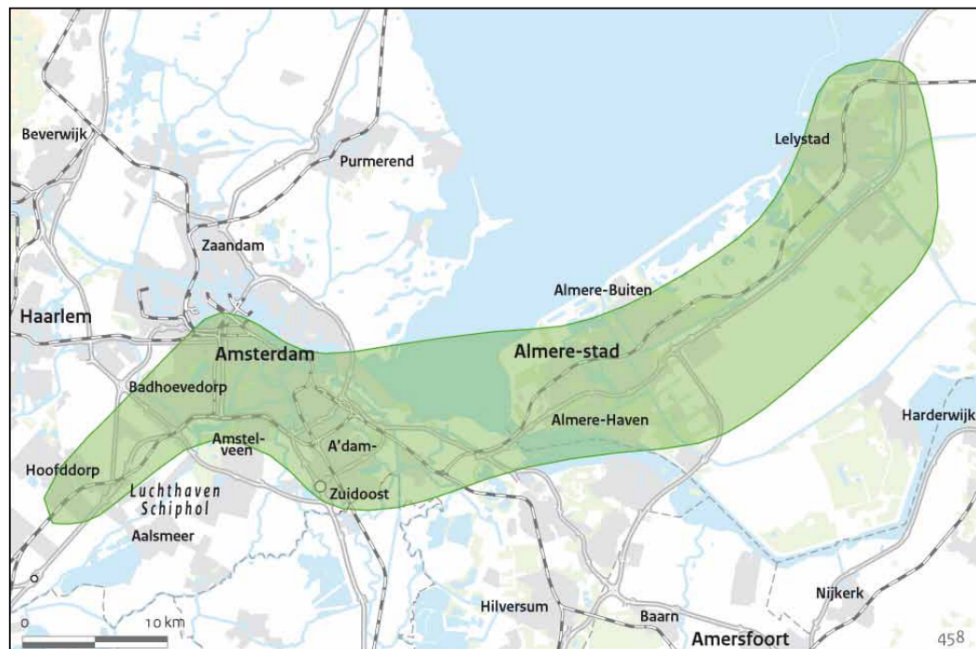


**Figure 1.2:** Corridor for the *OV Schiphol-Amsterdam-Almere-Lelystad (SAAL)* project. The project contains improvements and upgrades of the existing rail roads in the area (visualized in green).

Individual projects of national and international importance are covered in the multi-year plan on infrastructure and the environment: the Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT) [Ministry of Infrastructure and Water, 2018]. In the MIRT, Lelystad Airport in the province of Flevoland is depicted to accommodate flights from the national airport Schiphol, since the latter is reaching the limit of yearly allowed flights. Good accessibility of the Lelystad airport and suitable (public) transportation connections between the two airports is of major importance (see for example the *OV SAAL* project [Ministry of Infrastructure and Water, 2018, p. 153 - 155], Figure 1.2. The Dutch government, provinces and related municipalities made agreements on the further improvement of the accessibility of Lelystad airport, via road and public transport. The choice for the location of the Hyperloop test site is therefore also in the province of Flevoland, close to the airport, thus possibly part of a future – commercial – Hyperloop route between the two airports [Arup et al., 2017]. Therefore, there is a large-enough need for the demand of transportation envisioned in the selected region.

However, detailed implementation plans and/or considerations regarding route choice for infrastructures near Lelystad Airport are not included in SVIR and MIRT. Besides, the concept of "Hyperloop" is not included in those documents since the technology is currently in the testing phase: it is currently not ready to be used for transportation of people and/or goods.

## 1.3 MULTI CRITERIA DECISION PROBLEMS

The current planning practice in the Netherlands regarding large infrastructure projects for motorways focuses on the area surrounding the new infrastructure, thus next to the new infrastructure itself [Heeres et al., 2012]. Heeres et al. [2012] noticed a transition from *line-oriented* approaches to *area-oriented* approaches, where the former focuses only on the infrastructure itself and the latter incorporates the environment surrounding the planned infrastructure. Thus within infrastructure planning, also the attention for spatial quality of infrastructure and related spatial projects has gained importance. Spatial quality is the "outcome of an interaction process which brings stakeholders together, instead of a pre-defined value." [Macharis et al., 2012].

This makes the location problem for the Hyperloop track in the Netherlands a spatial planning problem in which multiple criteria have to be weighted. This type of complex problems can be classified as *multi-criteria decision problems* [Malczewski and Rinner, 2015]. It are complex decision problems with various important – economic, environmental, spatial, technical, and social – aspects, there are often various proposed alternatives, and a large amount of stakeholders can be involved. Stakeholders are "people who have an interest, financial or otherwise, in the consequences of any decisions taken" [Macharis et al., 2012]. How can these type of problems be solved, what approaches are available?

An answer can be found in a sub-field of GIS science, which is dedicated to the integration of GIS and tools for analyzing and solving those multi-criteria decision problems: GIS-MCDA. GIS-MCDA is a collection of methods and tools for transforming and combining the geographic data and preferences to obtain information for decision-making [Malczewski and Rinner, 2015].

Recent examples of applying a GIS-MCDA approach for site selection can be found in literature. For example Giuffrida et al. [2019] focused on the possibility of including Public Participation in quantitative evaluation methods such as MCDA. Terh and Cao [2018] created a GIS-MCDA framework for choosing cycle routes in Singapore, and it incorporates the preferences of various stakeholders into various scenarios. The authors showed how the comparison of different preferences among three key stakeholder groups – in their case the public, a transport expert, and a government planner for cycling – demonstrates how GIS-MCDA "enables a logical and comprehensible way of visualizing how differences in opinion can affect the planning out-

come", in the context of Singapore [Terh and Cao, 2018]. Farkas [2009] discussed another form of MCDA, utilizing a hierarchical decision tree model to find a location that meets predetermined selection criteria for a metro-rail route. Various objectives were prioritized to find the best location for such an infrastructure [Farkas, 2009]. Coutinho-Rodrigues et al. [2011] discussed their implementation of a GIS-based multicriteria Spatial Decision Support System (SDSS) for planning urban infrastructures. Their goal was to provide decision support in the selection of the "best" alternative of a set of alternatives, based on multiple evaluation criteria.

Thus a GIS-MCDA approach assumes a set of alternatives. However, for Hyperloop this set of alternative locations is not identified nor characterized, except for the proposed location for the test-track in Flevoland [Arup et al., 2017]. Thus, the *site selection for the route of the Hyperloop* is the complex decision problem to be solved.

The advantage of using an GIS-MCDA approach is that it utilizes the storage and analysis capabilities of GIS and the incorporation of value judgements of decision makers through MCDA [Malczewski and Rinner, 2015]. "MCDA can provide assistance in understanding the results of GIS-based decision making procedures, including trade-offs among conflicting evaluation criteria/objectives, and then use the results in a systematic and defensible way to develop policy recommendations." [Malczewski and Rinner, 2015, p.11 and p.328] [Nyerges and Jankowski, 2010].

Although the Dutch government has the ambition to invest in transportation innovations [Ministry of Infrastructure and Water, 2019] and a research is conducted on where in the Netherlands a test track for Hyperloop should be located [Arup et al., 2017], it is unknown where a future (test) track of a 40 kilometer Hyperloop between Lelystad Airport and Schiphol Airport should be located. The location problem for such an infrastructure system is characterized as a complex multiple criteria decision problem [Malczewski and Rinner, 2015]. Assumed that technological issues with Hyperloop technology are going to be solved, and assumed that something like the Hyperloop is "welcome" in the Netherlands: is it possible to find suitable routes for the Hyperloop, utilizing the GIS-MCDA approach?

## 1.4 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

### 1.4.1 Research objective

When the implementation of a new transportation infrastructure in a region is proposed the choice for the routing is of high importance. A scientific aspect of the GIS-MCDA approach is which criteria to include in the model. Namely, who decides to include a certain criterion in the decision making process, for whom or what is a certain criterion of importance? Choosing which criteria to include in an analysis is also the first step in GIS-MCDA [Malczewski and Rinner, 2015]. Further, the methodology for including the criteria in a GIS is another aspect of the GIS-MCDA approach. How is the data which represents a criterion quantified in such a way that it can be included in a GIS, while at the same time the data does not lose its quality? And how important is each individual criterion? Another aspect of GIS-MCDA is how the data is combined and how the data for making a decision is calculated transparently and objectively, i.e. the *decision rule* [Malczewski and Rinner, 2015]. For this study it is finding out which route calculation algorithm is suitable. How does that influence the outcome, i.e. a particular route?

Various people and (local) communities can be affected when a new transportation infrastructure is implemented: positively or negatively. It will affect users of the infrastructure positively, by decreasing transit time significantly. People or communities that can be affected negatively are likely those who have no direct or indirect benefit of the new infrastructure. Before (potential) negative aspects would outweigh positive aspects, which could lead to the cancellation of implementation of a new proposed infrastructure, it is worthwhile to investigate potential scenarios

and communicate objectively about it, in the Dutch planning practice. A tool that improves communication between various stakeholders is beneficial for the planning process. This research focuses on the design and implementation of such a tool.

In this research is a GIS-based route planning support framework proposed that includes multiple criteria to answer the question of where in the Netherlands to build Hyperloop infrastructure, taking which factors into account, and whether and how the preferred Hyperloop infrastructure routes change based on the perspectives of different stakeholder groups.

### 1.4.2 Research questions

The Hyperloop is a new type of infrastructure: for this innovation there is no institutional design. Currently there is no standard or agreed way for decision making. Therefore, GIS-MCDA is proposed a field of research which could give the solution for the location problem of the Hyperloop in the Netherlands. The research question is:

> *"Where to place the route of Hyperloop infrastructure in the Netherlands taken into account an origin and destination location, using a GIS-MCDA approach?"*

It is a qualitative question, since it includes selecting factors which are important in creating a route for Hyperloop infrastructure. Besides, the research question has a quantitative aspect, because the relevant important factors are quantified and included in a GIS. Relevant sub-questions for this research are:

- What is the Hyperloop? The first sub-question focuses on the proposed Hyperloop technology and the requirements of such a transportation system, such as technological barriers, the expected user demand, and which cities should be connected? A question that is relevant when the system is used to transport people (and not only goods) is: how does the design of the infrastructure affect the user experience regarding shocks and g-forces when speeds are above 1000 km/hour? What are the implications for the siting of the route?

- What is the GIS-Multi-Criteria Decision Analysis approach? With this question are various approaches to selecting optimal infrastructure routes, next to the proposed GIS-MCDA method. Next to that, with this sub-question is the methodology of GIS-MCDA for transportation infrastructures covered.

- What are relevant factors in a GIS-Multi-Criteria Decision Analysis approach for choosing optimal routes for a "Hyperloop" infrastructure to be implemented in the Netherlands? This question focuses on the selection procedure for the criteria in the GIS-MCDA approach, taking the Dutch context into account. Which criteria are relevant and which are not, which type of criteria can be used, is data available, does the criterion have a geographical component, which procedure is used to calculate the weighting factor for the various criteria, and how are the criteria standardized? [Malczewski and Rinner, 2015]. This selection procedure for criteria is described in a separate chapter (Chapter 3).

- How are the suggested routes evaluated? This sub-question focuses on the evaluation or validation of the results of the methodology. When is a suggested Hyperloop route an "optimal" route? What would be the added value of this methodology when compared to another methodology to identify an optimal route or corridor for the Hyperloop?

## 1.5 READING GUIDE

Chapter 2 discusses the theoretical background of this research. It contains an elaboration on Hyperloop and a possible institutional design for the governance of Hyperloop in the Netherlands, methodological frameworks for decision making, the core concepts of GIS-MCDA, literature reviews on GIS-MCDA, and ten articles on the application of GIS-MCDA in the field of (transportation) infrastructure route planning. The chapter ends with an overview of factors that are used in those ten studies, and a conceptual model in which important concepts are connected.

Chapter 3 uses the results from the discussion in the previous chapter as input and elaborates on the selection procedure for the criteria, specifically for this case study on Hyperloop routes in the Netherlands. The chapter concludes with a list of 17 criteria that are used in the methodology.

Chapter 4 elaborates on the methodology for identifying optimal routes or corridors for the case study. It includes a description to the study area, specific requirements for Hyperloop infrastructure, the method for defining importance of criteria, considerations when using data in raster format, and the procedures for calculating and evaluating routes.

In Chapter 5 are the results of the methodology described and discussed, a possible integration in the Dutch infrastructure planning framework is described, and drawbacks or shortcomings of the methodology are discussed.

Finally, in Chapter 6 is the research concluded by answering the research question, a reflection on the research, and recommendations for future work.

# 2 | THEORETICAL FRAMEWORK

## 2.1 THE HYPERLOOP

As a fifth mode of transportation, the Hyperloop will compete with other transport modes on the intermediate distances, i.e. 300 to 600 kilometers [Leibowicz, 2018]. It is estimated that 840 passengers can travel per hour (one direction) on the route Los Angeles - San Fransisco, thus around 7.4 million passengers per year. A trip between Los Angeles and San Fransisco would take around 35 minutes [SpaceX, 2013]. The total costs of the project in California, USA, are estimated at $6 billion and $7.5 billion for the passenger and cargo variants, respectively [Dudnikov, 2017; SpaceX, 2013].

The availability of Hyperloop as transportation mode will also lead to an increase of competition between airports in a region. Voltes-Dorta and Becker [2018] found that the largest airport in California, Los Angeles International, would benefit most from a Hyperloop service between Los Angeles and San Fransisco as envisioned in SpaceX [2013], because the catchment area of the airport is enlarged due to the availability of the fast Hyperloop service. Namely, passengers from the north of California who initially choose for an airport nearby, could travel to Los Angeles International easier by means of the Hyperloop [Voltes-Dorta and Becker, 2018]. Therefore, the Hyperloop can be seen as a disruptive technology for the current techno-institutional complex of transportation [Leibowicz, 2018].

A study on historical data for transportation in the USA shows that in the development of transportation systems in general the "diffusion of infrastructure precedes adoption of vehicles, which precedes expansion of travel" [Leibowicz, 2018]. In other words, availability of infrastructure can be seen as the main 'driver' for expansion of travel. Early in the technology lifecycle, infrastructure provision should be the major policy consideration [Leibowicz, 2018]. Therefore, **?** advises to support a change (or *transition*) to sustainable mobility effectively by investing public resources in various programs over time in a manner that corresponds with that sequence of diffusion processes.

However, Leibowicz [2018] also mentioned the limitations of the methodology, of which one was that patterns that are observed in the historical data might not be valid for a different spatial, sociopolitical, or temporal context. So it is possible that a Hyperloop transportation system follows a different development path than the systems investigated by Leibowicz [2018] – which were canals, railroads, motorized transportation, and airplanes – and for example does not have to overcome a technological lock-in situation. Especially if Hyperloop is developed first in countries in the developing world, where road and rail networks are limited and environmental problems are more acute, this technological solution can be more urgent and can develop differently [Leibowicz, 2018]. Also Ross [2016] mentions that it is expected that the first Hyperloop will be located in Asia, Africa, India or the Middle East because in developing countries there is no technological lock-in situation in contemporary transportation systems [Ross, 2016]. The study area for the current study is, however, the Netherlands.

Why would the Hyperloop be a good idea for the Netherlands? Developing the Hyperloop can give a *first mover* advantage, as mentioned in the advisory report by Arup et al. [2017]. With this advantage, a country which develops the technology can acquire a knowledge position and determine the standards. Besides, it will

|  | The Netherlands | Developing countries |
|---|---|---|
| Advantages | - Determining the standard (acquiring knowledge position) | - Technology leader |
|  | - Ensures that the Netherlands will be connected to an European Hyperloop network | - Acquiring good market position |
|  | - Binding R&D frontrunners to the Netherlands, growing up to a development hub | - Income from licenses |
| Disadvantages | - If the development ends the Netherlands could remain empty handed | - Sunk costs through not using the technology |
|  | - "First time" effect: relatively high investment costs | - Imitation by free-riders |

Table 2.1: Overview of advantages and disadvantages for the Netherlands and developing countries of being a "first-mover" with regard to the Hyperloop. Source: Arup et al. [2017].

ensure that the country is connected to an international network of Hyperloop infrastructure. Disadvantages are the risk that comes with the high investment cost for this transportation innovation: if the development stops a country can remain empty-handed [Arup et al., 2017]. See Table 2.1 for advantages and disadvantages for the Netherlands of being a first mover with regard to the Hyperloop. The first mover advantages and disadvantages for developing countries are also included in Table 2.1.

At the time of writing (2019) there is not (yet) a decision made if the Netherlands will invest in a Hyperloop track. In this study, however, it is *assumed* that the Netherlands will invest in a Hyperloop track, and the route will start at Lelystad Airport and finish at Schiphol Airport. Therefore, this study is a *hypothetical* case study. If the Netherlands would never invest in Hyperloop, the proposed methodology of this research could be used for other types of transportation infrastructure instead, for example conventional, high-speed, maglev, or lightrail railroad planning, or highway planning.

## 2.2 INSTITUTIONAL DESIGN

Implementing a new transportation infrastructure such as Hyperloop in the Netherlands touches upon the institutional design of the existing planning system and institutions. Institutional design is defined as *"the devising and realization of rules, procedures, and organizational structures that will enable and constrain behavior and action so as to accord with held values, achieve desired objectives, or execute given tasks"* [Alexander, 2005]. Planners are confronted with institutional design if a plan or policy includes new projects or programs, if a plan or policy implementation demands the reorganization of existing organizations or new organizations, if existing inter-organizational networks have to be transformed or new linkages have to be created, or if a policy or plan involves amended or new legislation or regulations [Alexander, 2005]. Next to a technological design – i.e. that which is visible, see for example Figure 2.1 – also an institutional design is needed argues [Koppenjan and Groenewegen, 2005]. Namely, technological (transport) systems – such as Hyperloop – also requires an institutional structure that is used to coordinate positions, relations, behavior of parties owning and operating the system [Koppenjan and Groenewegen, 2005]. The analysis of the institutional design setting involves the analysis of transactions between relevant actors [Alexander, 2005]. So institutional design is about the governance with regard to infrastructure.

Elements of institutional design are: laws, rules & regulations, standards, governments, markets, inter-organizational networks, and organizations. The interactions

that these elements intend to affect are: events, customary behavior, norms, habits, practices, and knowledge or world-views [Alexander, 2005]. These public, private, formal and informal arrangements are institutions necessary for a system to function [Koppenjan and Groenewegen, 2005]. In other words, the institutional design is the set of "rules of the game."

How could the Hyperloop be embedded in an existing institutional design? The answer for now is: such an institutional design needs to be created, together with the development of the Hyperloop technology itself. Namely, for the Hyperloop proposed as a "fifth mode of transportation" – after planes, cars, trains and boats [SpaceX, 2013; Palacin, 2016] – as of yet, there is no appropriate institutional framework.
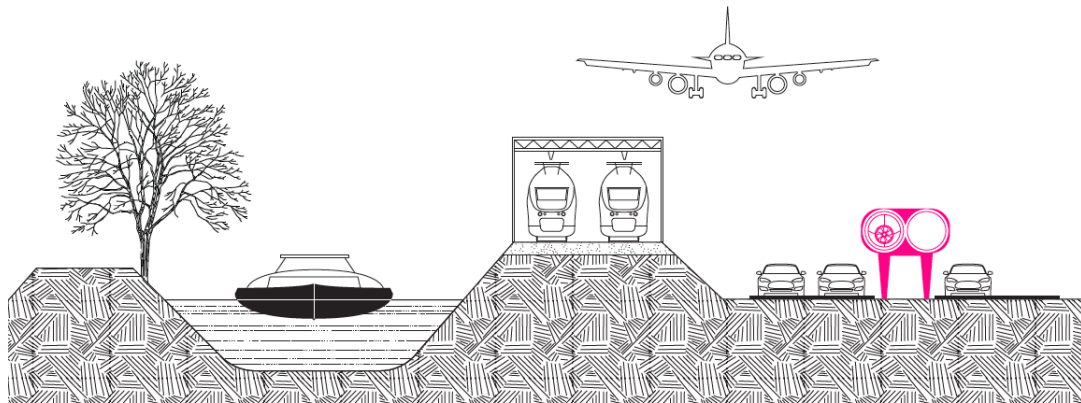


**Figure 2.1:** Future cross section of the variety of transportation infrastructure technologies? Design for the Hyperloop infrastructure is visualized in pink. Image from Van Lint [2019].

## 2.3 FRAMEWORKS FOR DECISION MAKING

The lack of a suitable institutional design for Hyperloop in the Netherlands makes the need for other means to decision-making processes. Various methodological frameworks have been used for the ex-ante and ex-post evaluation of transportation plans and projects. These frameworks can be grouped in two main categories: single criterion methods (the monetary approach) and multicriteria methods (the non-monetary approach) [Beria et al., 2012]. Cost Benefit Analysis (CBA) belongs to the first, Multicriteria Analysis (MCA) to the latter. In their work, Beria et al. [2012] compared the two approaches CBA and MCA for aiding decision-making with respect to projects in sustainable mobility, see table Table 2.2 which summarizes their findings. The methods are not mutually exclusive. Beria et al. [2012] argued that the two approaches could complete each other and joint use can add value to the assessment.

In this research, the MCA approach is chosen because it is a measure that is not only in monetary terms; Hyperloop technology is not existing (yet) thus costs for the infrastructure are difficult to estimate; and the MCA method combined with GIS, using the raster data type, is well-developed for analyzing site-selection problems [Malczewski and Rinner, 2015].

The next section desribes the main concepts of MCA for spatial problems. Thereafter, four literature reviews on GIS-MCDA methods and methodologies are discussed. That is followed by a discussion of selected studies in which the GIS-MCDA method for solving location problems has been applied for various infrastructure types. These studies are discussed because their implementation of the GIS-MCDA

| | MCA | CBA |
|---|---|---|
| Phases | - Definition of the projects or actions to be judged; <br>- Definition of judgement criteria; <br>- Analysis of the impacts of the actions; <br>- Judgment of the effects of the actions in terms of each of the selected criteria; <br>- Aggregation of judgments. | - Quantification of relevant effects of an investment; <br>- Translation of future costs and benefits to present day; <br>- Scheme with variation of surplus; <br>- Verify that surplus obtained by some actors exceeds surplus loss paid by others; <br>- Verify that scheme is marginal. |
| When | - Ex-post; ex ante | - Primarily ex ante and possibly ex-post |
| Where | - Micro-scale | - Primarily large scale |
| What | - Perception of the effect, including "soft" ones | - Quantifiable and measurable effects ("hard") |
| Why | - Effectiveness | - Efficiency |
| How many | - Multi(ple) criteria and indicators | - Single criterion and result |
| Priority/ranking | - Input (indications from decision makers) | - Output (support to decision makers) |
| Strengths | - Participation and legitimacy; <br>- Democracy; <br>- Allows qualitative measures; <br>- Informal. | - Rigour and rationality; <br>- Largely formalized; <br>- Transparency; <br>- "Common language", known and used worldwide; <br>- Easy communication of results; <br>- Independent from judgements; <br>- Potentially participative. |
| Weaknesses | - Potential ambiguity, subjectivity; <br>- Some components of arbitrariness, especially in the perception of public costs vs. private benefits; <br>- Risk of double counting; <br>- Lack of clarity, consistency, accountability. | - Difficult technique, expensive; <br>- Need of many data, sometimes hardly available; <br>- Practically impossible to assess "soft" effects (beauty, personal beliefs, attitudes); <br>- Equity is not a goal directly assessed, but left to decision maker. |

Table 2.2: MCA and CBA compared. Source: Beria et al. [2012].

approach can be useful for the methodology of this research. Besides, the discussion of these articles yield a large collection of potential (spatial) criteria to be used in the methodology.

## 2.4 CORE CONCEPTS OF THE GIS–MCDA APPROACH

Malczewski and Rinner [2015] define GIS-MCDA as "a collection of methods and tools for transforming and combining geographic data and preferences (...) to obtain information for decision making." There are a vast amount of GIS-MCDA methods for selecting a route for infrastructure. The authors distinguished two approaches to solving spatial decision problems: spatial simulation and spatial optimization.

### 2.4.1 Spatial simulation and spatial optimization

*Spatial simulation* uses a model of real-world spatial systems to perform various experiments. A range of possible solutions is obtained for the spatial problem, of which then the "best" solution is chosen.

*Spatial optimization* models try to find the optimal solution to well-defined spatial decision problems [Malczewski and Rinner, 2015]. The difference between the simulation and optimization approaches is the starting point: simulation approaches start with actions and then studies effects on the system objectives by testing various policies under various external conditions, while optimization approaches start with a definition of system objectives and then specifies actions that will satisfy those objectives at the optimum level. In other words, with simulation is a *descriptive* "what is" approach used, while with optimization a *normative* "what ought to be" approach is used [Malczewski and Rinner, 2015].

### 2.4.2 Value scaling, criteria weighting, and the combination rule

Malczewski and Rinner [2015] distinguishes three main concepts in the procedures for solving spatial multicriteria problems, such as finding possible infrastructure routes for Hyperloop. These concepts are: value scaling, criterion weighting, and a combination rule.

*Value scaling* is the transformation of raw data to comparable units, including a standardization procedure. It involves defining a standardized metric which can be used to compare various datasets, and which has the same value scale (for example: 0 = lowest cost, 1 = highest cost). For example, Terh and Cao [2018] used a standardization formula to make the various criteria comparable with each other.

A *criterion weight* is a value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration. For example, if the cost of criterion $A$ is much more important than the cost of a criterion $B$, criterion $A$ will be assigned a higher criterion weight, in such a way that criterion $A$ will have more influence on the outcome. Relatively simple methods for criterion weighting are for example the *ranking method*, *rating method*, *pairwise comparison*, and the *entropy-based criterion weight method*, while more advanced methods are the *proximity-adjusted criterion weights*, *range-based local criterion weights*, and *entropy-based local criterion weights* methods [Malczewski and Rinner, 2015]. Regarding criterion weighting, Terh and Cao [2018] conducted questionnaires focused on three key stakeholder groups (the public, transport experts, and government planners) to find the most relevant criteria for their routing problem. They used a Likert-type scale, which is a rating method.

Finally, a *combination rule* is a procedure or method for evaluating and ordering a set of decision alternatives.

## 2.5 LITERATURE REVIEWS ON GIS–MCDA

Four literature reviews that reflect on the field of GIS-MCDA are included in this theoretical framework because they discuss which methods and techniques are commonly used and in which fields of spatial planning GIS-MCDA can be applied.

Camargo Pérez et al. [2014] conducted a literature review on the application of Multi-Criteria Decision Making (MCDM) techniques for urban passenger transportation systems. They found that those techniques have mostly been used to aid decision-making in the long and medium term planning horizons. Also, the Analytic Hierarchy Process (AHP) technique is most often used for the criterion weighting. AHP is a technique that aids decision makers to order priorities. With the AHP method a series of pairwise comparisons is utilized in order to reduce decision complexity [Durmaz et al., 2019]. Furthermore, Camargo Pérez et al. [2014] observed that economic, logistic, and technical decision criteria were mainly considered in early works. Environmental, social, and land-use criteria have been considered in more recent works. Although Camargo Pérez et al. [2014] their literature review included 86 papers related to urban transportation, only six of those papers focused on *location problems* for infrastructure.

Zyoud and Fuchs-Hanusch [2017] conducted an analysis to estimate the global research productivity for the topic MCDA and to document growing interest in two MCDA methods: AHP and TOPSIS. The integration of GIS with AHP for different uses is coined as one of the "hot topics" in MCDA, and it will stay relevant for applications such as site selection, land use planning, remote sensing, and risk assessment [Zyoud and Fuchs-Hanusch, 2017].

The systematic literature review by Mardani et al. [2016] on MCDM techniques customized for solving transportation problems included 89 papers. The focus of their literature review was on application areas such as service quality and transportation performance evaluation. Planning of new transportation routes was not an application area. Mardani et al. [2016] found that AHP or *Fuzzy-*AHP methods were mostly used.

Traditionally, in the field of transport MCDA most applications work towards a common set of criteria, i.e. one value tree for all stakeholders [Macharis et al., 2012]. Macharis et al. [2012] argues that in the context of social decision problems the group of decision makers is not necessarily homogeneous – other than in a business setting where the objective of the group as a whole is the same – and will often have conflicting points of view, therefore a common hierarchy of criteria and weights in MCDA methods is not possible. They propose the use of Multi-Actor Multi-Criteria Analysis (MAMCA) for the evaluation of transport projects. The MAMCA methodology is an extension of MCDA, with the difference that stakeholders are explicitly taken into account. Moreover, the methodology allows the use of non-numeric and non-monetary values in the evaluation. Macharis et al. [2012] argue that MAMCA deals better with different points of view of the stakeholders, since the criteria included in the decision making and the weights of these criteria – which vary from stakeholder to stakeholder – are *not aggregated before* the MCDA is performed. Instead, only after performing individual MCDA analyses, with different sets of criteria and related weights, the results are aggregated. With that aggregation step of the MAMCA methodology are various alternatives ranked and strengths and weaknesses of the alternatives are revealed.

Moreover, Macharis et al. [2012] mentions that crucial steps of the methodology are the choice of stakeholders, the criteria set, weights of the criteria, and weights of the stakeholders. Strategic bias regarding those steps must be avoided. Strategic bias in the context of groups decision modeling occurs when individual stakeholders provide their preference information to a group decision model which, they perceive, will only improve their own outcomes and not the outcomes of the group [Macharis et al., 2012]. For example, Nadafianshahamabadi et al. [2017] evaluated outcomes of two MCDA's for a proposed highway project in Tehran, Iran. One MCDA

was conducted with input from technical experts: the other was conducted with input from a sample of community members [Nadafianshahamabadi et al., 2017]. Their findings demonstrated that differences in technical knowledge and values seem to result in different MCDA outcomes. This raises the important question: whose values and knowledge should be included?

This research, on finding optimal routes for Hyperloop infrastructure between Lelystad and Schiphol, also uses an approach inspired by MAMCA, where a variety of sets of weights for criteria are taken into account. Here, a "set of weights for criteria" depends on the group to which the stakeholder belongs. Stakeholders are consulted via questionnaires and the stakeholder groups are based on the stakeholders' organization background.

## 2.6 EXAMPLES OF GIS–MCDA IN INFRASTRUCTURE ROUTE PLANNING

Various recent (2001 to 2019) examples of the use of GIS-MCDA in the field of infrastructure route planning are now discussed. This variety of GIS-MCDA studies is inspiration for the design of the methodology for selecting Hyperloop routes. The studies are subdivided in two groups: spatial *simulation* and *optimization*. Besides, the discussion yield a list of potential spatial criteria that can be used. After this section, the use of Least Cost Path Analysis (LCPA) for selecting optimum routes is discussed since LCPA is a core element in most of these articles.

### 2.6.1 Applications with the *simulation* approach

*A clean sheet approach*

In their methodology for identifying appropriate corridors for a highway route in the eastern part of the USA, Grossardt et al. [2001] combined the "robust rational choice decision methodology" AHP with the "rigorous spatial analytic framework" raster-based GIS [Grossardt et al., 2001]. In traditional MCDA "cost" is the deciding factor: the authors used the spatial equivalent "impedance", since it is not necessarily a monetary based variable. The impedance variable was composed of the sum in total 50 individual impedance variables. These impedance variables (i.e. criteria) where grouped in various "affinity groups" (i.e. classes). With the pairwise comparison methodology was the relative importance of each criterion per theme identified, resulting in weights for criteria and weights for the affinity groups. Consequently, the 50 layers with the data for the criteria were converted to raster grids with a cell-size of 30 meters. For each cell were all values added up, resulting in a cost surface for the whole study area. This cost surface was then used to make a "least-accumulative-cost distance layer", representing the total cost from an origin point fo the route to any other point in the study area. Consequently, this layer is used to determine the "least-cost path" between the origin point and any location anywhere on the raster map [Grossardt et al., 2001]. With LCPA an accumulated cost surface is generated, on which a line can be identified which go from an origin point to a destination point in a study area [Bagli et al., 2011; Durmaz et al., 2019]. There are various approaches to the determination of the least cost path in space, see for example Stefanakis and Kavouras [1995].

Grossardt et al. [2001] stated that their methodology was "intended as a clean-sheet approach to determining the best corridor when the corridor location options are almost infinite and existing road infrastructure is minimal or nonexistent". Thus, the methodology is a type of simulation approach instead of an optimization approach [Malczewski and Rinner, 2015]. Namely, various options are simulated resulting in a selection of possible corridors or routes, after which an optimization

approach can be used to select the most optimal one. For the Hyperloop case in the Netherlands this is also suitable: there are currently no existing routes thus possible corridors have to be identified first, after which the most optimal route can be selected.

### A spatial MCDA followed by a non-spatial MCDA

More recently, Karlson et al. [2016] focused on ecological and geological criteria with regard to corridor planning for a railway north of Stockholm, Sweden. Their methodology framework consisted of two parts: a design part and evaluation part.

The *design* part was a Spatial Multi Criteria Analysis (SMCA) to create three railway corridor suitability (raster) maps, taking into account in total eight spatial factors. Three different weighting schemes for those factors resulted in three different scenarios. Consequently, the maps were input for a least cost path finding analysis. Since the original planning documents for the railway corridor north of Stockholm identified two potential origins and one destination (the airport), the least-cost path analysis was run from those two origins. Therefore, a total of 6 different railway corridors were identified for the study area.

Consequently, in the *evaluation* part of the framework was the performance of each of the 6 potential corridors assessed by calculating various performance metrics (e.g. habitat loss, corridor length, etc.) [Karlson et al., 2016]. Although an in-depth evaluation of performance of routes is not the objective for this Hyperloop route-simulation study, it is useful to have a performance metric that should be minimized. For this study, that metric is the sum of the least-cost path.

### Spatial constraints, benefits, and costs

Keshkamat et al. [2009] created "a planning system that directly takes into account environmental and socio-economic considerations in selecting alternative routes (...)". With their methodology, the authors generate "various optimal route alternatives under different policy visions, in a network of existing roads" [Keshkamat et al., 2009]. Further, Keshkamat et al. [2009] stated that the use of GIS in very preliminary stages of the planning of transport routes has hardly been done. The methodology was applied on the case of the Polish part of the Via Baltica highway project in east Europe. While the work of Grossardt et al. [2001] used a clean-sheet approach, i.e. completely new infrastructure; the approach of Keshkamat et al. [2009] utilized only existing roads, thus connecting parts of existing infrastructure into one continuous route for the Via Baltica.

The three main components of their methodology were: criteria and data identification; weighting of criteria and themes; and geospatial data-processing. With the criteria and data identification the relevant criteria were selected and assimilated in a model. Four themes ("affinity groups" in Grossardt et al. [2001]) that cover the various criteria are selected: transport efficiency, ecology, social impact and safety, and economic costs and benefits. Raster maps were used for scores per criterion. Every pixel in a raster map represents a suitability value for a specific criterion. The options for the value of a criterion are: constraint (absolutely not suitable, thus non-compensatable by a good performance of another criterion or constraint), spatial benefit (the higher the value, the better), or spatial cost (the lower the value, the better) [Keshkamat et al., 2009].

Weighting of the criteria and themes is the second part of the methodology and is based on stakeholder preferences and policy visions. Keshkamat et al. [2009] distinguished different perspectives or political "policy visions": equal vision, social vision, ecology vision, and economy vision. By putting different weights on these policy visions or themes, various routing scenarios can be compared. By using the expected value method are weights for those policy vision calculated.

The third part of the methodology, geospatial data-processing, is the combination of the various criteria and weights to generate optimal route maps. Geospatial
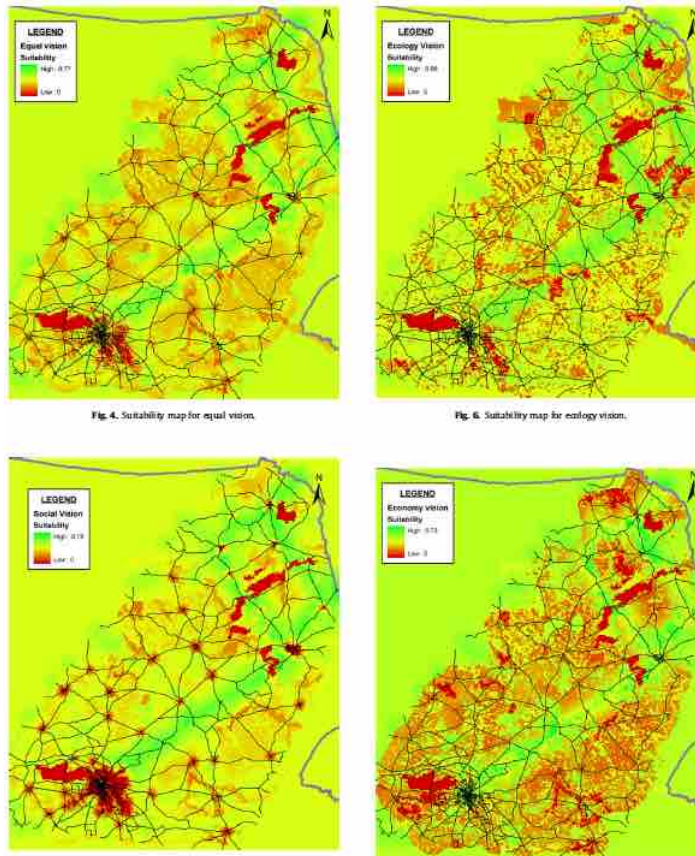
Figure 2.2: Impedence maps for four visions: equal, social, ecology, and economy [Keshka-mat et al., 2009]. These type of raster maps are input for a least-cost path search procedure.

datasets that represent the different criteria (21 in total) and their weights were combined to prepare routing suitability maps for the four distinguished policy visions [Keshkamat et al., 2009], see Figure 2.2. A "suitability map" corresponds to the "impedance map" from Grossardt et al. [2001]. The resulting raster grids have cell sizes of 1000 meters. This relatively wide cell-size is chosen because it relates to the "minimum direct impact distance", i.e. the effect of a road corridor on its surroundings, and the three raster sources used for the case study use a pixel resolution of 994 meter to 1000 meter, thus accuracy loss during resampling is avoided. Consequently, with a line-raster extracting algorithm the line weighted means from each resultant raster (suitability) map was extracted to the road vector layer which represents the existing infrastructure. The Dijkstra shortest path algorithm is used to find the path of least total – "policy vision"-specific – impedance among that network [Keshkamat et al., 2009].

In the Hyperloop case there is no layer that can represent the existing infrastructure, so this last step is irrelevant for this study. However, an advantage of the methodology by Keshkamat et al. [2009] is that it can be used to assess a predetermined route, in addition to objectively comparing four policy visions and their optimal routes.

### 2.6.2 Applications with the *optimization* approach

#### What if there is no expert knowledge available?

The aim of the study of Kim et al. [2014] was to determine most suitable locations for a new high-speed rail infrastructure in Texas, USA. Their work differs from other research in this discussion because the determination of weights for criteria was not accomplished by consulting experts since the authors noticed that the availability of expert knowledge is limited [Kim et al., 2014]. Instead, the authors used Principal Component Analysis (PCA) to determine which of the criteria should be placed together in (at total of five) groups. PCA was used to define the groups in a more scientific manner when compared with (subjective) opinions of experts, the authors argued.

Thereafter, the weights for the criteria group are based on choice: which group is most important in a specific scenario? Individual criteria are not weighted in this methodology. Like in the work of Grossardt et al. [2001], Terh and Cao [2018] and Keshkamat et al. [2009] the weights and criteria together resulted in a cost surface (i.e. "impedance map" or "suitability map") which is in raster format: each pixel indicates a suitability score based on the established scenarios and relationships between the variables. These cost surfaces were generated for each scenario. Then, a least cost analysis is performed to find the sequence of pixels with least possible scores between two points on the cost surface. The chosen points were locations of the major airports in respectively San Antonio and Austin.

So Kim et al. [2014] did not use expert knowledge or stakeholder input to determine weights for criteria. However, their transparent modeling process, whereby each scenario is calculated, encourages public participation in determining which input variables to include, and deciding which scenario to implement.

#### Sensitivity analysis on input data

Comparable to the approach of Kim et al. [2014] is the work of Yildirim and Bediroglu [2019]. The difference is that Yildirim and Bediroglu [2019] consulted in total 35 professionals through interviews and questionnaires in order to determine which criteria and weights to include in their GIS-MCDA approach. "Professionals" are those who have related work experience on similar high-speed rail engineering projects and who have been involved in inventing solutions for those projects, or those who have an academic background in related fields [Yildirim and Bediroglu,

| Source | Application | Stakeholder groups |
| --- | --- | --- |
| **Bagli et al. [2011]** | routeing of power lines | No stakeholders consulted in this research. Instead, *neutral*, *economic*, *health*, and *socio-economic* "perspectives" are used, with different weights. |
| **Coutinho-Rodrigues et al. [2011]** | water supply system | No stakeholders consulted in this research. |
| **Durmaz et al. [2019]** | gas pipe planning and evaluation | No distinction made between stakeholders or stakeholder groups. |
| **Farkas [2009]** | route/site selection for metro network | An expert group with *5 transportation engineers*, *3 mechanical engineers*, and *2 economists* |
| **Grossardt et al. [2001]** | highway corridor alignment | No distinction made between stakeholders or stakeholder groups |
| **Karlson et al. [2016]** | design and evaluation of railway corridors | No distinction made between stakeholders or stakeholder groups |
| **Keshkamat et al. [2009]** | transport route corridor planning | No distinction made between stakeholders or stakeholder groups. Instead, four "policy visions" used: *equal vision*, *social vision*, *ecology vision*, and *economy vision*. |
| **Kim et al. [2014]** | optimizing high-speed rail routes | No distinction made between stakeholders or stakeholder groups |
| **Yildirim and Bediroglu [2019]** | high-speed railway route determination | No distinction made between stakeholders or stakeholder groups. |
| **Terh and Cao [2018]** | cycling paths planning | Three key stakeholder groups: *the public (cyclists n=97* and *non-cyclists n=105)*, *transport expert (n=1)*, and *government planner (n=1)*. |

**Table 2.3:** Overview of stakeholder groups identified in the reviewed articles on GIS-MCDA for (transportation) infrastructure planning.

2019]. Moreover, the work of Yildirim and Bediroglu [2019] included a sensitivity analysis, which indicates how the output of a model changes with variations in input. The applied method was the "one-at-a-time" technique, which involves modifying input criteria one at a time and consequently observing the effect on the output [Yildirim and Bediroglu, 2019; Crosetto and Tarantola, 2001].

### 2.6.3 Involvement of stakeholder groups

In the abovementioned examples of GIS-MCDA for transportation route planning, some authors included a distinction of stakeholder groups. In other words, they took the question "whose values and knowledge should be included?" [Nadafianshahamabadi et al., 2017] into account. See Table 2.3 for an overview of identified stakeholder groups, from the reviewed articles. Only in the work of Farkas [2009] and Terh and Cao [2018] are explicit stakeholder groups identified.

## 2.7 LEAST COST PATH ANALYSIS AND ITS USE IN VARIOUS APPLICATIONS

The approaches used for the corridor planning in the above mentioned examples (from Grossardt et al. [2001], Keshkamat et al. [2009], Kim et al. [2014], Karlson et al. [2016], and Yildirim and Bediroglu [2019]) all used the "traditional" approach to LCPA [Stefanakis and Kavouras, 1995]. The traditional approach to LCPA can be used for planning of various linear infrastructures that affect its surroundings, ranging from roads to pipelines [Bagli et al., 2011]. This approach is described in Stefanakis and Kavouras [1995] and consists of three main steps:

1. Generation of a *friction surface* in raster format (map *b* in Figure 2.3);

2. Generation of an *accumulated cost surface*, which is a raster map that illustrates the cost of movement to any point $X,Y$ from a point of reference $X_0$, $Y_0$. The

point of reference may be either the departure location or the destination location of the trip. The accumulated cost surface is often created with a spread function, which is progressing step-by-step outward in all directions from a starting point and adding travel cost of each successive step to the accumulated cost back to that point (map *c* in Figure 2.3);

3. Determination of the *optimum path(s)*. One of the techniques to determine the optimum path(s) is the *seek* (also called *stream*) function. It starts from a cell that represents a point of interest on the accumulated cost surface, then it progresses to neighboring cell(s) with the lowest accumulated cost values. That operation is repeated until the point of reference is reached (maps *d* and *e* in Figure 2.3).
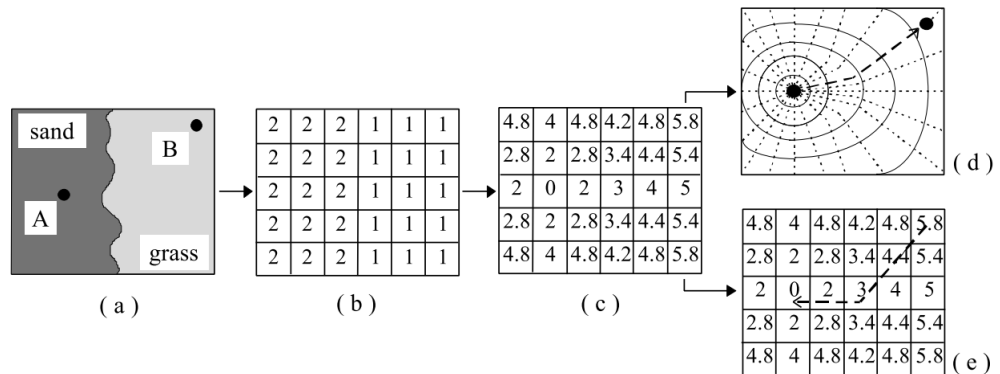


Figure 2.3: Traditional approach to Least Cost Path Analysis. Image from Stefanakis and Kavouras [1995].

One weakness of this approach mentioned by Stefanakis and Kavouras [1995] is that the generation of the accumulated cost surface is based on movements confined to eight directions, when a regular grid is used. That will lead to data loss. However, when a small enough pixel size is used this problem can be minimized for the purpose of this study, where possible routes for the Hyperloop are simulated. Also, the creation of friction surfaces from various maps, often done with a vector-to-raster conversion, is accompanied by a loss of information with regard to the structure under study. Again, with a small enough pixel size this problem can be minimized.

So, both mentioned disadvantages of the approach with the accumulated cost surface could be minimized by using a smaller pixel size. However, this results in larger files. Moreover, if the study area is also large this can lead to relatively long processing times.

Bagli et al. [2011] applied LCPA on route infrastructure planning for power lines. Bagli et al. [2011] found that small changes in the location of the start and end points of the power line can yield significantly different paths. These different paths can thus also have different impact levels. Therefore, they advice planners to consider alternative terminals (i.e. origin and destination points) for the infrastructure. Moreover, in their study are different weight scenarios introduced, which can help making the model adaptable to varying environmental and social contexts. These weight scenarios were: an human health perspective, economic perspective, and a nature/landscape perspective [Bagli et al., 2011].

LCPA is also applied in the field of natural gas pipe planning. Durmaz et al. [2019] used a distance analysis tool to evaluate the suitability of a realized route for a gas pipe in Turkey. Regarding the construction of gas pipes is the total amount of vertex points a critical factor, since a lower amount of vertex points makes construction work easier. Among other activities, for their study were relevant criteria for

their GIS-MCDA identified by consulting experts, the weights of these criteria were calculated with help of the pairwise comparison method and AHP, and LCPA was performed on the resulting (raster) cost surface map. This resulted in a 35% lower cost value and 2.36 km shorter total length for the calculated route, when compared with the gas pipe that was realized.

However, the amount of vertex points for the calculated route was relatively high. With a Line-Based Cartographic Simplification (LBCS) algorithm were vertices that are at relatively large distance from the "optimal route" – a straight line between the origin and destination points – removed. Although this increased the total cost, the total cost was still lower than the original pipeline. The total length also decreased [Durmaz et al., 2019].

The amount of vertices in a Hyperloop route should also be minimized. Therefore, an approach similar to the LBCS methodology should be used if the calculated route includes too many vertex points.

## 2.8  CONCLUSION THEORETICAL FRAMEWORK

In the previous sections are various examples from the literature on GIS-MCDA for infrastructure planning discussed. This review provides a stepwise approach to be followed: selecting criteria, weighting criteria, the creation of a "cost surface", "suitability map", or "impedance map", and a Least Cost Path analysis. In all those examples, the following factors were included, see Table 2.4.

The collection of criteria included in Table 2.4 is the basis from which the set of criteria in this research on Hyperloop is selected. This selection procedure is discussed in Chapter 3. To conclude this chapter, the conceptual model for this study is depicted in figure 2.4.

| Source | Application | Themes & Factors | Region | Cell size | O-D Distance |
|---|---|---|---|---|---|
| Bagli et al. [2011] | routeing of power lines | **human health**:<br>density of buildings, distance from buildings, distance from sensitive buildings, average height of buildings<br>**landscape**:<br>distance from highly valued cultural and recreational sites,<br>visibility from highly valued cultural and recreational sites, visibility from residential buildings<br>**nature**:<br>aspect of the slope, distance from infrastructure corridors, naturalness of land cover, ridges | North-eastern Italy | T.B.D. | 10km |
| Coutinho-Rodrigues et al. [2011] | water supply system | **costs of infrastructure**:<br>costs of conduits, costs of installation, creation of new streets, costs of new reservoirs,<br>reinforcement of water elevation stations<br>**operating and maintenance costs**:<br>costs of operating during the life of the project,<br>**profitability of the investment**:<br>increase of robustness to the overall water supply system, increase of capacity of the water supply system.<br>**impacts during the building of the new infrastructures**:<br>impacts over the road users, impacts over neighbor zones, interference with other existing infrastructures | Coimbra, Portugal | T.B.D. | 1km |
| Durmaz et al. [2019] | gas pipe planning and evaluation | **geographical**:<br>ridges, streams, slope,<br>**social**:<br>'risk of fire and explosion', urban areas with buffer of 750m,<br>**economic**:<br>agricultural irrigation areas, dam reservoirs<br>**environmental**:<br>high voltage powerlines, highways, fault lines | East western Turkey | 30m | 120km |
| Farkas [2009] | route/site selection for metro network | engineering characteristics and geological soil structure (rocks), ecological suitability, connectivity index, population density, projected construction costs | Cochabamba, Bolivia | 20m | 4km |
| Grossardt et al. [2001] | highway corridor alignment | **environmental**:<br>unique habitat, large viewshed, archeological feature, historic feature, streams, wetland, prime farmland,<br>fish hatchery, springs, sink holes, known caves, underground fuel tank, high probability of caves,<br>EPA project sites, low probability of caves, tire dump, landfills, hazardous materials<br>**man-made public features**:<br>hospital, water tank, school, public water supply, airport, sewage treatment, church, pumping station,<br>cemetery, pipeline, golfcourse, powerline, armory, railroad, power plant, water filtration, radio tower,<br>dams, electric substation<br>**dirt and rock**:<br>oil and gas wells, mine, strip mine, quarry, 15-25% slope, 10-15% slope, 5-10% slope, slope,<br>rock base, mixed/unknown base, soil base, soil classification<br>**socioeconomic**:<br>land value, poverty rate, median income, population growth rate, community impact<br>**regulatory practices**:<br>picnic area, national properties register, state park, wild and scenic river, public campground,<br>wildlife management area, endangered species, national forest, superfund site, close to natural attractions,<br>national park, military installation" | South eastern USA | 30m | 140km |
| Karlson et al. [2016] | design and evaluation of railway corridors | **ecological**:<br>valuable areas, movement pathways, stepping stones<br>**geological**:<br>suitability for construction, suitability for aggregates, slope, soil thickness | North of Stockholm, Sweden | T.B.D. | 10km |
| Keshkamat et al. [2009] | transport route corridor planning | **transport efficiency**:<br>proximity to existing rail network, proximity to proposed Rail Baltica, current traffic density<br>**ecology**:<br>Natura 2000 sites, nationally protected areas, forests and semi natural areas, wetlands and peat bogs,<br>water courses and lakes<br>**social impact and safety**:<br>proximity to urban areas, risk of accidents in urban space, population served, hazardous areas<br>**economic costs and benefits**:<br>current agriculture land-use, economic zones, best agricultural soils, current status of the road,<br>intersections with water bodies, intersections with secondary roads, problem soils for construction,<br>ancillary structures for urban areas | Via Baltica, Poland | 1000m | 300km |
| Kim et al. [2014] | optimizing high-speed rail routes | **engineering**:<br>roadway right of way (type of roads), slope/maximum grade<br>**environment**:<br>vegetation types, animal farms, crop farms, farm size, forestland and forestland patches, noise level<br>**natural resources**:<br>floodplain, surface waters, wetlands, geology/faults, soil types<br>**demographics**:<br>population density past (2000), population density current (2010)<br>**land**:<br>land use (urban/rural areas), property values | Texas, United States | 30m | 110km |
| Yildirim and Bediroglu [2019] | high-speed railway route determination | protected area, river, highway, slope, geology, soil, land cover, lake | Central Turkey | T.B.D. | 60km |
| Terh and Cao [2018] | cycling paths planning | slope, pedestrian traffic, distance from major roads with high traffic, proximity to educational institutions,<br>proximity to retail developments, proximity to employment zones, proximity to community amenities,<br>proximity to MRT/LRT stations, proximity to bus stops | Singapore | 5m | 6km |
| Tweede Kamer [1994] | high speed rail HSL-Zuid | **Natural environment**:<br>*landscape*:<br>openness, small-scaleness, orientation, cultural history, archaeology, geological<br>*ecology*:<br>quantitative loss of biotopes, qualitative loss of biotopes/fragmentation, qualitative<br>loss of biotopes/distortion, disruption of ecological relations<br>*water and water bottom*:<br>excavation of water bottom, intersection of water bottom protection areas,<br>intersection of ground water protection areas, volume of filler zand, volume of storage<br>of dredging spoil<br>**Spatial planning**:<br>*contribution to spatial developments*:<br>Randstad, Randstad green structure, Groene Hart, Stedenring Centraal NL<br>*living and working*:<br>large locations, VINEX locations, provincial locations<br>*recreation*:<br>recreational facilities, recreation connection routes<br>*agriculture*:<br>loss of agricultural area, intersection of house plots, intersection of agricultural<br>ribbon development, influence on landuse projects.<br>**Housing and environment**:<br>*Noise and vibration nuisance*:<br>noise nuisance in living environment, distortion of silence areas, noise nuisance<br>recreational areas (above 50dB), area exposed to noise, vibration nuisance<br>*Social aspects*:<br>forced departure of residents, social integration, visual nuisance, social safety | Randstad, NL | N.A. | 85km |

Table 2.4: Overview of factors that are used in the reviewed articles on GIS-MCDA for (transportation) infrastructure planning.
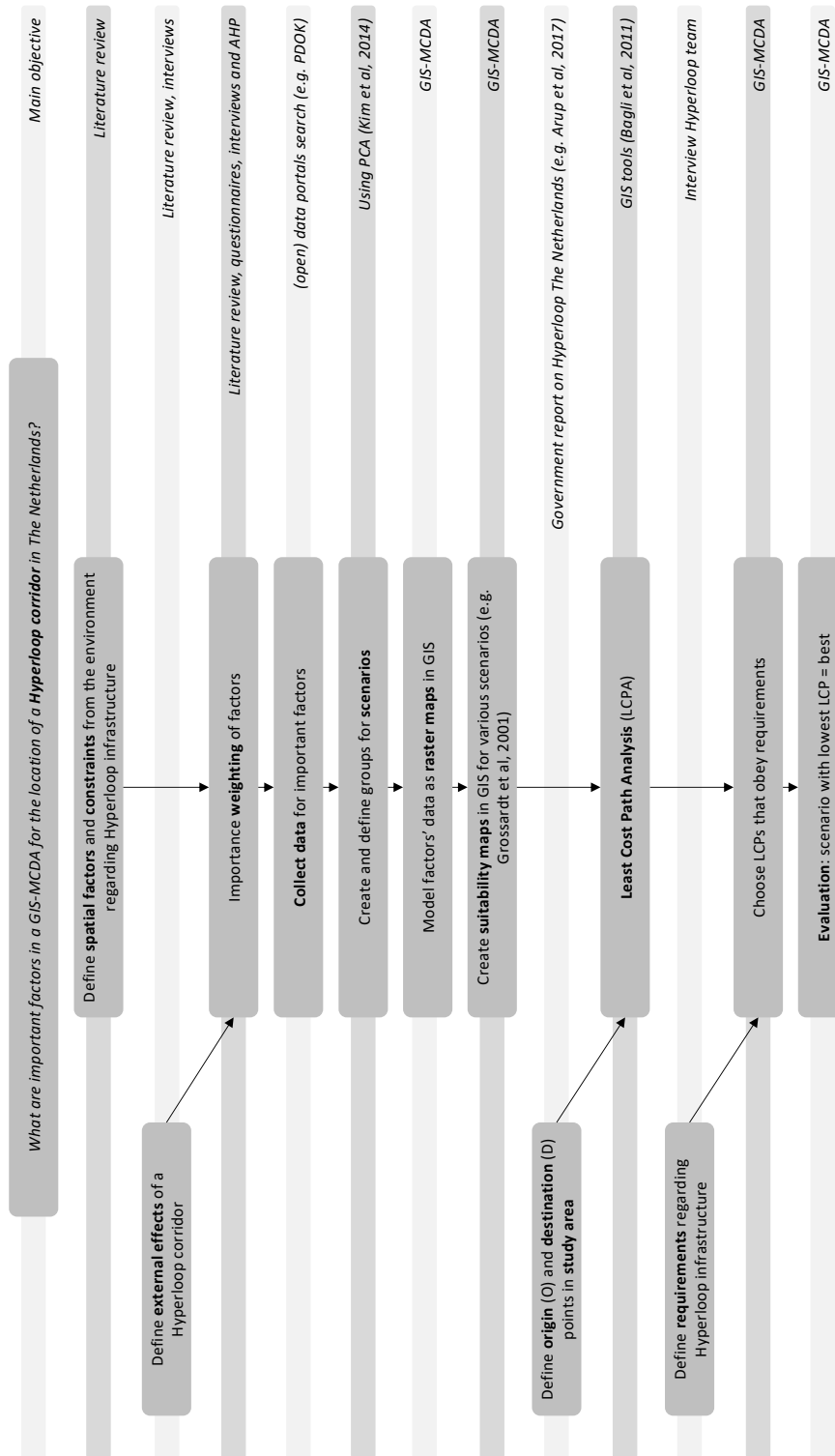
**Figure 2.4:** Conceptual model

# 3 | SELECTION OF CRITERIA

The previous chapter yielded an overview of criteria which are used in various GIS-MCDA research projects. From this set of potential criteria are those chosen which are relevant for this research, i.e. in the Dutch context. In total 17 criteria are selected, which are used in the methodology (Chapter 4).

## 3.1 REQUIREMENTS FOR CRITERIA

A criterion is placed on the shortlist if it satisfies the following three requirements:

1. Does the criterion have a *location-component*? It is found that all criteria from 2.4 have a geo-component, i.e. their values have a location and it would be meaningful to plot the data on a map.

2. Is the criterion *focusing on the area surrounding the Hyperloop infrastructure*, instead of the Hyperloop infrastructure itself? This requirement is inspired by the difference between line-oriented and area-oriented approaches in road infrastructure planning [Heeres et al., 2012]. *Line-oriented* approaches are sector-oriented and neglect the physical incorporation of the road within a wider area. *Area-oriented* planning integrates objectives for transportation with further developments in a specific area: it takes into account all the interests in an area, also called total design [Heeres et al., 2012]. Although the Hyperloop infrastructure is disconnected from the area surrounding it, and has therefore a line-oriented character, the goal of this research is to find possible routes for the Hyperloop which minimizes the (negative) effects of Hyperloop infrastructure on the area surrounding it, i.e. area-oriented in the sense that the infrastructure should not decrease the spatial quality of an area. Thus, the criterion should be involved with the effects of Hyperloop infrastructure on the area. See Figure 3.1 where the difference between line-oriented and area-oriented is illustrated.

3. Is an *open dataset available*? Various Dutch open GIS data portals (e.g. PDOK[1], NGR[2], CBS/StatLline[3], data.overheid.nl[4], Risicokaart[5]) are consulted in the search for datasets that could belong to a criterion.

4. Can the criterion *not be combined with another criterion* and does it not belong to a more general class? For example, facilities with a relatively specific function, such as *bezinkbak* (settling tank), can be part of a new class such as *public facilities* or *industry and agriculture facilities*. Or a building with the function *train station* can become part of the criterion *train infrastructure* or *train tracks*. In other words, it is in both cases possible to combine the features from various datasets and therewith minimize the amount of criteria.

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1 https://www.pdok.nl/datasets
2 https://www.nationaalgeoregister.nl/
3 https://opendata.cbs.nl/
4 https://data.overheid.nl
5 https://www.risicokaart.nl
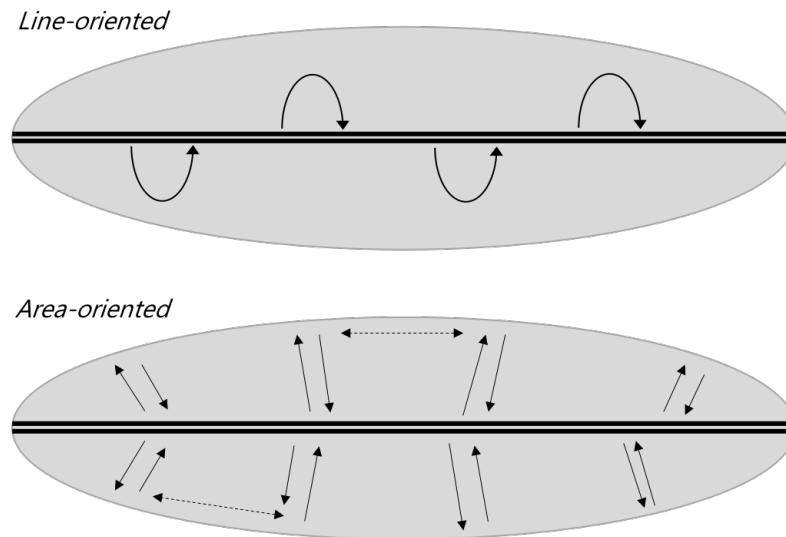
**Figure 3.1:** Line-oriented versus area-oriented criteria. Figure created by the author and inspired by Heeres et al. [2012]. The area-oriented approaches in (road) infrastructure planning combine two perspectives: inside-out and outside-in, which is also shown in this figure. In this research, the shortlist of criteria should be involved with matters regarding the area surrounding the Hyperloop infrastructure, i.e. area-oriented criteria.

The large-scale administration of buildings and addresses *BAG*[6] is the data source for a number of criteria in this methodology. It is a useful dataset because of its completeness: BAG includes most if not all buildings and addresses in the Netherlands. A specific layer in the BAG dataset, *pand*, contains the geometries of the buildings, which is therefore used in this research. *Pand* also contains an attribute which specifies the function of a building (*gebruiksdoel*). The *gebruiksdoel* attribute acts as filter in the methodology.

One *pand* feature can contain more than one function. For example, the iconic multifunctional Johan Cruijff ArenA stadium in Amsterdam is one feature in the *pand* layer and has 5 functions: sports, gathering, office, sports, retail, and 'undefined use function' (*sportfunctie*, *bijeenkomstfunctie*, *kantoorfunctie*, *winkelfunctie*, and *overige gebruiksfunctie*). This means that there are various accommodation objects (*verblijfsobjecten*) in the stadium. An accommodation object is an independent space in a building with a specific function. For example, the stadium is subdivided into 12 accommodation objects, see Figure 3.2. Criteria that use data from BAG are *Educational and science*, *Industry and agriculture*, *Leisure and recreation*, *Health*, and *Housing facilities*. For each criterion are the related use functions from BAG also discussed.

## 3.2 SELECTED CRITERIA

The following shortlist is based on a heuristic search for relevant criteria. Table 2.4 is used for inspiration. A variety of the mentioned (Dutch) open data portals are consulted. And the four mentioned requirements – *location-component*, *area-oriented*, *open dataset available*, *unique* – are taken into account.

### *High risk infrastructure*

This criterion contains dangerous and high risk infrastructures such as gas tubes or oil tubes, and locations which contains facilities that use dangerous and high

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6 https://www.pdok.nl/introductie/-/article/basisregistratie-adressen-en-gebouwen-ba-1
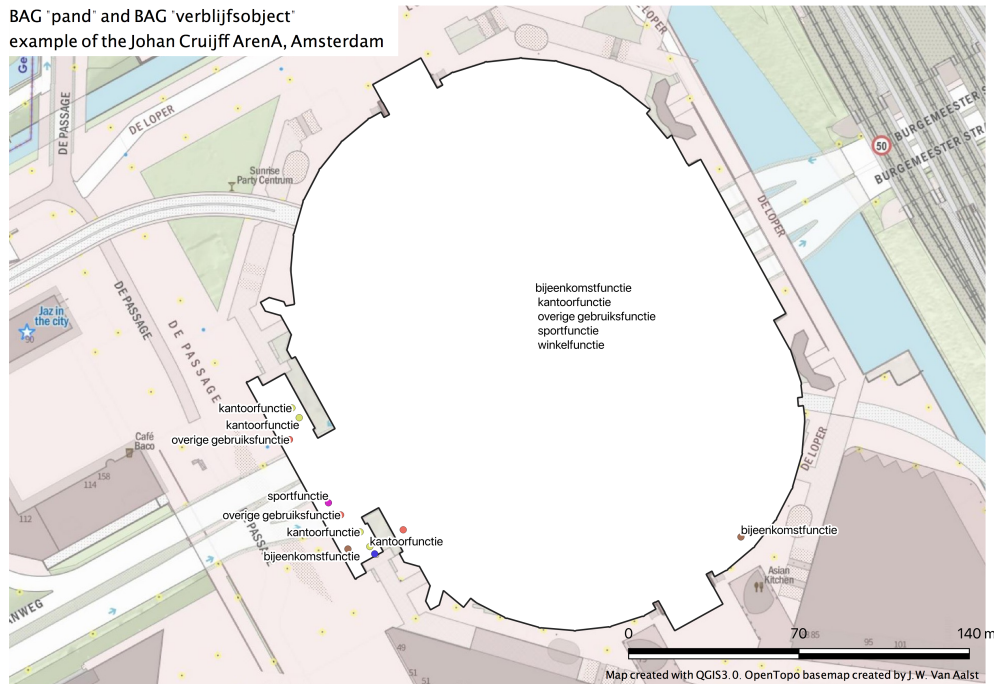
**Figure 3.2:** Example of the ArenA: pand layer and verblijfsobject layer.

risk substances, such as for example LPG installations or firework warehouses. A buffer of 5 meter is computed around the high risk infrastructure features. That distance is chosen because it is the minimum width distance for an "obstruction strip" *(belemmeringenstrook)* which is reserved space for maintenance works regarding the tube[7]. The source dataset is the national risk map *Risicokaart*[8], from which only the datasets of "Facilities" and "Transportation" from the group "Dangerous substances" are selected.

*Train infrastructure*

Criterion "Train infrastructure" includes utilities, tracks and facilities with regard to the Dutch rail network. This can be a relatively important criterion since it is proposed to bundle the Hyperloop with existing infrastructure [SpaceX, 2013; Dudnikov, 2017; Walker, 2018]. The rail infrastructures are widened with an extra buffer (30 meter) on both sides of the trace. This buffer size is chosen so space is reserved for bundling. Two sources are used for creating the surfaces that represent the Train infrastructure criterion. Those are the "Trace" layer from the *Spoorwegen*[9] dataset owned by the national railway infrastructure agency ProRail. And selected features with the use function "overig gebruiksdoel" from the *BGT*[10] dataset (where the selected features intersect with the Trace layer). These features are the train stations.

*Highways side*

Like the previous criterion can "Highways side" also be a relatively important criterion, because of the expected bundling advantage with existing infrastructure. This criterion includes those areas that are not occupied by buildings in the vicinity of

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7 See article 14 in "Besluit externe veiligheid buisleidingen" (https://wetten.overheid.nl/BWBR0028265/2018-03-31)
8 https://flamingo.bij12.nl/risicokaart-viewer/app/Risicokaart-openbaar
9 https://www.pdok.nl/geo-services/-/article/spoorwegen
10 https://www.pdok.nl/introductie/-/article/basisregistratie-grootschalige-topografie-bgt-

highways, and which are therefore suitable for hosting Hyperloop infrastructure. The data source for the Highways side criterion is the $DTB$[11] dataset managed by the national road- and waterway agency Rijkswaterstaat, containing all national highways and shores among major waterbodies. From this dataset are features selected which have a description that would infer a location among the highway but not the highway itself (i.e. the description *omschr* field is 'gras', 'onverhard', 'struiken', 'beek', 'beschoeiing' or 'braak'). Consequently, only those features that are within a range of 30 meter from a highway are selected.

### Highways

"Highways" as criterion is regarded as a spatial cost, since the roads themselves are already occupied and therefore not suitable for the construction of a Hyperloop infrastructure. The data source for this criterion is the *DTB* dataset (same as with "Highways side"). Only those features with description *omschr* value "bituumverharding" are selected.

### Housing

Locations with a housing function are regarded as spatial cost. By far most features in the source dataset for this criterion, the BAG dataset, are buildings where people live. Only those features with *gebruiksdoel* 'woonfunctie' are selected for this criterion.

### Industry and agriculture facilities

The source dataset is BAG and this criterion is regarded as a spatial cost. Only the features with *gebruiksdoel* 'industriefunctie' or 'NULL' are selected. Namely, agriculture facilities are in a large amount of cases not categorized as such in the BAG: the attribute value for *gebruiksdoel* is empty i.e. NULL. In other cases, when the pand feature with *gebruiksdoel* 'NULL' is not a farm, the feature is often located on an industrial area, thus having an industry function. Therefore, it is useful to put industry and agriculture facilities together as criterion. See the table in the Appendix for an overview of BAG function-categories that are regarded as "Industry and agriculture facilities" (and as Housing, Health, Retail, Educational and science, Offices, and Leisure and recreation facilities) in this research.

### Health facilities

Locations which are characterized as health facilities are regarded as spatial cost. All features which contain *gebruiksdoel* 'zorgfunctie' are selected for this criterion. Thus also features which have more functions, such as for example 'zorgfunctie', 'winkelfunctie', 'woonfunctie'. In such cases, the feature is regarded as health facility.

### Retail facilities

The locations characterized as shopping or retail area are regarded as spatial cost. From the BAG are all those features selected which contain "winkelfunctie" *gebruiksdoel*, except for features which contain as *gebruiksdoel* "zorgfunctie".

### Educational and science

The criterion "Educational and science facilities" represent those buildings and locations which are used for teaching or scientific activities, and is regarded as a spatial cost in this methodology. From the BAG are the features selected which

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11 https://www.pdok.nl/introductie/-/article/digitaal-topografisch-bestand-dtb-

contain *gebruiksdoel* "onderwijsfunctie", except for features containing *gebruiksdoel* "zorgfunctie" or "winkelfunctie".

### Offices

Buildings which are used as offices are regarded as spatial cost in the methodology. From the BAG are the features selected which contain *gebruiksdoel* "kantoorfunctie", except for features containing *gebruiksdoel* "zorgfunctie", "winkelfunctie" or "onderwijsfunctie".

### Leisure and recreation

Buildings that are used for leisure and/or recreation activities are a spatial cost. From the BAG are all features selected which contain *gebruiksdoel* "bijeenkomstfunctie", except for features containing *gebruiksdoel* "zorgfunctie", "winkelfunctie", "onderwijsfunctie" or "kantoorfunctie".

### Nature areas

The spatial factor "nature area" is regarded as a spatial cost, since it is not allowed to build in these areas. Three datasets are used: Nature2000 areas[12], Protected nature monuments[13], and National parks[14].

### Water areas

Water bodies areas such as seas, lakes, and rivers, where it should be possible to construct (Hyperloop) infrastructure, though at higher construction costs. Therefore, areas indicated as *water body* will get a spatial cost value: the higher the value, the less favorable for construction. The dataset[15], containing the water bodies that are managed by the Dutch agency of water and highways, Rijkswaterstaat, is used as one data source. Small water bodies such as ditches or ponds are not included in this dataset. However, it includes not all inland waterways such as canals. Another dataset, NWB Vaarwegen[16] is used to complete the dataset. All *vaarwegvakken* which do not overlap with water bodies from the first dataset are included in the dataset.

### Agriculture grassland

Areas that are used for agriculture and which are mainly grassland are a spatial cost. The dataset for agriculture grassland is BRP[17]. The datasets contains all parcels that are used for agriculture, and an attribute *gewascategorie* referring to the category to which the parcel belongs: "grasland", "bouwland" or "braakland" i.e. grassland, cropland or fallow/vacant land. This criterion includes all features if *gewascategorie* is filtered on "grasland".

### Agriculture cropland

Areas that are used for agriculture and which are mainly cropland are a spatial cost. Like the previous criterion, the data source is BRP. Only those features when *gewascategorie* is filtered on "bouwland".

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12 https://www.pdok.nl/introductie/-/article/natura-2000
13 https://www.pdok.nl/introductie/-/article/beschermde-natuurmonumenten
14 https://www.pdok.nl/introductie/-/article/nationale-parken
15 https://www.pdok.nl/geo-services/-/article/oppervlaktewaterlichamen
16 https://www.pdok.nl/introductie/-/article/nationaal-wegen-bestand-nwb-
17 https://www.pdok.nl/introductie/-/article/basisregistratie-gewaspercelen-brp-

| nr. | Name | Theme | (Initial) cost value | Total area (hectare) |
|---|---|---|---|---|
| 1 | High risk infrastructure | infrastructure | 1 | 4870 |
| 2 | Train tracks | infrastructure | 1 | 1707 |
| 3 | Highways side | infrastructure | 1 | 3162 |
| 4 | Highways | infrastructure | 1 | 1571 |
| 5 | Educational and science facilities | building | 1 | 273 |
| 6 | Retail facilities | building | 1 | 799 |
| 7 | Industry and agriculture facilities | building | 1 | 1675 |
| 8 | Leisure and recreation | building | 1 | 480 |
| 9 | Health facilities | building | 1 | 187 |
| 10 | Housing | building | 1 | 4976 |
| 11 | Office | building | 1 | 884 |
| 12 | Nature area | area | 1 | 63697 |
| 13 | Water area | area | 1 | 77423 |
| 14 | Agriculture grassland | area | 1 | 40531 |
| 15 | Agriculture cropland | area | 1 | 30096 |
| 16 | Agriculture fallow land | area | 1 | 14 |
| 17 | Slope above 10 percent | area | 1 | 3674 |

**Table 3.1:** Overview of selected criteria.

### *Agriculture fallow land*

Agriculture areas that are (temporally) not used is fallow/vacant land and are a spatial benefit for building a Hyperloop infrastructure. The BRP data source contains a category for these type of areas: *gewascategorie* is "braakland".

### *Slope above 10 percent*

Areas with a slope increase construction cost for a high-speed rail infrastructure and are therefore not preferred [Yildirim and Bediroglu, 2019; Karlson et al., 2016], and the steepness of vertical alignment of the Hyperloop infrastructure should be limited [SpaceX, 2013; Arup et al., 2017]. Namely, an infrastructure with variations in vertical alignment would cause a "bumpy" ride. By using the vertical pillars, Hyperloop infrastructure is designed in such a way that small height differences can be compensated relatively easily by adjusting the pillar height. However, areas with a more extreme slope (i.e. above 10%) should be regarded as a spatial cost for the infrastructure: a flat area is considered most preferable.

## 3.3 PREPROCESSING OF DATASETS

To be valid input data for the analysis in this research, these datasets have to be preprocessed. Various preprocessing actions that are applied are: clip shapefiles, merge shapefiles, dissolve polygons, solve self-intersecting polygon features, and create a convex hull in order to simplify geometries. Besides, each feature in each individual dataset is assigned a new attribute named *value*, with a value of 1. See Figure 3.3 for a map with all 17 preprocessed individual layers combined. The total area (hectare) per criterion is depicted in Table 3.1.

## 3.4 CONCLUSION SELECTION OF CRITERIA

In this chapter are 17 criteria selected which are included in this research for finding where in the Netherlands the Hyperloop should be located (see Table 3.1). These criteria are selected because they obey the requirements as introduced in this chapter: having a location-component, area-oriented, and the availability of of an (open) dataset, and their uniqueness. These criteria are input for the methodology, described in the next chapter.
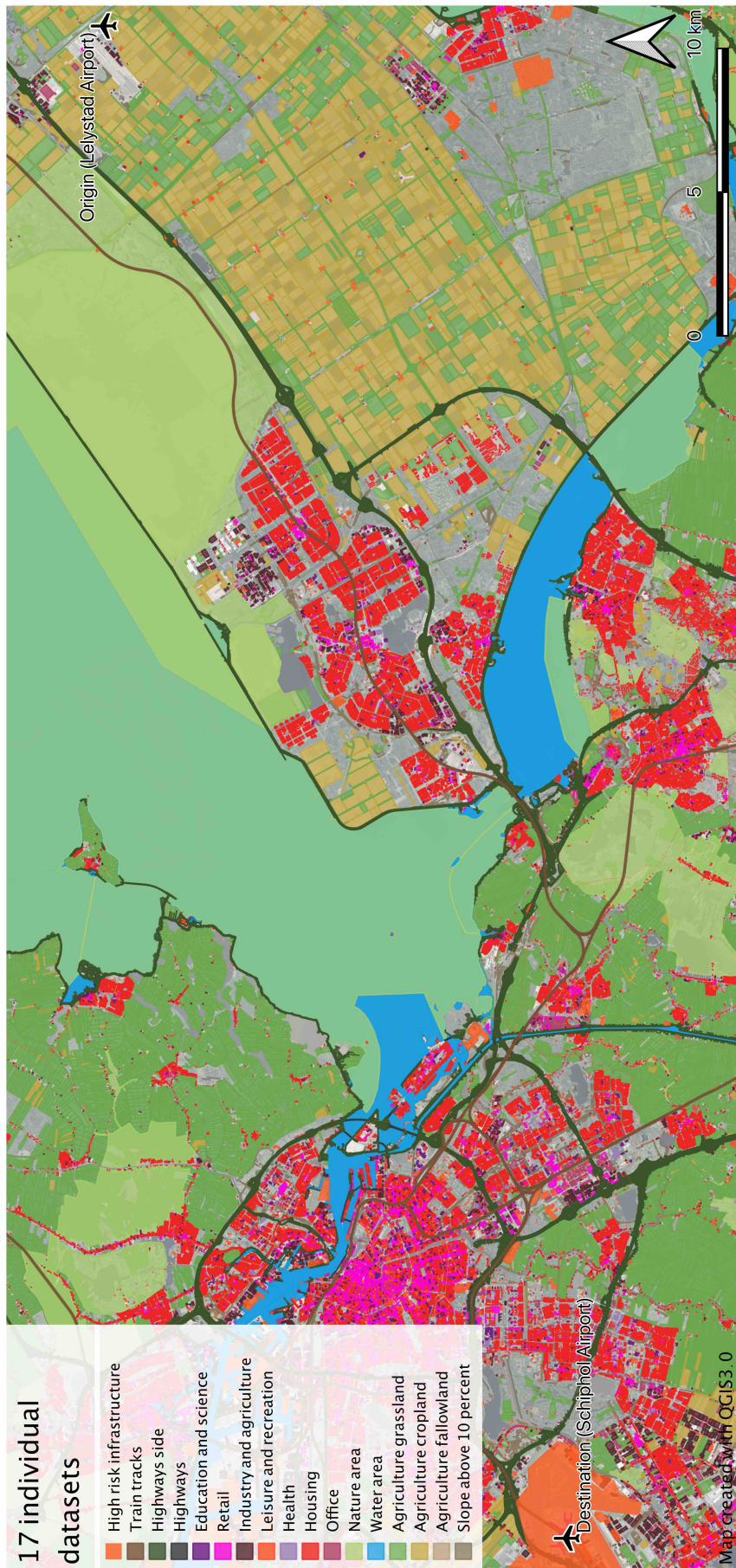
**Figure 3.3:** All 17 individual layers from Table 3.1 in the study area.

# 4 | METHODOLOGY

This methodology describes a route planning framework using a GIS-MCDA approach in a case study for Hyperloop routes in the Netherlands. In this research, the rationale is that the current configuration of the land-use proposes a route for the Hyperloop, given a start and end point for the route. Thus: except for those start and end points, the route for the Hyperloop is not well-defined: *where* to place the route between those points is unknown. Thus, a bottom-up approach which utilizes a *simulation* method is used in this research. The methodology contains of the following steps (also illustrated in Figure 2.4):

1. Proof of Concept for methodology;
2. Study area for Hyperloop in the Netherlands;
3. Criteria from the environment regarding Hyperloop infrastructure;
4. Requirements of Hyperloop infrastructure;
5. Importance of criteria with Pairwise Comparison;
6. Rasterization
7. Cost Surface maps
8. Calculating a route from a Cost Surface;
9. Evaluation of calculated Least Cost Paths;
10. Least Cost Path that obeys requirements of Hyperloop infrastructure;
11. Conclusion methodology.

These steps are discussed in the next sections of this chapter.

## 4.1 PROOF OF CONCEPT FOR METHODOLOGY

Since the study area will be relatively large – having a diamater of around 60 kilometers – it is useful to test and apply (parts of) the methodology on a smaller study area, and verify if the methodology works. Namely, applying the suggested methodology on a large area would consume a large amount of processing and computing time. If the application of the methodology on a smaller area yield meaningful results it acts as a *Proof of Concept*, and the methodology can be performed on the large study area. A Proof of Concept is "evidence, typically derived from an experiment or pilot project, which demonstrates that a design concept, business proposal, etc. is feasible" [Oxford Dictionary, 2019]. In this study, the Proof of Concept serves as an example of the implementation of the methodology, using a smaller study area and a limited set of factors, in order to verify that the basic functionalities of the proposed methodology works.

## 4.2 STUDY AREA FOR HYPERLOOP IN THE NETHERLANDS

The study area for the Hyperloop is defined as the region between Lelystad Airport and Schiphol Airport, including a bufferzone of 7 kilometer around those two locations. This study area is chosen because in the report of Arup et al. [2017] it is envisioned as search area for a possible future commercial Hyperloop track. For example, Arup et al. [2017] propose to locate the test track parallel to the Vogelweg in the province of Flevoland, south of Lelystad Airport [Arup et al., 2017] (see Figure 4.1), which is also located in this study area.

For this study, the origin point (52.4661 latitude, 5.5197 longitude) is set at close proximity to Lelystad Airport, and the destination point (52.3095 latitude, 4.7624 longitude) at Schiphol Airport. These points will be used as origin and destination points for the route calculation, as is discussed later in this methodology. However, the origin and/or destination points can be moved in order to achieve a more suitable route (i.e. a route with lower cost for the Least Cost Path (LCP)). Namely, a variation of hundreds of meters of the origin and destination points of the path may significantly affect the path itself [Bagli et al., 2011]. Varying these locations slightly would allow the identification of new and possibly less costly routes for the Hyperloop. Besides, the location of a Hyperloop terminal on these airports is also unknown.
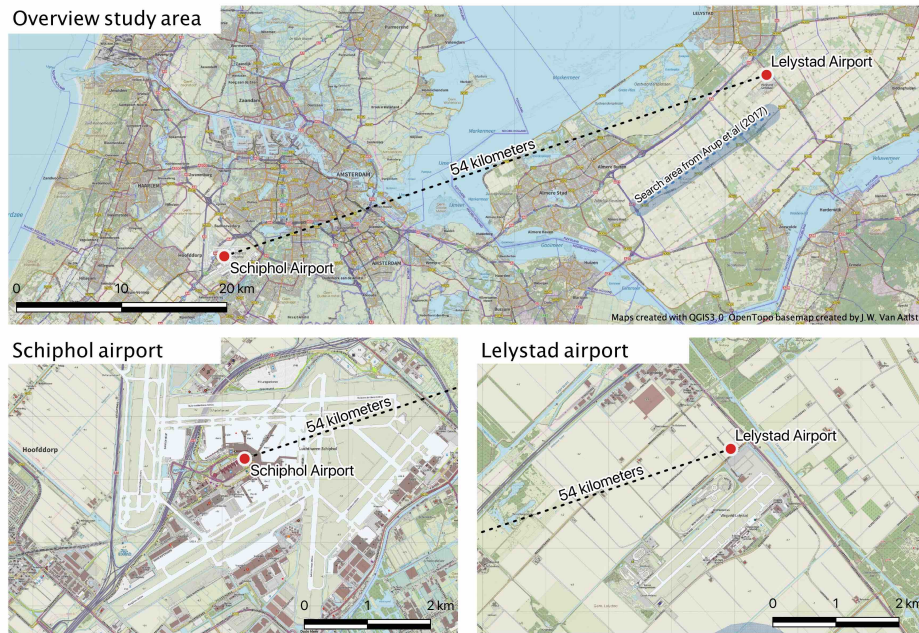


**Figure 4.1:** The study area with the airports of Lelystad and Schiphol. The shortest possible path between those locations is 54 kilometers. Included on the map is the search area for the test track from Arup et al. [2017].

For the creation of the Proof of Concept for this research, a small study area is chosen, see Figure 4.2. In the figure, the origin and destination points are located 2000m apart from each other.

## 4.3 CRITERIA FROM THE ENVIRONMENT REGARDING HY- PERLOOP INFRASTRUCTURE

The goal of this research is to find possible routes for the Hyperloop infrastructure in the Netherlands, by taking a "descriptive" GIS-MCDA approach. Thereby, the environment itself is the constraining factor of what is possible with regard to the routes. Therefore, the factors or *criteria* that describe that environment are important: these criteria sets the limits on possible routes. Therefore, this is a crucial step in this research.

A spatial criterion is information about resources in the environment of the study area. A spatial criterion can be a *spatial benefit* – the higher the value, the better – or a *spatial cost* – the lower the value, the better. A *spatial constraint* is a type of spatial factor which makes a location absolutely not suitable. If the factor is a constraining
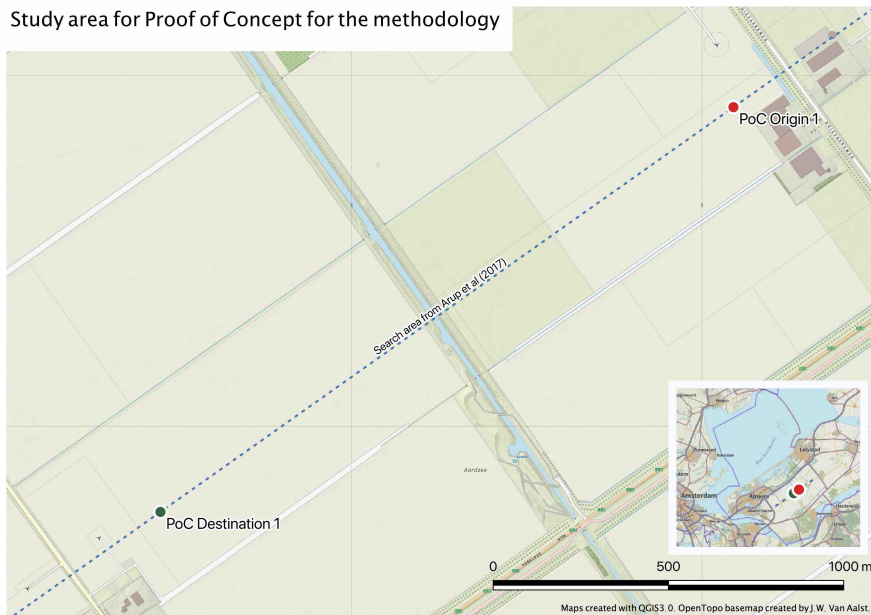
**Figure 4.2:** Study area for the Proof of Concept, which is used to test (parts of) the methodology.

factor, it cannot be compensated by good performance of another factor or (spatial) constraint [Keshkamat et al., 2009; Karlson et al., 2016]. The suitability of a location with regard to a criterion depends on the value of the indicator or indicators in which that factor is expressed.

For example, Hyperloop infrastructure costs increase if it has to cross a lake: it is beneficial not to place the infrastructure on places where it has to cross a lake, although it is not impossible. Thus, the spatial factor "water body" is a spatial cost and should be minimized. The factor can be expressed in various indicators, for example lake, river, wetland, sea, or ocean. Various datasets supply the data for these indicators.

The literature overview in Chapter 2 yielded an extensive amount of factors that affect the suitability of an area for transportation infrastructures in general, when applying a GIS-MCDA methodology, see Table 2.4. The discussion in Chapter 3 resulted in a shortlist of 17 criteria that are used in this research. It was also mentioned that all features that belong to a layer which represent a criterion get an (initial) cost value of 0. Indeed, in this study are all spatial criteria regarded as *spatial cost* (the lower the value, the better). Namely, if these criterion-types were mixed up, that would lead to a more complicated questionnaire.

In Section 4.5 is the calculation of the importance of criteria – by using questionnaires – discussed. For the Proof of Concept, the criteria from the *infrastructure* group are selected: high risk infrastructure, train tracks, highway side, and highways. But first: what are requirements from the Hyperloop infrastructure itself?

## 4.4 REQUIREMENTS OF HYPERLOOP INFRASTRUCTURE

There is no peer-reviewed literature available on requirements for the Hyperloop infrastructure found. However, in other literature and reports are three requirements for Hyperloop infrastructure described: regarding the curvature of the track, above or below ground, and the acceleration of the vehicles.

### 4.4.1 Curvature of the track

A relatively straight track is needed because lateral forces on passengers should stay below 0.1g in order to ensure acceptable levels of passenger comfort. The vehicle will travel with reduced speed on sections with curves. Therefore, it is proposed to place the Hyperloop parallel with highways or bundled with other infrastructure [SpaceX, 2013; Dudnikov, 2017; Walker, 2018]. The speed of the vehicles in the Hyperloop system is "480 kilometers/hour where local geography necessitates a tube bend radii below 1.6 kilometers, (and) 1220 kilometers/hour where local geography allows a tube bend above 4.8 kilometers or where local geography permits a straight tube" [SpaceX, 2013]. For high-speed trains, this tube bend radius can be interpreted as the radius of a circle whereon a vehicle is located [Huston, 2017]. See Figure 4.3, where this radius is expressed as *R*. As Huston [2017] found, the minimum curve bend radius depends on the square of the speed of the vehicle.
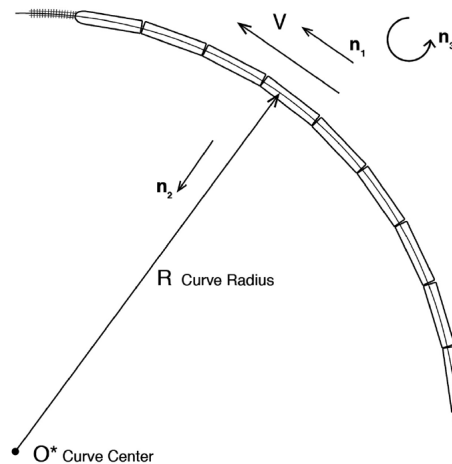


**Figure 4.3:** A train travels with speed *V* through the curve, i.e. over the arch of an (imaginary) circle, with center *O* and curve bend radius *R*. Image from [Huston, 2017].

For reference, the curve bend radii of 1.6 kilometer and 4.8 kilometer for speeds of 480 km/h and 1220 km/h respectively, are displayed in Figure 4.4. Here, the origin point is Lelystad Airport and the destination point is Schiphol Airport. In those two hypothetical Hyperloop routes, the minimal curve bend radii are illustrated for speeds up to 480 km/h and 1220 km/h (maximum speed). On the map is shown how much space is needed for these turns, at those speeds. The map shows that a turn at the highest speed (1220 km/h) requires much more space than a turn at lower speeds (480 km/h).

### 4.4.2 Above or below ground

Construction above and below ground are both possible. Above ground, the approach is to build the infrastructure on pylons of around 5 meters height, see Figure 4.5 for a picture of the test track of Virgin Hyperloop One in the Nevada desert, USA. Below ground, the infrastructure is placed in a drilled tunnel [SpaceX, 2013; Walker, 2018]. Construction above ground is preferred because it is economically beneficial. However, it is expected that building below ground is cheaper when compared to infrastructure cost of conventional high-speed rail tunnels, since the tube diameter is smaller. Besides, tunneling could speed up the planning process and issues with acquiring right of way for the Hyperloop can be reduced [Walker, 2018].

This study will only investigate potential Hyperloop routes *above* ground, since construction costs will be lower. Besides, the Hyperloop technology infrastructure
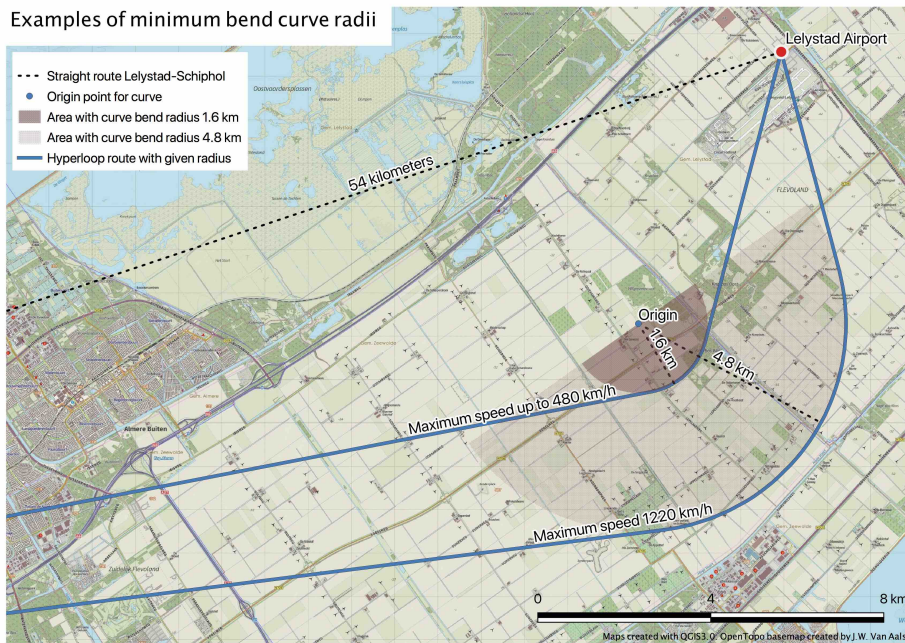
**Figure 4.4:** The minimum curve bend radii for the Hyperloop illustrated in the study area. For vehicle speeds up to 480 km/h the radius is 1.6 km, and for speeds up to 1220 km/h the radius is 4.8 km [SpaceX, 2013].

will first be used as test track. Solving potential issues or problems with the technology on the infrastructure is easier done when the infrastructure is located above ground instead of below ground.

### 4.4.3 Acceleration of the vehicles

Acceleration forces on the passengers is limited to 0.5g [SpaceX, 2013]. Since the maximum speed can not be reached within the first kilometers it is possible to have more curves in the infrastructure closer to the stations. At the "middle" parts, where the maximum speed is reached and there is no acceleration, the infrastructure should follow a (nearly) straight path.

### 4.4.4 Proof of Concept: requirements of Hyperloop infrastructure

The requirements for the Hyperloop infrastructure are evaluated after the simulation of Least Cost Paths, i.e. potential routes (in Section 4.10). Thus, first a potential route is calculated, after which is checked if that potential route obeys Hyperloop infrastructure requirements.

## 4.5 IMPORTANCE OF CRITERIA WITH PAIRWISE COMPAR-ISON

In GIS-MCDA are various methods available acquire appropriate weighting ratios for criteria. A weight is defined as the "value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration" [Malczewski and Rinner, 2015]. Two groups of weighting methods can be classified: global and local methods. Global methods assign a single weight to each criterion because they are based on the assumption of spatial homogeneity of the preferences. On the

**Figure 4.5:** Hyperloop test track in the Nevada desert, USA. Image from Virgin Hyperloop One.

other hand, local methods take heterogeneity of preferences into account, i.e. these methods are spatially explicit [Malczewski and Rinner, 2015].

Since there are no examples of **local** weighting methods found in the literature on implementing a GIS-MCDA for infrastructure route simulation or optimization, a **global** method is used in this research: the *pairwise comparison method*. This method is developed by Saaty [1987] as part of the AHP method for decision making. Pairwise comparison was used in the works of Grossardt et al. [2001]; Farkas [2009] and Durmaz et al. [2019], and it is the most often used technique for obtaining criterion weights in GIS-MCDA applications [Malczewski and Rinner, 2015]. Moreover, the pairwise comparison method has the ability to represent trade-off between individual criteria more effectively than for example rating methods [Terh and Cao, 2018].

AHP is a method with which relative priorities in decision making can be achieved [Saaty, 2008]. AHP has three main principles: a hierarchical decomposition of objectives and criteria, a comparison of judgements with the pairwise comparison in order to achieve weights for the criteria, and a synthesis of priorities in order to make a decision i.e. selecting the best alternative [Saaty, 1987].

The pairwise comparison method is the fundamental part of the AHP method for decision making: it is used to derive ratio scales which represents the importance of each individual criterion. With pairwise comparison are the priorities for criteria established by judging criteria into pairs for their relative importance. When two objects are compared with respect to a property for which there is not an established measure or scale, a scale is derived by comparing two objects at a time, therefore: "in pairs".

Preferences for each criterion are rated on a scale with values ranging from 1 to 9. This scale is the *fundamental scale*, that is a mapping of objects to a numerical system, see Figure 4.6. So, to achieve the relative judgements, respondents are consulted via a questionnaire and are asked what is according to them the relative importance of each criterion.

All these comparisons result in a *pairwise comparison matrix*. Following the method of Saaty [1987, 2008], the scale of priorities of criteria (i.e. weights) is achieved by solving the principal eigenvector of the pairwise comparison matrix and then normalizing the result.

In this study on Hyperloop routes are various respondents asked for their judgements on the importance of criteria. In AHP, a judgement is a group judgement when judgements of several individuals are combined and a decision is made for a best alternative. Differences in group judgements are resolved through a consistency check as described in Saaty [1987]. The Excel template created by Goepel

| Intensity of Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal Importance | Two activities contribute equally to the objective |
| 2 | Weak or slight | |
| 3 | Moderate importance | Experience and judgement slightly favour one activity over another |
| 4 | Moderate plus | |
| 5 | Strong importance | Experience and judgement strongly favour one activity over another |
| 6 | Strong plus | |
| 7 | Very strong or demonstrated importance | An activity is favoured very strongly over another; its dominance demonstrated in practice |
| 8 | Very, very strong | |
| 9 | Extreme importance | The evidence favouring one activity over another is of the highest possible order of affirmation |
| Reciprocals of above | If activity $i$ has one of the above non-zero numbers assigned to it when compared with activity $j$, then $j$ has the reciprocal value when compared with $i$ | A reasonable assumption |
| 1.1–1.9 | If the activities are very close | May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities. |

**Figure 4.6:** The fundamental scale of absolute numbers for pairwise comparison. Figure from Saaty [2008].

| When taking the following types of infrastructure into account, on what type of infrastructure do you prefer the Hyperloop? | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| at a high risk infrastructure | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | **9** | at train tracks |
| at a high risk infrastructure | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | **9** | at the side of the highway |
| at a high risk infrastructure | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | **4** | 5 | 6 | 7 | 8 | 9 | at highways |
| at train tracks | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | **3** | 4 | 5 | 6 | 7 | 8 | 9 | at the side of the highway |
| at train tracks | 9 | 8 | 7 | 6 | 5 | 4 | **3** | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | at highways |
| at the side of the highway | **9** | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | at highways |

**Table 4.1:** Example of the Pairwise Comparison questionnaire for the Proof of Concept.

[2013] is used for calculating the weights of factors and consistency ratios for the pairwise comparison questionaries. This template is used to calculate importance weights for criteria in each of the three groups as defined in Chapter 3: infrastructures (4 criteria), buildings (7 criteria), and areas (6 criteria).

A respondent will be asked to complete the "Pairwise comparison questionnaire" as shown in Table 4.1. In this questionnaire, the respondent is asked which of two criteria is more important, and how much more important, with regard to a dependent variable, in this case the Hyperloop route. The respondent then indicates which spatial factor is more important to him or her by filling in a score which is taken from the fundamental scale shown in Figure 4.6.

For example, when comparing the spatial criteria *high risk infrastructure* and *train tracks*, if the respondent thinks it is extremely important that the Hyperloop should not cross an infrastructure which is characterized as high risk infrastructure – pipelines, gas-lines, etcetera – while crossing a train track infrastructure is not a problem, the respondent could decide to give a score of "9" at the side of train tracks. Then the respondent continues with the questionnaire until all pairwise comparisons are finished. The fictitious responses for this example are shown in bold.

### Consistency checks

Consequently, the consistency of the pairwise comparison as filled in by an individual respondent is validated. If the consistency ratio *CR* is below 0.10, the questionnaire results are consistent and correct. If the *CR* exceeds 0.10, then the question-

| n | RI (random consistency index) |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 0.58 |
| 4 | 0.90 |
| 5 | 1.12 |
| 6 | 1.24 |
| 7 | 1.32 |
| 8 | 1.41 |
| 9 | 1.45 |
| 10 | 1.49 |

**Table 4.2:** Random consistency index *RI* for various amounts of factors *n* included in the pairwise comparison. Source: Saaty [1987].

naire results are not consistent and should be reexamined or left out of the study [Saaty, 1987]. The consistency ratio *CR* is calculated as follows:

$$CR = CI/RI \tag{4.1}$$

Where *CI* is the consistency index and *RI* is the random consistency index. *CI* of Pairwise Comparison Matrix (PCM) and is calculated as follows:

$$CI = (\lambda - n)/(n - 1) \tag{4.2}$$

Where $\lambda$ is the eigenvalue of the PCM [Dijkstra, 2013] and *n* is the amount of criteria included in the pairwise comparison. *RI* from Equation 4.1 depends on the amount of criteria *n* included in the pairwise comparison and is taken from Table 4.2.

The consistency ratio *CR* for the pairwise comparison shown in Table 4.1 is $(-)0.07$ which is $< 0.10$. Thus the PCM from the example is consistent and can be included in the study. Consequently, the PCM of a response is included in one "general" PCM for all responses if the consistency check is satisfied. The Excel template created by Goepel [2013] is used to calculate the weights and consistency ratios for the responses in this study.

However, it is also possible that the answers from the respondents are not consistent. The Excel template of Goepel [2013] includes a feature which suggests modifications to weight scores which would lead to a consistent result. For example, as shown in Figure 4.7, changing a respondent's score from 6 (strong to very strong importance) to 2 (equal to moderate importance) makes the answers from this respondent consistent, i.e. a consistency ratio of 8% instead of 13%. This type of modification of the respondent's results is *only applied on the weight scales*. Thus, if it is suggested to change the more important criterion itself, e.g. A instead of B, the responses from the respondent will be excluded from the research.

In the supplementary dataset of this study (Pairwise Comparison responses and modifications.zip) are all modifications to the respondent's answers included, with similar figures as Figure 4.7. Overall, only two of the pairwise comparison matrices needed a change of the more important criterion itself in order to be consistent (and are therefore left out of the study). However, most of the matrices needed a (small) modification of the weight scales, in order to be consistent.

### Google Forms questionnaires

Respondents are asked to fill in the questionnaire via a Google Forms application. The responses to the questionnaire are then stored in an online spreadsheet. From there, the Excel template of Goepel [2013] is provided with the correct data. An example of the Google Forms application is available online (in Dutch[1] and En-

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[1] Questionnaire in Dutch: `https://forms.gle/mftb9AGDGED4VDDJ9`
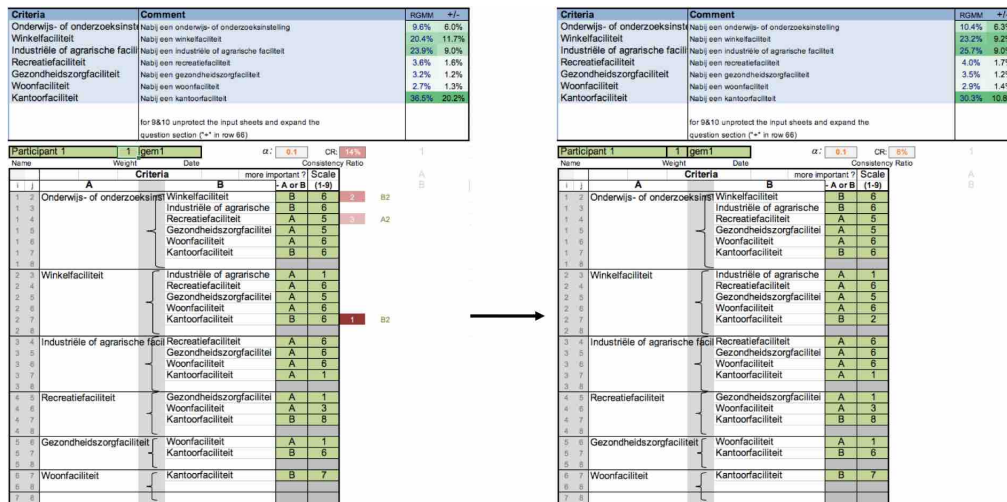
**Figure 4.7:** Example of how the "suggested modification" feature from the Excel template of Goepel [2013] leads to consistent responses.

glish[2]). See Figure 4.8 for a screenshot of the Dutch version of the Google Forms questionnaire.

Next to the pairwise comparison questions, the respondents are asked some general questions, regarding study background, organization type, age, and gender. The organization type is used to classify the respondent in a "stakeholder group". Four "stakeholder groups" are defined: *municipal government*, *provincial government*, *national government*, and *research institutions*. Within such a group are weights for the criteria aggregated. Besides, a fifth group – *all equal weights* – is added, whereby all criteria are assigned the same weight. Assumed that the weights for criteria differ between all these five groups, the goal with those "stakeholder groups" is to analyze how these different weights (i.e. different opinions regarding the importance of certain criteria) can yield different Least Cost Paths.

### *Calculating cost value for individual rasters*

The consolidated weights, which is the output of the Excel template by Goepel [2013], can *not* be directly applied on the raster datasets. That is because the responses (and thus also the weights) represent a *preference* while the raster dataset represents a *cost*. Instead, multiplying a weight with the pixel value from a cost raster should result in *lower* cost value for preferred features. Therefore, the cost value for a cell in a cost raster is computed as follows:

$$CostValue_{C_{xy}} = CellValue_{C_{xy}} * (1 - (WeightValue_C * \frac{NCriteriaInGroup_C}{NCriteriaTotal})) \quad (4.3)$$

Where $CellValue_{C_{xy}}$ is the initial value of a cell in a raster layer for a criterion $C$ on location $xy$, $WeightValue_C$ is the weight for that criterion $C$ from the pairwise comparison questionnaire, $NCriteriaInGroup_C$ is the amount of criteria in the group to which the criterion $C$ belongs (i.e. 4 in the Infrastructure group, 7 in the Buildings group, and 6 in the Areas group), and $NCriteriaInTotal$ is the total amount of criteria (i.e. 17). Then, the $CostValue_{C_{xy}}$ is the value of a cell in a cost raster layer for criterion $C$ on location $xy$.

The weighted raster layers are input for the Cost Surface raster maps, which is discussed in Section 4.7. But first, how are the raster layers for individual criteria created?

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2 Questionnaire in English: https://forms.gle/kgteicQQk45dxU9D9
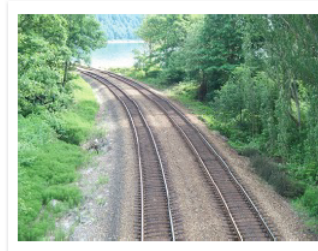
**Figure 4.8:** Screenshot of the Google Forms questionnaire.

## 4.6 RASTERIZATION

Maps in raster format were used in most of the reviewed articles on GIS–MCDA for transportation infrastructure route simulation or optimization [Bagli et al., 2011]. A map in raster format consists of a grid with evenly distributed cells that represent a value for each cell (or *pixel*). Input data for criteria are often objects in vector format. In the vector data format, criterion values are assigned to various spatial objects (or *features*). With GIS-MCDA the output maps should represent the overall values for that criterion and for each location in the study area [Malczewski and Rinner, 2015]. Therefore, the features in vector format should be converted to pixels in raster format, covering the whole study area.

Later in the process are those individual raster maps combined in a Cost Surface. Thus, the Cost Surface is a map in raster format which consists of cells who are assigned values which represent the cost of movement across them [Stefanakis and Kavouras, 1995]. Each cell is assigned a cost which represents how "expensive" it is to cross that cell [Bagli et al., 2011].

The raster data map will have a certain *cell size* (or pixel size). The conversion from vector to raster data formats is called *rasterization*. In the context of this research, there are now two topics discussed with regard to rasterization: cell size and buffer size.

| Cell size (m) | Pixels X | Pixels Y | Area | Datasets | Process time |
|---|---|---|---|---|---|
| 50 | 1384 | 646 | Study area | 17 | < 1 minute |
| 40 | 1730 | 808 | Study area | 17 | < 1 minute |
| 30 | 2307 | 1078 | Study area | 17 | < 1 minute |
| 25 | 2768 | 1294 | Study area | 17 | < 5 minutes |
| 20 | 3460 | 1618 | Study area | 17 | < 5 minutes |
| 12.5 | 5536 | 2590 | Study area | 17 | 5-7 minutes |
| 10 | 6920 | 3238 | Study area | 17 | 5-10 minutes |
| 7.5 | 9226 | 4318 | Study area | 17 | 15-25 minutes |
| 5 | 13839 | 6477 | Study area | 17 | 35-45 minutes |

**Table 4.3:** Raster cell size and processing times.

### 4.6.1 Cell size

In general, a smaller cell size leads to more cells in the map and therefore longer computation time, while choosing a larger cell size would lead to the disappearance of semantic or geometric information. What would be the ideal cell size for the raster maps, in this research?

As a general method for choosing the correct cell size, Zlatanova et al. [2016] advice: the size of cells (2D) and voxels (3D) should be smaller than the size of the actual objects to be represented. The size of objects to be represented depends on the application, and can range from fine (e.g. 0.1m for representing building interiors) to coarse (e.g. 100m for representing geological features).

In Table 2.4 are also the specified cell sizes of the used Cost Surface maps included, ranging from 5m to 1000m. In the example studies, the chosen cell size depends on the size of the study area (i.e. the larger the study area, the larger the cell size), or the size of the geometries of the attributes that represent the infrastructures (e.g. the impact of a highway in Keshkamat et al. [2009] or the width of a bicycle road in Terh and Cao [2018]), or the resolution of input (raster) datasets (e.g. the Digital Elevation Model (DEM) in Durmaz et al. [2019] has a resolution of 30m, and therefore 30m was chosen as cell size for their cost surface).

In this study the raster size for the cells would ideally be 5 m. That corresponds to the width of the passenger version of the Hyperloop tube as explained in the original white paper for the technology, as described in SpaceX [2013]. Namely, the width of the passenger version is 2.23m (inner diameter of the tube) plus 0.04m (two tube walls) plus 0.5m (space between two tubes), thus 5.04m in total. Following the rule from Zlatanova et al. [2016] that "the size of voxels (and also for pixels) should be smaller than the size of the actual object to be represented", the 5m resolution for the raster cells is chosen. Each input (vector) data map is converted into a raster map using the *gdal_rasterize*[3] utility which is available in the open-source GIS software QGIS3.

A disadvantage of the 5m cell size is the long computation time for calculating the Least Cost Path. The computation time for calculating this most optimal path through the raster map increases exponentially, see Table 4.3.

### 4.6.2 Buffer size

Creating a buffer around features in a spatial layer is a solution to a problem which could emerge with rasterization. This problem emerged during testing with the Proof of Concept for this study. Namely, if a feature in vector format has a small size, it could disappear when it is rasterized: also when the cell size of 5 meter was chosen. Especially the criteria that belong to the *building* group as discussed in Chapter 3 have a relatively small size.

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3 GDAL rasterize utility: `https://gdal.org/programs/gdal_rasterize.html`

Therefore, the features in vector format will first be enlarged by making a buffer of a predefined size, before they are rasterized. In this study is the buffer size set at 25 meter. See the maps in Figure 4.9 for an example.

The buffer size of 25 meter is chosen because it ensures that (most of the) smaller building features will be included in the study. Besides solving the "disappearance problem" with rasterization, the enlargement of vector features with a buffer has an other advantage. Namely, it will minimize the chance that a calculated optimal *Hyperloop* route is attached to an existing building. And it will minimize the chance that a Hyperloop will cross a typical backyard in a Dutch neighborhood, which goes back 10 to 20 meters.
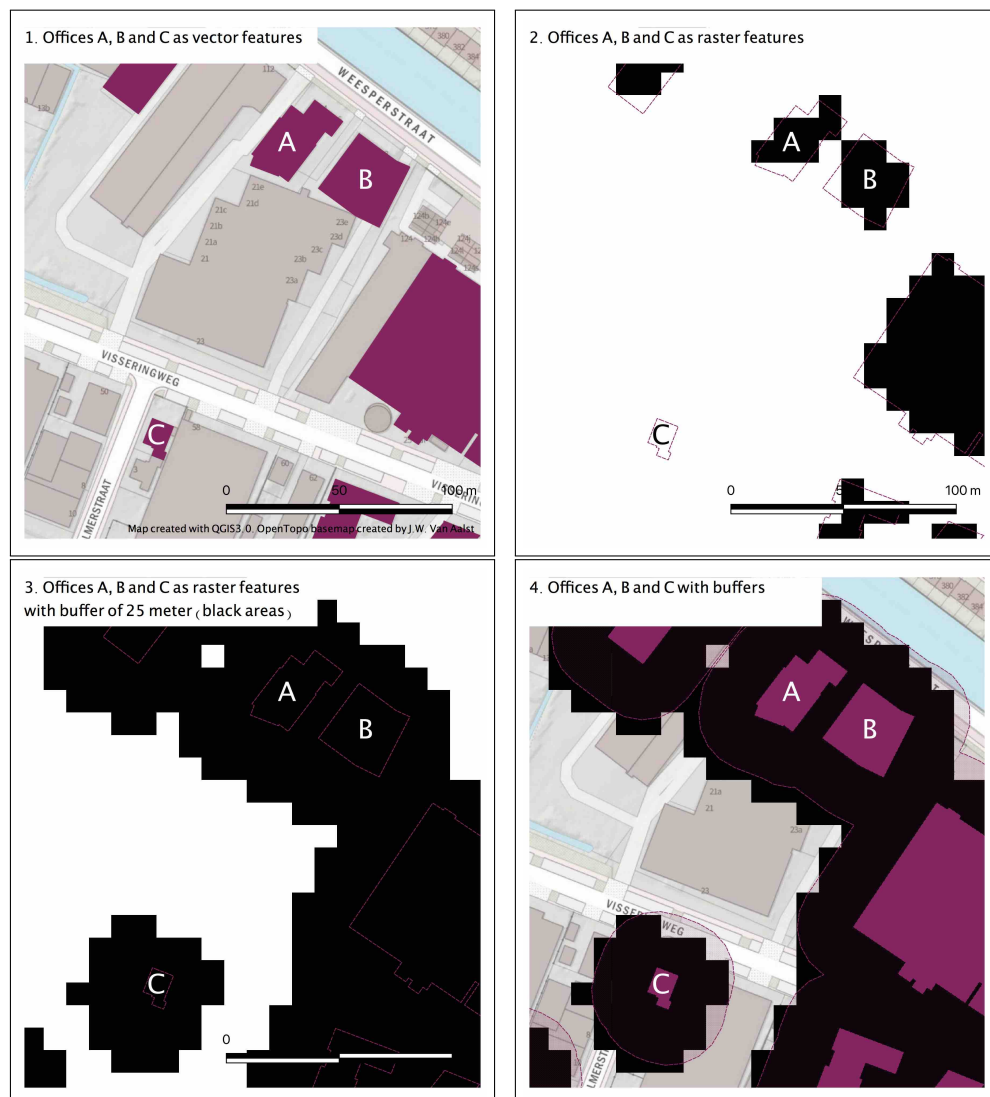


Figure 4.9: **Map 1:** Offices A, B and C as vector features.
**Map 2:** Rasterized map, without a buffer applied. Offices A and B are still included on the map, as black pixels, while office C disappeared.
**Map 3:** Rasterized map, with a buffer applied. Offices A, B and C are all still visible on the map.
**Map 4:** Shows all features from this example: the vector features in purple, the 25m buffer around it, and the rasterized layer.

## 4.7 COST SURFACE MAPS

The Cost Surface is a raster map for which each pixel value represents the sum of the individual cost raster pixel values, taking into account their weights. In other studies could this cost surface have different names, for example impedance map in Grossardt et al. [2001] or suitability map in Karlson et al. [2016] and Keshkamat et al. [2009], although it contains the same type of information: each pixel in the raster map indicates a suitability score based on the established scenarios and relationships between the individual criteria. In this study, there are 17 individual criteria, beloning to one of three groups, and having a relationship that is expressed in an 'importance' or 'weight'.

See Figure 4.10 for a schematic overview of how the datasets are combined into one cost surface. First, in each group are the individual raster maps that belong to the same group summed. Consequently, these intermediate group-cost surfaces are summed, resulting into one cost surface. Thereafter, the cost surface is input for the Least Cost Path algorithm.
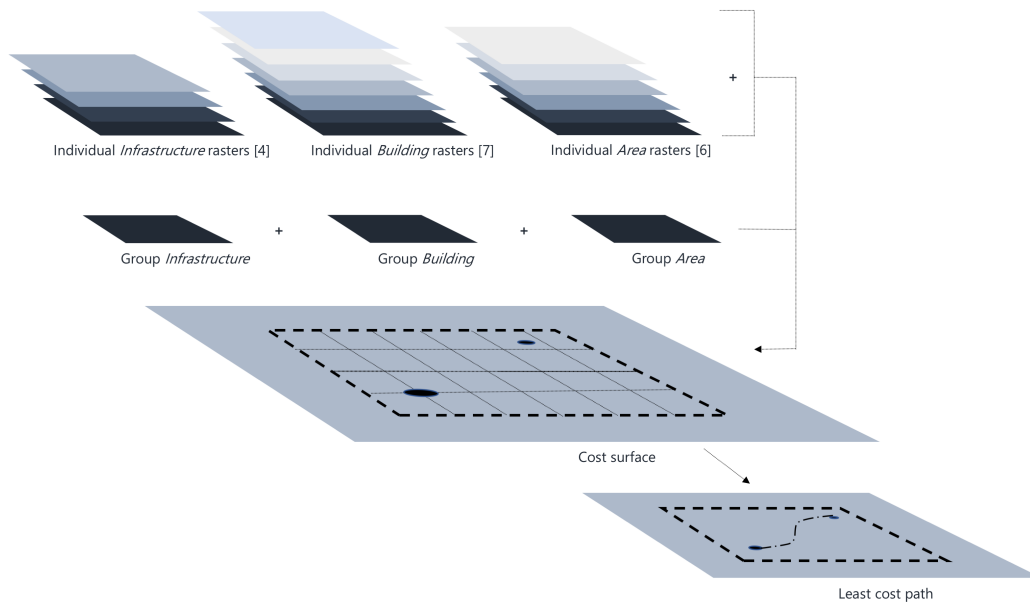


**Figure 4.10:** Creation of a Cost Surface map from individual raster layers. Afterwards, the Least Cost Path is calculated from the Cost Surface.

## 4.8 CALCULATING A ROUTE FROM A COST SURFACE

The minimum cost to cross a surface between two locations can be identified with Least Cost Path analysis [Karlson et al., 2016]. LCP starts at the origin pixel and from there every neighboring cell is evaluated. The path moves to the next pixel with the smallest accumulated value. That process continues until the origin pixel and destination pixel are connected with each other, by the Least Cost Path. Thus, in theory, if all pixels in the Cost Surface were assigned the same value then the least cost path equals the shortest path [Karlson et al., 2016].

In this study is the LCP algorithm *Least Cost Path*[4] used. It is provided as an open-source plugin for QGIS3, thus free of charge. The plugin utilizes the Dijkstra algorithm that is often applied for creating a path on an accumulated cost surface

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4 Repository for Least Cost Path plugin: `https://github.com/Gooong/LeastCostPath`

[Grossardt et al., 2001]. In the terminology of the plugin, Lelystad Airport is selected as start-point layer and Schiphol Airport as end-point layer. The plugin requires the following data:

- Cost raster layer. This is the Cost Surface, which is calculated from the 17 individual criteria and their weights. For example: `SUM_all_5_aligned_buffer25_groupC`.

- Cost raster band. The input band of the cost raster. By default this is `Band1`.

- Start-point layer: A layer which contains only one point feature. In this study, this is the shapefile `Origin`, which is Lelystad Airport.

- End-point(s) layer: A layer which contains at least one point feature. In this study, this is the shapefile `Destination`, which is Schiphol Airport.

- Output least cost path: The name of the output file. In this study, the output file name is structured as follows: For example: `LCP_5_aligned_buffer25_groupC_OD`.

All input data must have the same Coordinate Reference System (CRS). In this research is the Dutch national CRS *RD New* (EPSG:28992) used for all input data.

## 4.9   EVALUATION OF CALCULATED LEAST COST PATHS

Finally, the total accumulated cost of the Least Cost Paths is calculated. Since this study uses the "area oriented" approach, as conceptualized by Heeres et al. [2012] and discussed in Section 3.1, the "best" route will be the route with the lowest "cost" value. That route will be – in theory – the most suitable when taking criteria from the surrounding area into account.

In Chapter 5 are results for Cost Surface maps and Least Cost Paths discussed and evaluated, and the Least Cost Paths that obey requirements of Hyperloop infrastructure are discussed. Since the methodology as described in this research contains some parameters which could affect the outcome, such as the weights for criteria per response group, the raster cell size for individual rasters and Cost Surface maps, and buffer sizes around "building" features, it is not possible that this research will yield "one best Hyperloop route". Instead, this research will yield a variety of "best Hyperloop routes", depending on the specific configuration of those parameters.

The variety of possible Least Cost Paths for the Hyperloop is illustrated in Figure 4.11. The dots in the bottom part of the figure refer to the applied weight groups, defined as A, B, C, D, and E. Each group has a distinct color scheme.

- Group A: All equal weights

- Group B: Weights from municipal governments

- Group C: Weights from provincial governments

- Group D: Weights from national governmental institutions

- Group E: Weights from research institutions
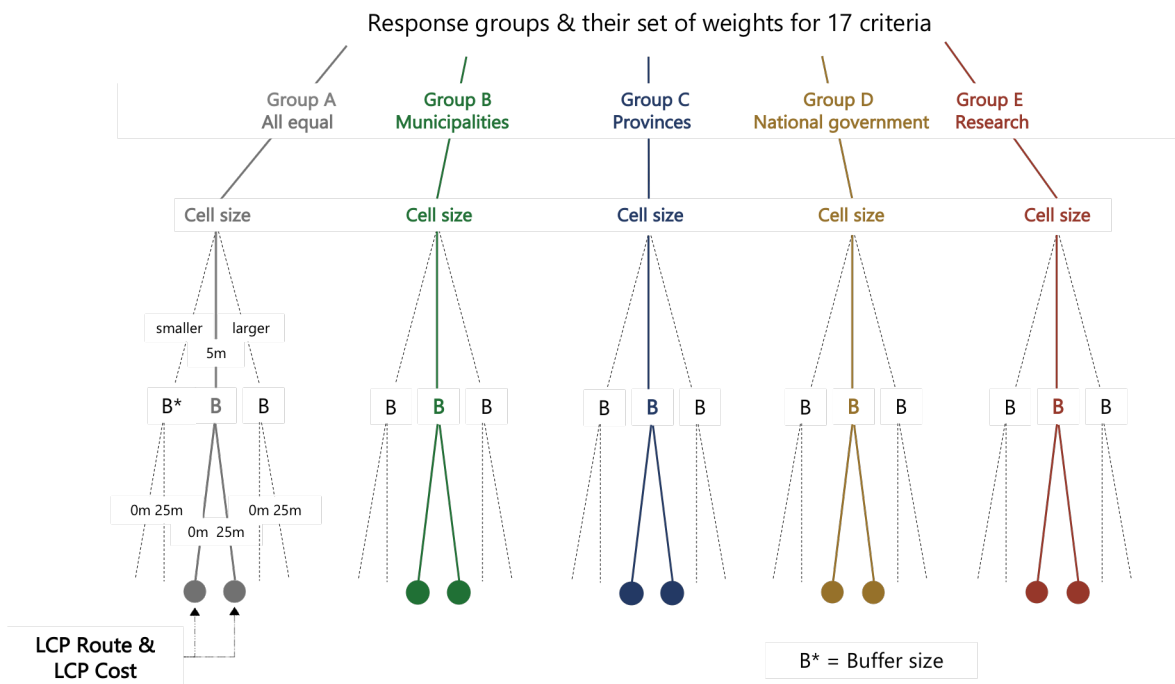
**Figure 4.11:** The variety of possible Least Cost Paths for the Hyperloop, taking the parameters into account as defined in this research (various weights for criteria, the pixel size of the rasters, and buffer size around "building" type criteria). The dots represent an outcome: LCP Route and LCP Cost. The colors of the dots clarify which weight group is applied to the resulting LCP.

## 4.10 LEAST COST PATH THAT OBEYS REQUIREMENTS OF HYPERLOOP INFRASTRUCTURE

Until so far is in this study the "area oriented" approach used to assess the quality of suggested routes for the Hyperloop. From now, the "line oriented" approach will be used, so the (Hyperloop) infrastructure itself is considered – and not the area surrounding the infrastructure. Other performance metrics are now relevant: the total length of the infrastructure, maximum bend radius, and straightness of the infrastructure.

Total length of the infrastructure will directly influence monetary construction costs. This metric is calculated with the native GIS function *length*[5].

In Section 4.4 are requirements for Hyperloop infrastructure discussed. One of these is the maximum bend radius. If the maximum bend radius of a suggested LCP is smaller than 1.6km (for 480 km/h), the suggested LCP is excluded from further analysis.

Straightness of a line feature can be expressed with the *sinuosity* metric. Sinuosity is a concept used in hydrology and river studies [Mueller, 1968] and has also been used as evaluation metric for transportation infrastructure [Gutiérrez et al., 1998]. It measures deviation of a line from the shortest path between two points, and is calculated by dividing total length by the shortest possible path[6]. A straight line will have a sinuosity index of 1, and the larger the index the less straight the infrastructure.

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5 Length https://docs.qgis.org/2.14/en/docs/user_manual/working_with_vector/field_calculator.html
6 Sinuosity https://www.arcgis.com/home/item.html?id=00e708a448b74810a0e805c4a97f9d46

## 4.11   CONCLUSION METHODOLOGY

In this chapter is the methodology discussed which will be used to answer the main research question. The study area for the Hyperloop in the Netherlands between Lelystad and Schiphol, criteria that are involved in this GIS-MCDA application, requirements of Hyperloop infrastructure, a method in order to define the importance of individual criteria, creation of cost rasters, calculation of Least Cost Paths, and evaluation considerations, have all been covered in previous paragraphs. The next Chapter 5 include the results of the implemented methodology.

In the remainder of this report are only possible LCP routes that are created from Cost Surfaces with cell sizes of 5 meter and buffer sizes of 0 and 25 meter discussed.

# 5 | RESULTS AND DISCUSSION

In Chapter 3 are 17 criteria selected to include in this case study for finding routes for Hyperloop in the Netherlands. Applying the methodology described Chapter 4 will yield a variety of results. In this chapter are first the results from the online questionnaires discussed. Then, the Cost Surface maps are discussed in Section 5.2, followed by a discussion on the results for the Least Cost Paths in Section 5.3. Consequently, a possible integration of the results of this study into the Dutch Planning procedure for large infrastructure projects – Tracéwet – is discussed. The remainder of this chapter elaborates on drawbacks of this methodology (Section 5.4).

## 5.1 QUESTIONNAIRE INVITATIONS AND RESPONSES

Public organizations invited to fill in the questionnaire were all located in the study area for this research: between Lelystad and Schiphol. In total 31 organizations were invited, of which 16 were municipalities, 3 provinces, 7 national public organizations, and 5 research organizations or individuals. The data collection period of three weeks took place between November 18th 2019 and December 9th 2019. In the last week, a reminder email was sent to all organizations.

This resulted in a total of 16 responses, of which 6 responses were from municipalities, 3 from provincial governments, 4 from national governments, and 3 from research organizations. Then, using the respondent's answers, the weights for criteria were determined. For each group (municipalities, provinces, national governments, research) were *consolidated* weights from the Excel template of Goepel [2013] used. The consolidated decision matrix combines all participant's decision matrices into an aggregated group result by calculating the weighted geometric mean[1]. The consolidated weights per response group and per category (infrastructure, building, area) are shown in Figure 5.1.

## 5.2 COST SURFACES ON THE MAP

Implementing the methodology as described in the previous chapter resulted in a variety of cost surfaces and Least Cost Paths. Figure 5.2 and Figure 5.3 show the Cost Surface maps for the five weight groups (all equal weights, municipalities, provinces, national governmental institutions, and research institutions). These five Cost Surface maps have a cell size of 5 meter and a buffer of 25 meter around building features, as discussed in the methodology and illustrated in Figure 4.11.

In the Cost Surface maps are suitable and unsuitable areas for Hyperloop infrastructure depicted. Suitable locations have a low cost and are symbolized by the colour green, while unsuitable locations have a high cost and are symbolized by the colour red. Locations with intermediate costs are depicted by colors of the gradient between green and red. The minimal cost value for each pixel is 1, the maximum cost value was found in the map from group E. All maximum pixel values are around that value (ranging from 6.64 to 6.71). In the remainder of this section are

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1 AHP Excel template version 2018 based on Goepel [2013]: https://bpmsg.com/new-ahp-excel-template-with-multiple-inputs/

more remarks regarding the Cost Surface maps discussed. See Figure 5.3c for the locations of some named geographic features in this discussion.



**(a)** Infrastructures



**(b)** Buildings



**(c)** Areas
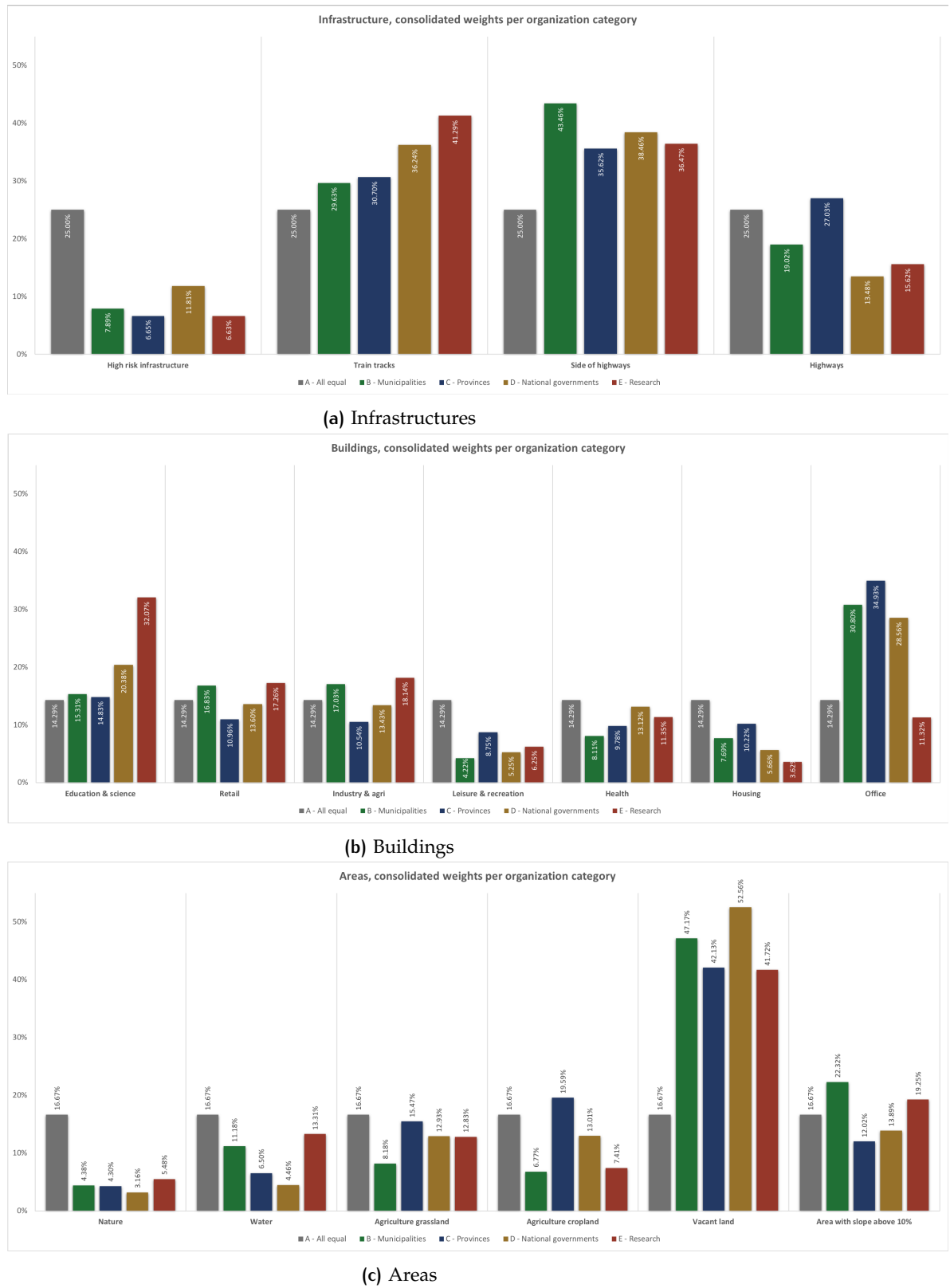
**Figure 5.1:** These bar charts indicate the consolidated weights per criterion and per response group (all equal weights, municipalities, provinces, national government, research).
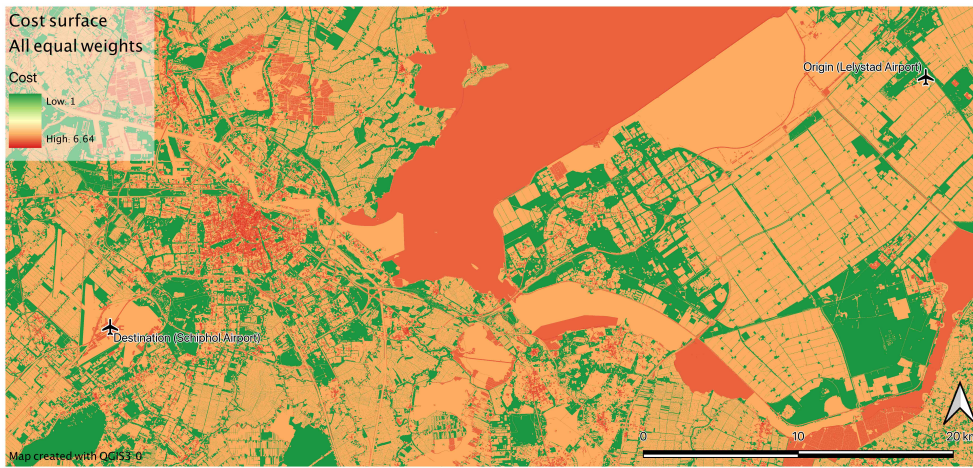
**(a)** All equal weights
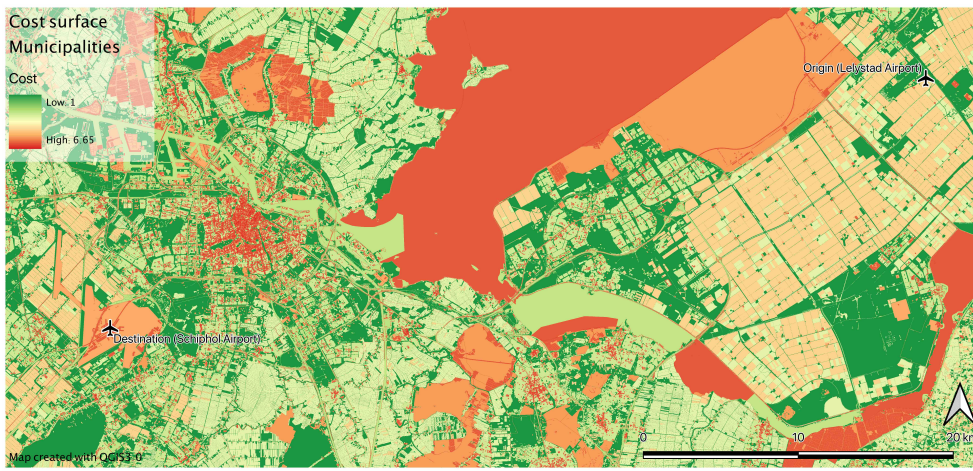


**(b)** Weights from municipal governments
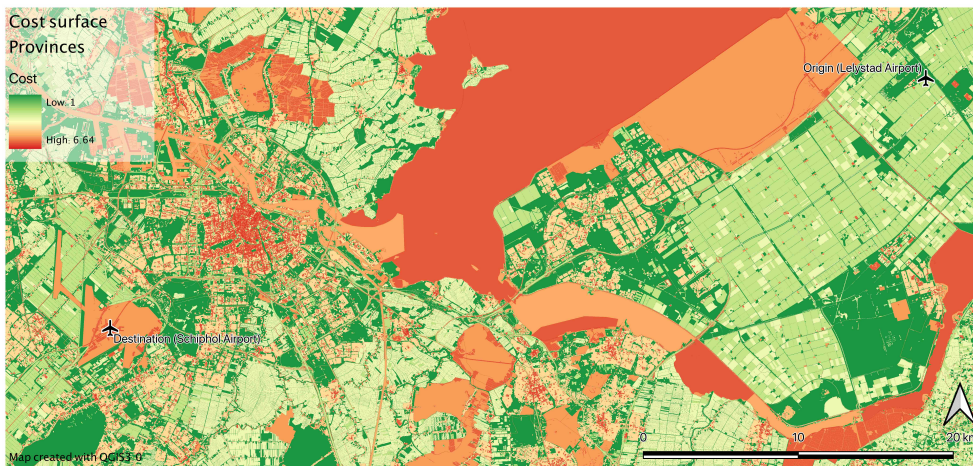


**(c)** Weights from provincial governments

**Figure 5.2:** Cost surfaces when various weights are applied: All equal weights, weights from municipalities, and weights from provinces.
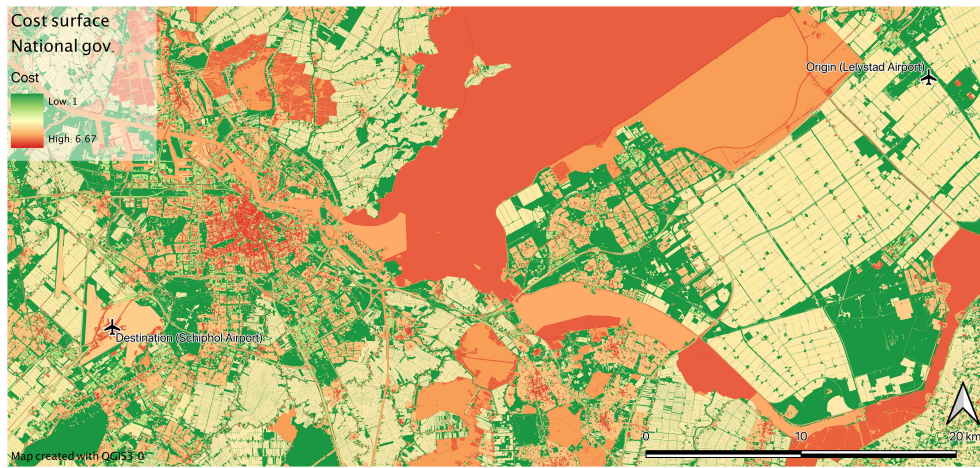
**(a)** Weights from National governmental institutions
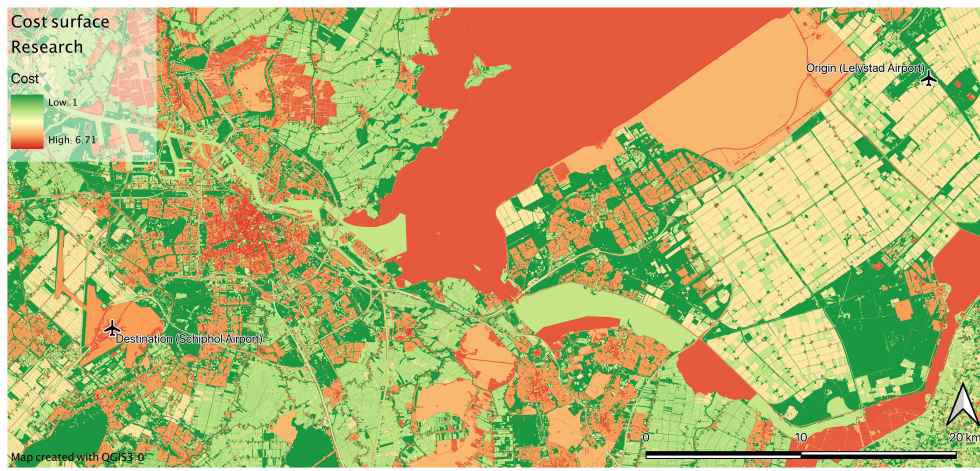


**(b)** Weights from Research institutions



**(c)** Named geographic features in the study area. The waterways *Vecht*, *Amsterdam Rijnkanaal*, *Ringvaart*, and the water bodies *Gooimeer* and *IJmeer* can be considered as obstructions or bottlenecks.

**Figure 5.3:** Cost surfaces when various weights are applied: weights from national governmental institutions and weights from research institutions.

First, the Markermeer and IJmeer lakes have a high cost value in all five maps. That is because these lakes are water bodies and at the same time nature areas.

Secondly, cities are distinguishable in all five maps, since there are more overlapping criteria at those areas. However, the city (center) of Amsterdam is better

| | Parameters (V2) | | | Results LCP | | | |
|---|---|---|---|---|---|---|---|
| UID | Weight group | Cell (m) | Buffer (m) | Cost | Length (m) | Sinuosity | Computation time |
| A1 | A (all equal) | 5 | 25 | 13562.124302 | 62076 | 1.127614 | 39 (minutes) |
| B1 | B (municipalities) | 5 | 25 | 13580.420077 | 62167 | 1.129266 | 47 |
| C1 | C (provinces) | 5 | 25 | 13584.107405 | 62142 | 1.128818 | 41 |
| D1 | D (national gov.) | 5 | 25 | 13581.930329 | 62146 | 1.128893 | 41 |
| E1 | E (research) | 5 | 25 | 13584.173168 | 62167 | 1.129266 | 40 |
| A2 | A (all equal) | 5 | 0 | 13295.810147 | 61323 | 1.113932 | 41 |
| B2 | B (municipalities) | 5 | 0 | 13315.018710 | 61368 | 1.114762 | 40 |
| C2 | C (provinces) | 5 | 0 | 13315.505604 | 61323 | 1.113932 | 41 |
| D2 | D (national gov.) | 5 | 0 | 13313.118981 | 61323 | 1.113932 | 40 |
| E2 | E (research) | 5 | 0 | 13315.484868 | 61323 | 1.113932 | 40 |

**Table 5.1:** Least Cost Path results for various parameter values.

visible than Almere, which could be a consequence of more mixed functionalities and facilities in Amsterdam than in Almere.

Schiphol Airport is in all five maps displayed as an area with high cost, while Lelystad Airport is not defined as an area with high cost. That is because the whole terrain of Schiphol is included in the "High Risk Infrastructure" layer, while the terrain of Lelystad Airport is not.

The "All equal weights" group A map has a large amount of locations with an intermediate-to-high cost value (colored orange). The other four maps show more large areas with relatively low cost (colored light yellow and green). This can result in a relatively high accumulated cost value for the LCP when the weights from group A are applied.

Finally, between the provinces of Flevoland and North Holland is a water body called Gooimeer. In the Cost Surface maps for A (al equal), C (provincial), and D (national governments) is the cost of this area high, while low in the other two Cost Surface maps. That could lead to various locations where the suggested LCP route for the Hyperloop crosses the Gooimeer.

## 5.3 LEAST COST PATHS

Using the Least Cost Path algorithm as discussed in the methodology, the least cost paths between origin Lelystad Airport and destination Schiphol Airport are calculated for the five Cost Surface maps. Table 5.1 shows the accumulated "cost" value and the needed computation time for all 10 calculated LCP. For both building buffer size groups (25m and 0m), the LCP which is computed with the weights from group A (all equal weights) has the lowest cost value. The routes which are calculated with weights from group B, C, D, and E have a similar cost value, with a maximum difference of 3. The performance metrics *length* and *sinuosity* of the calculated routes are all between 61.3-62.2 kilometers and 1.11-1.13, respectively. So the calculated Least Cost Paths are not equal to the shortest path that is possible in the study area, which is a straight line of 54 kilometer from origin to destination (Figure 4.1). At the same time, with sinuosity values ranging from 1.11 to 1.13 the routes are classified as moderately 'sinuous' [Mueller, 1968].

The 10 calculated routes are also illustrated on Figure 5.4. For each of the five weight groups (A, B, C, D, E) are two Least Cost Paths included in the map: one LCP whereby a buffer of 25 meter around building features in the Cost Surface was applied (visualized with solid lines), and one without buffer around those building features (visualized with dotted lines).
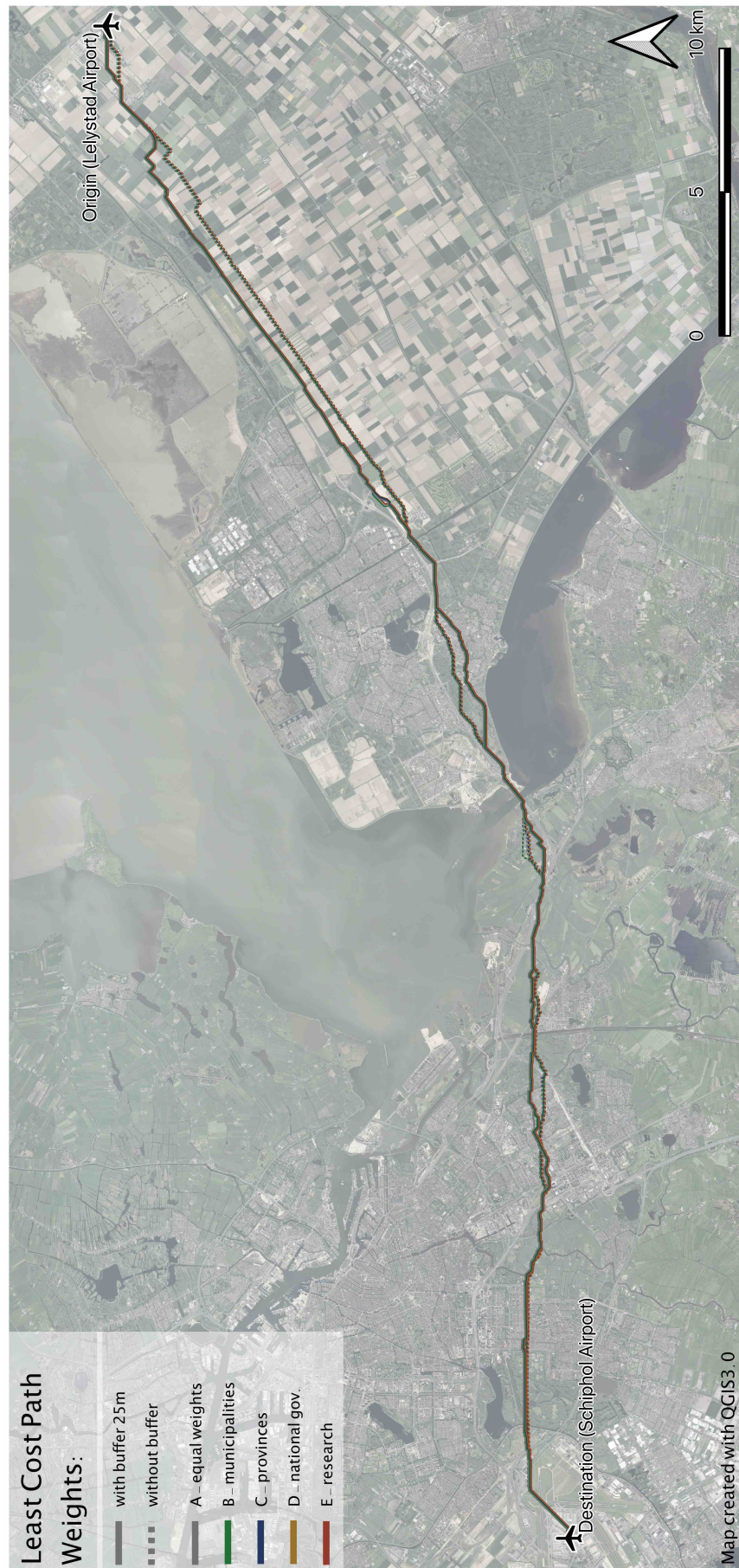
**Figure 5.4:** Least Cost Paths for five weight groups.
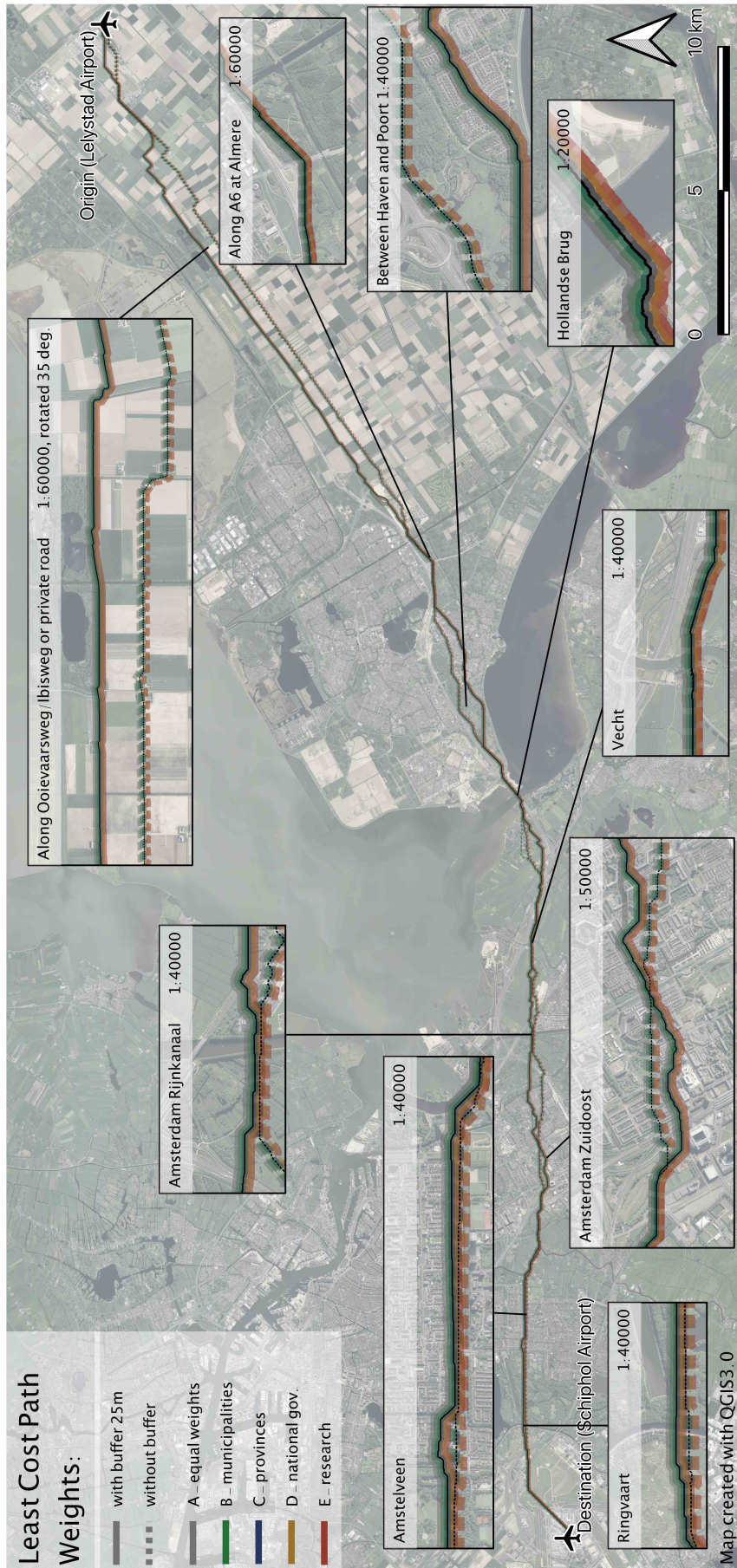
Figure 5.5: Least Cost Paths for five weight groups, including detail maps at locations discussed in Section 5.2.

When inspecting the results shown in the column **Cost** in Table 5.1, different weight groups do not necessarily result in different suggested routes, using this methodology. The difference between the scenario where no weight is applied (A) is larger. And applying the buffers around building features also has a (much) larger effect on the Cost value of an LCP, instead of applying weights for criteria. On the map of Figure 5.4 are these small differences between the calculated routes also visible: all ten Least Cost Paths describe roughly the same route. There is no location in the study area where the suggested routes are more than 1000 meter apart from each other. Thus, applying different weight groups to the criteria did not yield major differences in suggested routes.

The Least Cost Paths are now discussed by analyzing where the calculated routes are placed in the study area. This discussion starts at the origin (Lelystad Airport) and follows the routes until the destination (Schiphol). Figure 5.5 includes zoom maps with more detail.

1. Calculated LCP routes in Flevoland are mainly parallel with existing roads. Some routes are closest to the Ibisweg or Ooievaarsweg, other suggested routes follow a private road. When in the city of Almere, the routes are mainly bundled with the A6 highway. From the river "Vecht" onwards, the suggested routes are less bundled with the existing highways.

2. The Hyperloop route has to cross the water body "Gooimeer/IJmeer" between the provinces of Flevoland and North Holland somewhere. All suggested routes cross this water body at exactly the same location: using the existing bridge "Hollandse Brug" between those provinces (see zoom map "Hollandse Brug" in Figure 5.5).

3. The place where the river "Vecht" is crossed is also at the same location for each of the suggested routes: around 250 meter south of the aquaduct "Vechtzicht", with the A1 highway.

4. Also the location where the Hyperloop could cross the canal "Amsterdam Rijnkanaal" is roughly the same for all 10 suggested LCP routes: around 400 meters south of the existing "Muiderspoorbrug" railway bridge over that same canal.

5. All ten calculated routes cross neighborhoods in Amsterdam Zuidoost. This is a relatively densely populated area, see Figure 5.6. It might be a better option to built Hyperloop infrastructure (partly) below ground at densely populated areas.

6. Over the 12 kilometers through Amstelveen, roughly the part of the route between Amsterdam-Zuidoost and Schiphol, crossing the municipality of Amstelveen, there is a minimal difference between the suggested LCP routes. All suggested routes cross the area along a 100 meter wide strip parallel with the river "Kleine Wetering".

7. The location where the Hyperloop can cross the canal "Ringvaart" is also the same for all 10 suggested routes.

Thus, for a large part are the calculated Hyperloop routes parallel or bundled with existing (highway) infrastructure. And the places where the Hyperloop intersects with major waterways in the study area are similar for all 10 routes: the used methodology does not result in a variety of options for these "bottlenecks".

**Figure 5.6:** Least Cost Paths and population density, south of Amsterdam.
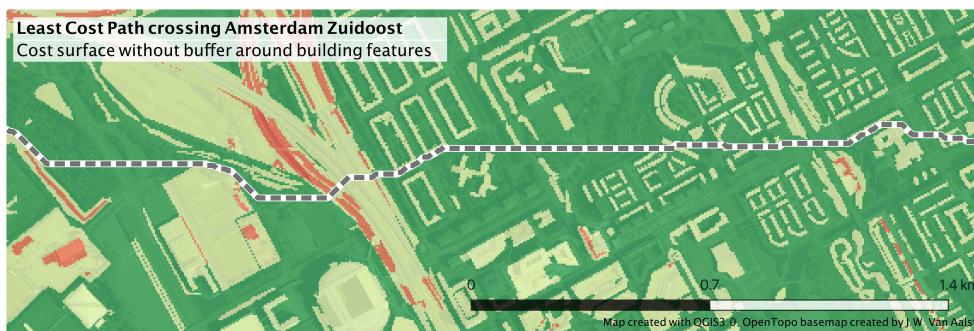


**(a)** Cost Surface Map without buffer around building features
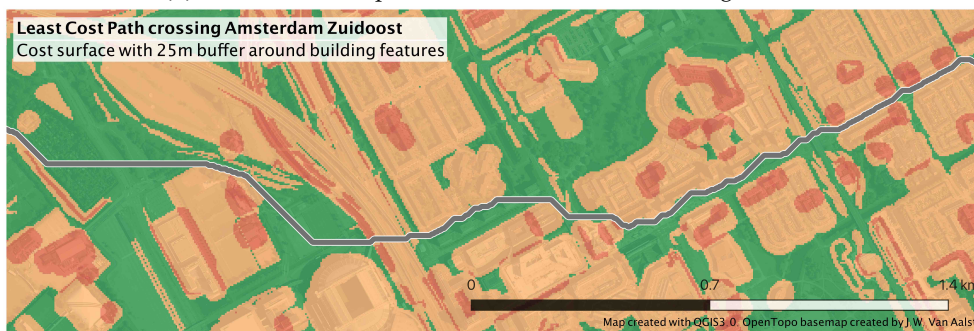


**(b)** Cost Surface Map with buffer of 25 meter around building features

**Figure 5.7:** Effect of buffers around building features on the resulting Least Cost Paths.

As mentioned, the largest differences between the suggested routes are a consequence of applying the buffer of 25 meter around building features. See for example zoom maps "Between Haven and Poort" and "Amsterdam Zuidoost" in Figure 5.5. It seems that the buffer parameter has more influence in outcomes than the criteria weight parameters. That can be explained by the fact that a buffer around features can "block" a whole area: then specific areas are not "suitable" anymore to be used for LCP routes. That is shown clearly in Figure 5.7: while the LCP that was created from a Cost Surface without buffer around building features crosses the Bijlmer

area in Amsterdam Zuidoost in a relatively straight line, from right to left, the LCP that was created from a Cost Surface *with 25 meter buffer* is *avoiding* some of those "empty" areas.

It is therefore suggested to investigate the influence of this buffer parameter more. For example: what will be the result of using a parameter of 5, 10, 50, or 100 meter instead of the applied 25 meter? However, investigating and solving this problem is not the scope of this research. Namely, the 25 meter buffer was applied because it overcomes the problem of 'disappearing building features', as discussed in Section 4.6.1: the buffer was not applied with the intention of being a parameter which would influence the LCP outcome significantly. To conclude, a suggestion for solving the 'disappearing building features' problem is to use a buffer of 5 meter, which is the same as the cell size in this study. Then, all building features would be included in the analysis while at the same time the effect of using the larger features is minimized.

## 5.4 INTEGRATION WITH DUTCH PRACTICE OF DESIGN-ING TRANSPORTATION CORRIDORS

The output of this study is a collection of suggested routes for Hyperloop infrastructure. This whole study and the outputs are hypothetical: there are no specific plans of constructing a Hyperloop between the mentioned locations. Like the research project by Arup et al. [2017], this was also an explorative study.

However, how usable are the results of this methodology for designing transportation corridors? In other words, how can these results be integrated in the Dutch planning practice? In Dutch law, the *Tracéwet* covers decision-making regarding construction of new infrastructures which are of national interest[2]. The Tracéwet planning procedure for a new road, rail or waterway infrastructure contains the following steps:

1. **Startbeslissing (start decision)**. A problem with regard to transportation infrastructure, as a consequence of a lack of infrastructure, is defined. The start decision includes the geographic area (study area), relevant spatial developments in the area, the procedure for how the public, civil society organizations, and governments are going to be involved, and a time planning.

2. **Verkenning (exploration)**. How can the problem be solved? Relevant data and information regarding the study area, the type of problem, relevant spatial development, and possible solutions are collected.

3. **Voorkeursbeslissing (preferred decision)**. The results of the exploration phase leads to a preferred decision for solving the problem. Possible effects on the environment are also investigated and shared in this phase of the Tracéwet. The public and public organizations have the possibility to respond on the contents of the preferred decision.

4. **Ontwerptracébesluit (draft tracé decision)**. The preferred decision is investigated more in depth. Also, an environmental impact report is composed in which expected effects of the project on the environment are described.

5. **Tracébesluit (tracé decision)**. The responsible Minister makes the definitive tracé decision. Involved provinces and municipalities have to adjust the zoning plans in such a way that the project can be realized.

6. **Realisatie (realization/construction)**. All procedures are completed, financial resources are available: the realization of the project can start.

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2 Tracéwethttps://wetten.overheid.nl/BWBR0006147/2017-05-01

7. **Oplevering en monitoring (delivery/completion and monitoring)**. After realization of the project, an Environmental impact assessment is done, in which the effects of the realized infrastructure are consistent with the expected effects.

The methodology as described in this research can be part of the exploration phase. There, the relevant data and information for the study area is collected. This is relatable to the step where – in this research – the relevant criteria are selected, i.e. Chapter 3. It is possible that in another setting other criteria are considered relevant, instead of the 17 criteria as defined in this research. Moreover, another possible solution can be suggested, instead of the Hyperloop (e.g. a conventional (rail) road, a high-speed railroad, maglev, etcetera). Another possible solution will also have other requirements (Section 3.1). Consulting the public and experts – as done with the questionnaires in Section 4.5 – could also be a relevant part in the exploration phase.

LCP routes themselves, which are output of this research, can be valuable input for the third step in the Tracéwet: Preferred decision. The distance between suggested routes and currently existing areas, infrastructure, and buildings can be calculated. Risk analyses can be performed. Related municipalities and provinces can explore if the suggested routes can possibly fit in existing zoning plans. And designers and construction engineers can put effort in finding solutions to the issue of integrating the infrastructure in local areas. This can all be included in a GIS environment, which features large storage capabilities, processing power, visualization options, and covers the whole study area.

Since the public and public organizations have the possibility to respond to the preferred decision (step 3), and since it is unlikely that a suggested LCP route will fit in all zoning plans without any adaptations, the output of this research can not be used for the next steps of the Tracéwet procedure (steps 4 to 7). However, new insights and discussion, for example regarding which criteria to include, which criteria are important, and/or origin and destination terminals, can lead to an adapted set of criteria, weights, and/or terminal locations. A re-calculation of Cost Surfaces can lead to new Least Cost Paths, thus new suggested routes. Therefore, this methodology can be a (valuable) part of an *iterative* process for finding optimal routes.

## 5.5 DRAWBACKS OF THIS METHODOLOGY

One drawback of the designed methodology is the amount of pre-processing steps that are needed before the datasets can be used in a Cost Surface map. If there is data available in the first place, it has to be converted into individual raster format files, before it can be combined in a cost raster. During all those relatively repetitive steps something can go wrong, and errors with for example one raster layer are difficult to find if all (in this study 17) individual datasets are combined into a cost raster. Therefore, it is important to store the intermediate results in a clear storage-structure.

Further, the proposed methodology included a finite set of 17 criteria. Those criteria were included in other research in the field of GIS-MCDA for infrastructure corridor planning, as discussed in chapter Chapter 2. However, using a different set of criteria could result in different suggested routes for the (Hyperloop) infrastructure. Therefore, it is unknown if the 17 criteria – and the suggested routes – are "good". This research showed how it can be done with this set of criteria that suits this study and the study objective. Other research could apply the same methodology for the same objective with a different set of criteria. Or apply the same methodology for another objective with a different set of criteria.

Another drawback is the computation time for calculating the Least Cost Path with the Dijkstra algorithm. With the decrease of the cell size of the cost raster, the computation time for the Least Cost Path increases exponentially, see Figure 5.8. Since there was a high-performance computer available (with an i7 processor with 8 cores at 2.6 GHz and 32GB RAM) for calculating the LCP the computing times were reasonable: around 40 minutes, see also Table 5.1. However, with a lower performing computer it would take more than 8 hours to calculate the LCP at a cell size of 5 meter for a study area of this size. Moreover, creating the Cost Surfaces from each individual layer that represents a criterion also takes longer computation time. Those long computation times make the methodology not suitable for workshop sessions, which are often limited by time.
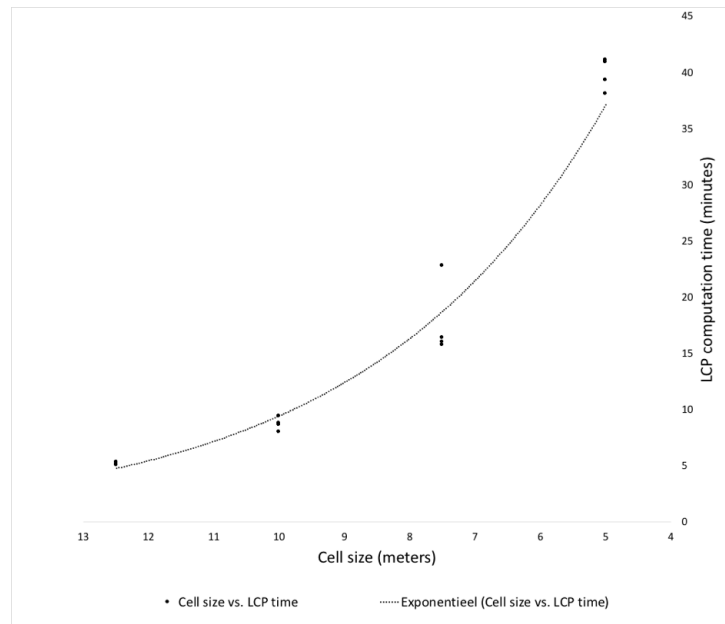


**Figure 5.8**: Computing time for calculating the Least Cost Paths using a high-performance computer. If cell size (horizontal axis) decreases computing time (vertical axis) increases exponentially.

Regarding the evaluation of the suggested LCP routes for Hyperloop infrastructure are in this research these metrics used: the accumulated cost value from Cost Surfaces, total length of infrastructure, straightness expressed in sinuosity, and the minimum curve bend radius. However, other evaluation metrics could be used. For example:

- Number of changes of direction in the suggested route: the more changes of direction the less "straight", thus the less suitable. Total amount of bends can be calculated with native GIS functions, such as *Explodelines* which finds all individual segments of a line. The amount of segments give an indication of the amount of bends of the line. This is a "line oriented" metric [Heeres et al., 2012].

- Amount of overlap with areas of a specific land use. The less overlap, the more suitable. For example, a suggested Hyperloop route could cross an area which is used as nature area. The total amount of overlap of the route with that nature area can be calculated and used as evaluation metric. This is an "area oriented" metric.

Besides, the used evaluation criteria – (accumulated) cost value, total length, straightness, minimum curve bend radius – could *themselves* be investigated further: which evaluation criterion is most important, and which is not so important?

Karlson et al. [2016] for example used a spatial MCDA to calculate a variety of suggested routes, then defined five evaluation criteria and, consequently, investigated which of those suggested route is "best" with another (non-spatial) Multi Criteria Analysis. This extra step of evaluating the suggested routes is in the current study on Hyperloop routes not performed, since in principle there is only one evaluation criterion: the (accumulated) cost value of the route. Moreover, that evaluation criterion suits better to the "area oriented" approach, while the others focus on the infrastructure itself ("line oriented"). Therefore, using a (non-spatial) MCA for evaluating suggested Hyperloop routes is a suggestion for future work.

Finally, the previous Section 5.4 ended with the notion that this methodology can be a (valuable) part of an iterative process, for finding optimal routes for transportation infrastructure routes, in this case Hyperloop. For that type of application, it can be useful to automate the process. In the current research are only several aspects automated or semi-automated. The methodology can be subdivided in the following activities:

1. Preprocessing of the data. Involving the collection and combination of various datasets that represent one of the defined criteria, and consequently adding an attribute called *value* with a value of 1 to every feature in the dataset. This is done with QGIS software and it is not likely that it can be automated.

2. Transform individual vector files to raster files. It involves the transformation of an individual vector file – representing a criterion – to an individual raster file. Important parameters are the cell size and – possibly – buffer size around specific features. A burn value is also specified, which relates to the *value* from the previous activity. The output of this activity is a raster file for an individual criterion with a specified cell size and buffer size. In this research is QGIS software used and the activity is semi-automated with a *Processing Model*, see Figure D.1.

3. Data collection for assigning weights to individual criteria. Google Forms software is used for designing the online questionnaires and collecting responses. Excel is used to calculate the weights (with the template by **???**

4. Applying weights on individual raster files. FME software is used to calculate the weighted raster files. See Figure D.2 for a screenshot of the workbench. FME was also used to calculate the Cost Surface maps from individual layers, see Figure D.3

5. Least Cost Path calculation. A plugin for QGIS is used for calculating the Least Cost Path from Cost Surface maps.

Some of the processing steps can be combined and automated in a custom software application. For example, step 2, 4 and 5 can be combined. Ideally, this application runs in one program (e.g. FME, QGIS, or ArcGIS software).

# 6 | CONCLUSION

## 6.1 ANSWER MAIN RESEARCH QUESTION

The main research question was defined as follows:

> *"Where to place the route of Hyperloop infrastructure in the Netherlands taken into account an origin and destination location, using a GIS-MCDA approach?"*

This research demonstrated the GIS-MCDA approach for finding possible corridors for a Hyperloop in The Netherlands. The GIS-MCDA approach was chosen because this type of complex problem can be defined as a multi-criteria decision problem [Malczewski and Rinner, 2015]. With such types of problems, a variety of criteria have to be taken into account and various stakeholders are involved. The origin and destination locations for the Hyperloop in The Netherlands were set at Lelystad Airport and Schiphol Airport. Those possible locations were also mentioned in Arup et al. [2017].

With those two premises taken into account – i.e. using the GIS-MCDA approach for finding suitable infrastructure corridors and a fixed origin and destination location – related research was discussed in Chapter 2. The Hyperloop and the lack of an institutional design for Hyperloop in The Netherlands was discussed. Also, the main components of the GIS-MCDA approach were introduced: value scaling, criterion weighting, and a combination rule. The chapter ended with an extensive list of (more than 100) potential criteria that were used in related research in the field of GIS-MCDA for finding infrastructure corridors.

In Chapter 3 was the extensive list reduced to a set of 17 criteria, subdivided into three groups. A criterion is selected if it has a location-component, if it focuses on the area surrounding Hyperloop infrastructure, if there is an open dataset available for the criterion, and if the criterion is unique. The three defined groups are "Infrastructure", "Buildings", and "Areas", containing 4, 7, and 6 criteria, respectively.

The methodology for the research was discussed in Chapter 4. The area between Lelystad and Schiphol is introduced as study area for the research. The requirements for the Hyperloop infrastructure were described: in the middle part of the track a relatively straight track is needed, the speed profile of the Hyperloop vehicles allows to have more turns at the starts and ends of the track, and in this research is only above-ground infrastructure taken into account.

Consequently, the procedure for defining the importance of each of the 17 individual criteria was discussed. The AHP method of Saaty [1987] is used to transform questionnaire responses into a weight value for a criterion. The consulted experts are subdivided into four groups: municipal employees, provincial employees, national government employees, and researchers. Then, the rasterization procedure is discussed, where I argued to use a cell size of 5 meter and a buffer of 25 meter around "Building" features. A Least Cost Path algorithm is used to calculate the most optimal route between the defined origin and destination locations. Figure 4.10 illustrates the procedure of going from 17 individual raster layers for criteria to one Cost Surface and one Least Cost Path.

The results are discussed in Chapter 5. The five response groups (A, B, C, D, and E) each resulted in a different set of weights for the criteria, and various routes for the Hyperloop.

Although the weights differed per response group, there were no large differences in suggested LCP routes. For four "bottlenecks" in the study area, where a Hyper-

loop crosses major waterways – IJmeer/Gooimeer, Vecht, Amsterdam Rijnkanaal, Ringvaart – the places where the waterways are crossed are the same for all routes. Also, the resulting LCP are for a large part close to existing highway infrastructure.

## 6.2 REFLECTION ON THE RESEARCH

- The 17 chosen criteria have a large influence on the outcome. The reasons why these 17 criteria are chosen must therefore be clear. Choosing these 17 – or more or less criteria – could also be subject of a questionnaire, for which an expert panel could be consulted. On the other hand, the 17 criteria are based on an in-depth literature review, covering 10 articles that used the GIS-MCDA approach for infrastructure route or corridor planning, see Table 2.4.

- Before analysis, the criteria were not investigated well enough. For example, the features that belong to the criterion *Agriculture fallow land* were in total only 14 hectare, and most of these features were located at the borders of the study area. Therefore, this criterion should have been let out of the analysis, since it could not make any difference in the outcome. The statistics of individual criteria should therefore be investigated before the research is performed. Two requirements could have been added in Section 3.1: features of the criteria have to be *represented in the study area*, and a requirement with regard to the *minimum total area covered* by features from that criterion.

- A relatively small amount of responses on the questionnaires for the provinces (n=3), national government (n=4), and research groups (n=3). Although it was not mentioned in the methodology, the ambition was to get at least 6 valid responses per defined respondent-group. Unfortunately, this amount was only reached for the municipalities-group (n=6).

- Doubts about the calculation of weight values, since the variety in weights had a minimal impact on the resulting suggested routes. Investigating how another formula could lead to different results is therefore recommended for future research. A sensitivity analysis can be performed to gauge the impact of the input data [Crosetto and Tarantola, 2001].

- Long processing times for calculating the cost surfaces and LCP. This is directly dependent on the chosen cell size (5m). Fortunately, a high-performance computer with fast CPU was donated for these processing tasks.

- Although the concept of *curvature* of transportation infrastructure is introduced in the Methodology, it is not discussed in the Results and Discussion section. That is, because it would take more effort than expected, since there are no GIS tools available to calculate it. Besides, it is not part of the scope of this research, since this research takes the *area oriented* approach: with the proposed methodology is a "best" location for a Hyperloop infrastructure a location where the amount of conflicts with *the area surrounding the infrastructure* is minimized.

## 6.3 RECOMMENDATIONS FOR FUTURE WORK

A recommendation for future work is to investigate the effects of using buffer sizes around specific features in-depth. In this study are only buffer sizes of 0 meter and 25 meter applied: other buffer sizes are not investigated.

Another recommendation is to use strategic factors to select the most optimal route from the possibilities, as in Kim et al. [2014]. For example, the total suitability

score for each route, an estimation of construction cost for a route, or the expected land acquisition cost. These evaluation criteria for the suggested routes can be used in a non-spatial MCA to select the "best" route, like in the work of Karlson et al. [2016].

As mentioned in the reflection, the impact of input data on the outcomes can be analyzed with a sensitivity analysis.

The final recommendation for future work is to apply the methodology on another study area (can be larger or smaller), provided that data that represent the criteria is available.

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# A | SELECTION PROCEDURE FOR CRITERIA

| Criterion | Mentioned in sources | [1] Location component | [2] Focus | [3] Dataset available | Dataset name | [4] Can it be combined and Remarks |
|---|---|---|---|---|---|---|
| (density of) buildings | 1 | Yes | Area-oriented | Yes | BAG | Yes, subdivided into various BAG classes |
| distance from buildings | 1 | Yes | Area-oriented | Yes | BAG | Yes, subdivided into various BAG classes |
| distance from sensitive buildings | 1 | Yes | Area-oriented | Yes | BAG | Yes, subdivided into various BAG classes |
| average height of buildings | 1 | Yes | Area-oriented | Yes | BAG | Yes, subdivided into various BAG classes |
| highly valued cultural and recreational sites / cultural history | 2 | Yes | Area-oriented | Yes | CultGIS | Not used, very large dataset |
| visibility from highly valued cultural and recreational sites | 1 | Yes | Area-oriented | No | | |
| visibility from residential buildings | 1 | Yes | Area-oriented | No | | |
| aspect of the slope | 7 | Yes | Area-oriented | Yes | AHN3 | **slope above 10 percent** |
| distance from infrastructure corridors | 1 | Yes | Area-oriented | Yes | DTB | **highways side** |
| naturalness of land cover | 1 | Yes | Area-oriented | No | | |
| ridges | 2 | Yes | Area-oriented | Yes | AHN3 | Removed because there are no ridges in study area |
| costs of conduits (tubes etcetera) | 1 | No | Line-oriented | No | | |
| costs of installation | 1 | No | Line-oriented | No | | |
| creation of new streets | 1 | Yes | Area-oriented | No | | |
| costs of new reservoirs | 1 | No | Line-oriented | | | |
| reinforcement of water elevation stations | 1 | No | Line-oriented | | | |
| costs of operating during the life of the project | 1 | No | Line-oriented | | | |
| increase of robustness to the overall water supply system | 1 | No | Line-oriented | | | |
| increase of capacity of the water supply system | 1 | No | Line-oriented | | | |
| impacts over the road users | 1 | Yes | Area-oriented | No | | |
| impacts over neighbor zones | 1 | Yes | Area-oriented | No | | |
| interference with other existing infrastructures | 1 | Yes | Area-oriented | Yes | Various: DTB, NS | **highways, train tracks** |
| streams | 2 | Yes | Area-oriented | Yes | Oppervlaktewateren | **water bodies** |
| risk of fire and explosion / risk of accidents in urban space | 2 | Yes | Area-oriented | Yes | Risicokaart | **high risk infrastructure** |
| urban areas with buffer of 750m / proximity to urban areas | 2 | Yes | Area-oriented | No | | |
| agricultural irrigation areas | 1 | Yes | Area-oriented | No | | |
| dam reservoirs | 2 | Yes | Area-oriented | Yes | BGT | Removed because no dam reservoirs in study area |
| high voltage power lines / powerline | 2 | Yes | Area-oriented | Yes | TenneT grid maps | |
| highways | 2 | Yes | Area-oriented | Yes | DTB | **highways** |
| fault lines / geology faults | 2 | Yes | Area-oriented | No | | |
| engineering characteristics and geological soil structure / rock base / suitability for construction / soil types / geology / soil / geology | 7 | Yes | Line-oriented | | | |
| ecological suitability | 1 | Yes | Area-oriented | Yes | Nature areas | **nature areas** |
| connectivity index | 1 | No | Area-oriented | No | | |
| population density / population density (past and present) | 2 | Yes | Area-oriented | Yes | CBS buurt | **housing** |
| projected construction costs | 1 | No | Line-oriented | | | |
| unique habitat | 1 | Yes | Area-oriented | Yes | Nature areas | **nature areas** |
| large viewshed / openness | 2 | Yes | Area-oriented | No | | |
| archeological feature / archealology | 2 | Yes | Area-oriented | Yes | Monumentenkaart | **leisure and recreation facilities** |
| historic feature | 1 | Yes | Area-oriented | Yes | Monumentenkaart | **leisure and recreation facilities** |
| wetland / wetlands and peat bogs / problem soils for construction | 4 | Yes | Area-oriented | Yes | BGT | **nature areas** |
| prime farmland | 1 | Yes | Area-oriented | Yes | BRP | **agriculture cropland or grassland** |
| fish hatchery | 1 | Yes | Area-oriented | No | | |
| springs (waterbron) | 1 | Yes | Area-oriented | No | | |
| sink hole | 1 | Yes | Area-oriented | No | | |
| known caves | 1 | Yes | Area-oriented | No | | |
| underground fuel tank | 1 | Yes | Area-oriented | No | | |
| high probability of caves | 1 | Yes | Area-oriented | No | | |
| EPA project sites / superfund site (i.e. contaminated sites) | 1 | Yes | Area-oriented | No | | |
| low probability of caves | 1 | Yes | Area-oriented | No | | |
| tire dump / landfills | 1 | Yes | Area-oriented | Yes | BGT | **industry and agriculture facilities** |
| hazardous materials / hazardous areas | 2 | Yes | Area-oriented | Yes | Risicokaart | **high risk infrastructure** |
| hospital (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **health facilities** |
| water tank (public facility site class) | 1 | Yes | Area-oriented | Yes | BGT | **industry and agriculture facilities** |
| public water supply (public facility site class) | 1 | Yes | Area-oriented | Yes | Afvalwater - stedelijke waterz.inst. | **industry and agriculture facilities** |
| airport (public facility site class) | 1 | Yes | Area-oriented | Yes | Vervoersnetwerken | **industry and agriculture facilities** |
| sewage treatment (public facility site class) | 1 | Yes | Area-oriented | Yes | BGT | **industry and agriculture facilities** |
| church (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **leisure and recreation facilities** |
| pumping station (public facility site class) | 1 | Yes | Area-oriented | Yes | BGT | **industry and agriculture facilities** |
| cemetery (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **leisure and recreation facilities** |
| pipeline and other dangerous structures | 1 | Yes | Area-oriented | Yes | Risicokaart | **high risk infrastructure** |
| golfcourse (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **leisure and recreation facilities** |
| armory (public facility site class) | 1 | Yes | Area-oriented | No | | |
| railroad | 1 | Yes | Area-oriented | Yes | Spoorwegen (WFS) | **train tracks** |
| power plant (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **industry and agriculture facilities** |
| water filtration (public facility site class) | 1 | Yes | Area-oriented | Yes | BGT | **industry and agriculture facilities** |
| radio tower (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **industry and agriculture facilities** |
| electric substation (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **industry and agriculture facilities** |
| oil and gas wells (public facility site class) | 1 | Yes | Area-oriented | Yes | BAG | **industry and agriculture facilities** |
| .... continue with this list!!!!!1 | | | | | | |

**Table A.1:** Procedure for selecting criteria

# B | QUESTIONNAIRE FOR WEIGHTING OF CRITERIA

**Questionnaire for finding Hyperloop routes**

Thank you for taking time to fill in this questionnaire! This questionnaire belongs to a graduation project for the master program Environmental & Infrastructure Planning. The goal of the research project is to find optimal routes for a *Hyperloop* test track in the Netherlands. Hyperloop is envisioned as an innovative transportation system for people and goods, using a dedicated infrastructure that consists of near-vacuum tubes. At the time of writing, 2019, nowhere in the world such a system exists.

This research is an attempt to find optimal routes for such an Hyperloop infrastructure in the Netherlands between Lelystad Airport and Schiphol Airport. The Geographic Information Systems Multi-Criteria Decision Analysis (GIS-MCDA) approach is used. With this approach, the search for the location of Hyperloop is regarded as a complex multi-criteria decision problem, whereby interests of a variety of stakeholders have to be taken into account (Malczewski & Rinner, 2015). The GIS-MCDA approach is used in other research as well, for example to find optimal routes for high-speed rail connections, highways or pipelines (see bibliography). A crucial part of the GIS-MCDA approach for finding optimal routes is defining the importance of the relevant criteria.

In this research, a shortlist of 17 criteria is suggested, categorized into three groups. The criteria are chosen because they have an explicit spatial component, there is (open) data available for the criterion, and they are successfully applied in related GIS-MCDA research. The three groups are:
- *Infrastructure,* with 4 criteria that have a network-like characteristic;
- *Building*, with 7 criteria that represent use-functions of existing buildings;
- *Area*, with 6 criteria representing a type of land-cover.

The goal of the survey is to find the relative importance of each individual criterion. Therefore, in each group, we will compare each criterion with one another.

The question that you will get in this survey is: *When taking the following types of infrastructure into account, on what type of infrastructure do you prefer the Hyperloop?* **A** or **B.** *And on a scale of 1 to 9, how much do you prefer the one over the other?*

For example, if you prefer A very strongly over B, you will check the "7" on the side of A. In the questionnaire, it looks like this:

| When taking the following types of *infrastructure* into account, on what type of *infrastructure* do you prefer the Hyperloop?" | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme | Very strong | Strong | Moderate | Weak | Equal | Weak | Moderate | Strong | Very strong | Extreme | |
| **A** | 9 | ✓ | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | **B** |

You can use the "Fill & Sign" tool in order to fill in the questionnaire. The Fill & Sign tool is included in the free version of Adobe Acrobat Reader (https://get.adobe.com/nl/reader/). When you finished the questionnaire, please save and send it to n.bebelaar@student.rug.nl.

Good luck with completing the questionnaire!

Questionnaire for finding Hyperloop routes

**Figure B.1:** Questionnaire page 1 of 4

| General questions | |
|---|---|
| Profession: | |
| Study background: | |
| Gender: | |
| Age: | |

| When taking the following types of *infrastructure* into account, on what type of *infrastructure* do you prefer the Hyperloop?" | Extreme | Very strong | Strong | Moderate | Weak | Equal | Weak | Moderate | Strong | Very strong | Extreme | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| at a high risk infrastructure | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at train tracks |
| at a high risk infrastructure | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at the side of the highway |
| at a high risk infrastructure | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at highways |
| at train tracks | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at the side of the highway |
| at train tracks | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at highways |
| at the side of the highway | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at highways |

Questionnaire for finding Hyperloop routes

**Figure B.2:** Questionnaire page 2 of 4

| When taking the following types of building into account, on what type of building would you prefer the Hyperloop? | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme | Very strong | Strong | Moderate | Weak | Equal | Weak | Moderate | Strong | Very strong | Extreme | |
| education and science facility | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | retail facility |
| education and science facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | industry or agriculture facility |
| education and science facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | leisure and recreation facility |
| education and science facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a health facility |
| education and science facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a housing facility |
| education and science facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |
| retail facility | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | industry or agriculture facility |
| retail facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | leisure and recreation facility |
| retail facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a health facility |
| retail facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a housing facility |
| retail facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |
| industry or agriculture facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | leisure and recreation facility |
| industry or agriculture facility | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a health facility |
| industry or agriculture facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a housing facility |
| industry or agriculture facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |
| leisure and recreation facility | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a health facility |
| leisure and recreation facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a housing facility |
| leisure and recreation facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |
| at a health facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a housing facility |
| at a health facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |
| at a housing facility | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at an office facility |

Questionnaire for finding Hyperloop routes

**Figure B.3:** Questionnaire page 3 of 4

| When taking the following types of area into account, on what type of area would you prefer the Hyperloop? | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Extreme | Very strong | Strong | Moderate | Weak | Equal | Weak | Moderate | Strong | Very strong | Extreme | |
| at a nature area | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | at a water area |
| at a nature area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture grassland area |
| at a nature area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture cropland area |
| at a nature area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture vacant land area |
| at a nature area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | area with slope above 10% |
| at a water area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture grassland area |
| at a water area | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture cropland area |
| at a water area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture vacant land area |
| at a water area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | area with slope above 10% |
| agriculture grassland area | 9 | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture cropland area |
| agriculture grassland area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture vacant land area |
| agriculture grassland area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | area with slope above 10% |
| agriculture cropland area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | agriculture vacant land area |
| agriculture cropland area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | area with slope above 10% |
| agriculture vacant land area | 9 | 7 | 6 | 3 | 1 | 0 | 1 | 3 | 5 | 7 | 9 | area with slope above 10% |

Questionnaire for finding Hyperloop routes

**Figure B.4:** Questionnaire page 4 of 4

# C | BAG *GEBRUIKSDOEL* CATEGORY PER DEFINED CRITERION

| Criterion. | BAG *gebruiksdoel* |
|---|---|
| Housing | woonfunctie |
| Industry and agriculture facilities | industriefunctie |
| | celfunctie |
| | overige gebruiksfunctie |
| | overige gebruiksfunctie, woonfunctie |
| | industriefunctie, overige gebruiksfunctie |
| | industriefunctie, overige gebruiksfunctie, woonfunctie |
| | NULL/no data |
| Health facilities | gezondheidszorgfunctie, woonfunctie |
| | gezondheidszorgfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, onderwijsfunctie, sportfunctie, winkelfunctie |
| | gezondheidszorgfunctie, industriefunctie, woonfunctie |
| | gezondheidszorgfunctie, industriefunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, woonfunctie |
| | gezondheidszorgfunctie, overige gebruiksfunctie, woonfunctie |
| | gezondheidszorgfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, kantoorfunctie, winkelfunctie |
| | gezondheidszorgfunctie, logiesfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, overige gebruiksfunctie |
| | gezondheidszorgfunctie, logiesfunctie, overige gebruiksfunctie |
| | gezondheidszorgfunctie, industriefunctie, sportfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, industriefunctie, kantoorfunctie |
| | gezondheidszorgfunctie, industriefunctie, kantoorfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, overige gebruiksfunctie |
| | gezondheidszorgfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | gezondheidszorgfunctie, winkelfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | gezondheidszorgfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, sportfunctie, woonfunctie |
| | gezondheidszorgfunctie, logiesfunctie, woonfunctie |
| | gezondheidszorgfunctie, industriefunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, sportfunctie, woonfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, sportfunctie, winkelfunctie |
| | gezondheidszorgfunctie, industriefunctie |
| | gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, onderwijsfunctie |
| | gezondheidszorgfunctie, sportfunctie |
| | gezondheidszorgfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, sportfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, onderwijsfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, sportfunctie |
| | gezondheidszorgfunctie, logiesfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, industriefunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, logiesfunctie, overige gebruiksfunctie |
| | gezondheidszorgfunctie, kantoorfunctie, onderwijsfunctie |
| | gezondheidszorgfunctie, onderwijsfunctie, woonfunctie |
| | bijeenkomstfunctie, gezondheidszorgfunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | gezondheidszorgfunctie, industriefunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |

**Table C.1**: Overview of BAG *gebruiksdoel* categories per defined criterion (1 of 3)

| Criterion. | BAG *gebruiksdoel* |
|---|---|
| Retail facilities | kantoorfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, winkelfunctie, woonfunctie |
| | winkelfunctie, woonfunctie |
| | winkelfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, winkelfunctie |
| | industriefunctie, kantoorfunctie, winkelfunctie |
| | kantoorfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | onderwijsfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, winkelfunctie |
| | industriefunctie, overige gebruiksfunctie, winkelfunctie |
| | industriefunctie, sportfunctie, winkelfunctie |
| | overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, winkelfunctie |
| | kantoorfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, winkelfunctie |
| | logiesfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | kantoorfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, onderwijsfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, logiesfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, overige gebruiksfunctie, winkelfunctie |
| | logiesfunctie, winkelfunctie |
| | sportfunctie, winkelfunctie, woonfunctie |
| | kantoorfunctie, onderwijsfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, sportfunctie, winkelfunctie |
| | logiesfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | onderwijsfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie |
| | onderwijsfunctie, overige gebruiksfunctie, winkelfunctie |
| | kantoorfunctie, onderwijsfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, onderwijsfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | kantoorfunctie, logiesfunctie, overige gebruiksfunctie, winkelfunctie |
| | kantoorfunctie, logiesfunctie, winkelfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, winkelfunctie |
| | logiesfunctie, overige gebruiksfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, winkelfunctie, woonfunctie |
| | onderwijsfunctie, winkelfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie |
| | industriefunctie, kantoorfunctie, onderwijsfunctie, winkelfunctie |
| | bijeenkomstfunctie, kantoorfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | logiesfunctie, overige gebruiksfunctie, winkelfunctie, woonfunctie |
| | industriefunctie, onderwijsfunctie, winkelfunctie |
| | kantoorfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, winkelfunctie |
| | kantoorfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, sportfunctie, winkelfunctie, woonfunctie |
| | sportfunctie, winkelfunctie |
| | bijeenkomstfunctie, industriefunctie, onderwijsfunctie, winkelfunctie, woonfunctie |
| Education and science facilities | onderwijsfunctie |
| | onderwijsfunctie, sportfunctie |
| | bijeenkomstfunctie, onderwijsfunctie |
| | onderwijsfunctie, woonfunctie |
| | kantoorfunctie, onderwijsfunctie, woonfunctie |
| | onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, woonfunctie |
| | kantoorfunctie, onderwijsfunctie, sportfunctie |
| | kantoorfunctie, onderwijsfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, logiesfunctie, onderwijsfunctie, sportfunctie |
| | industriefunctie, kantoorfunctie, onderwijsfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie |
| | kantoorfunctie, onderwijsfunctie, sportfunctie, woonfunctie |
| | kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | industriefunctie, onderwijsfunctie, woonfunctie |

**Table C.2:** Overview of BAG *gebruiksdoel* categories per defined criterion (cont'd, 2 of 3

| Criterion. | BAG *gebruiksdoel* |
|---|---|
| Education and science facilities (cont'd) | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, sportfunctie, woonfunctie |
| | industriefunctie, onderwijsfunctie |
| | bijeenkomstfunctie, logiesfunctie, onderwijsfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | onderwijsfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, sportfunctie |
| | industriefunctie, onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | kantoorfunctie, logiesfunctie, onderwijsfunctie, woonfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | logiesfunctie, onderwijsfunctie, woonfunctie |
| | kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, industriefunctie, onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, sportfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, onderwijsfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, onderwijsfunctie, sportfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, onderwijsfunctie, overige gebruiksfunctie |
| | celfunctie, kantoorfunctie |
| | industriefunctie, kantoorfunctie, logiesfunctie, woonfunctie |
| | celfunctie, industriefunctie, kantoorfunctie |
| Offices | kantoorfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie |
| | kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie |
| | industriefunctie, kantoorfunctie |
| | industriefunctie, kantoorfunctie, overige gebruiksfunctie |
| | kantoorfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie |
| | kantoorfunctie, overige gebruiksfunctie |
| | celfunctie, kantoorfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, sportfunctie |
| | industriefunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | kantoorfunctie, logiesfunctie |
| | kantoorfunctie, logiesfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, logiesfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, woonfunctie |
| | kantoorfunctie, logiesfunctie, sportfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | kantoorfunctie, sportfunctie |
| | kantoorfunctie, logiesfunctie, woonfunctie |
| | kantoorfunctie, overige gebruiksfunctie, sportfunctie |
| | industriefunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | celfunctie, kantoorfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, woonfunctie |
| | kantoorfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, kantoorfunctie, sportfunctie, woonfunctie |
| | kantoorfunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, sportfunctie |
| | bijeenkomstfunctie, industriefunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie |
| | industriefunctie, kantoorfunctie, sportfunctie, woonfunctie |
| | celfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | industriefunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, kantoorfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, kantoorfunctie, logiesfunctie, overige gebruiksfunctie, sportfunctie |
| | celfunctie, kantoorfunctie |
| | industriefunctie, kantoorfunctie, logiesfunctie, woonfunctie |
| | celfunctie, industriefunctie, kantoorfunctie |
| Leisure and recreation facilities | bijeenkomstfunctie |
| | bijeenkomstfunctie, logiesfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, sportfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, logiesfunctie |
| | bijeenkomstfunctie, industriefunctie |
| | bijeenkomstfunctie, industriefunctie, woonfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, logiesfunctie, overige gebruiksfunctie |
| | bijeenkomstfunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, sportfunctie |
| | bijeenkomstfunctie, industriefunctie, logiesfunctie, woonfunctie |
| | bijeenkomstfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, industriefunctie, sportfunctie |
| | bijeenkomstfunctie, industriefunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | bijeenkomstfunctie, logiesfunctie, overige gebruiksfunctie, sportfunctie |
| | bijeenkomstfunctie, industriefunctie, logiesfunctie |
| | sportfunctie |
| | overige gebruiksfunctie, sportfunctie, woonfunctie |
| | sportfunctie, woonfunctie |
| | industriefunctie, sportfunctie, woonfunctie |
| | industriefunctie, sportfunctie |
| | logiesfunctie, sportfunctie, woonfunctie |
| | logiesfunctie, overige gebruiksfunctie, sportfunctie |
| | overige gebruiksfunctie, sportfunctie |
| | industriefunctie, overige gebruiksfunctie, sportfunctie, woonfunctie |
| | industriefunctie, logiesfunctie, woonfunctie |
| | logiesfunctie |
| | logiesfunctie, woonfunctie |
| | industriefunctie, logiesfunctie |
| | logiesfunctie, overige gebruiksfunctie |
| | logiesfunctie, overige gebruiksfunctie, woonfunctie |
| | industriefunctie, logiesfunctie, overige gebruiksfunctie, woonfunctie |

**Table C.3:** Overview of BAG *gebruiksdoel* categories per defined criterion (cont'd, 3 of 3)
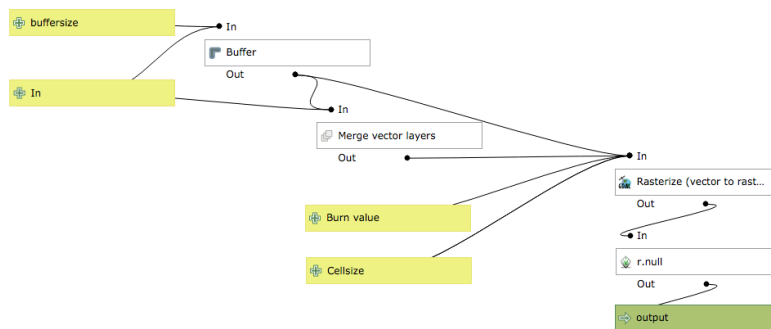
# D | PROCESSING MODELS IN GIS SOFTWARE

**(a)** Processing model for creating raster files (user interface mode QGIS3.0)



**(b)** Processing model for creating raster files (edit mode Graphical Modeler QGIS3.0)

**Figure D.1:** The semi-automated process for transforming vector files into raster files.
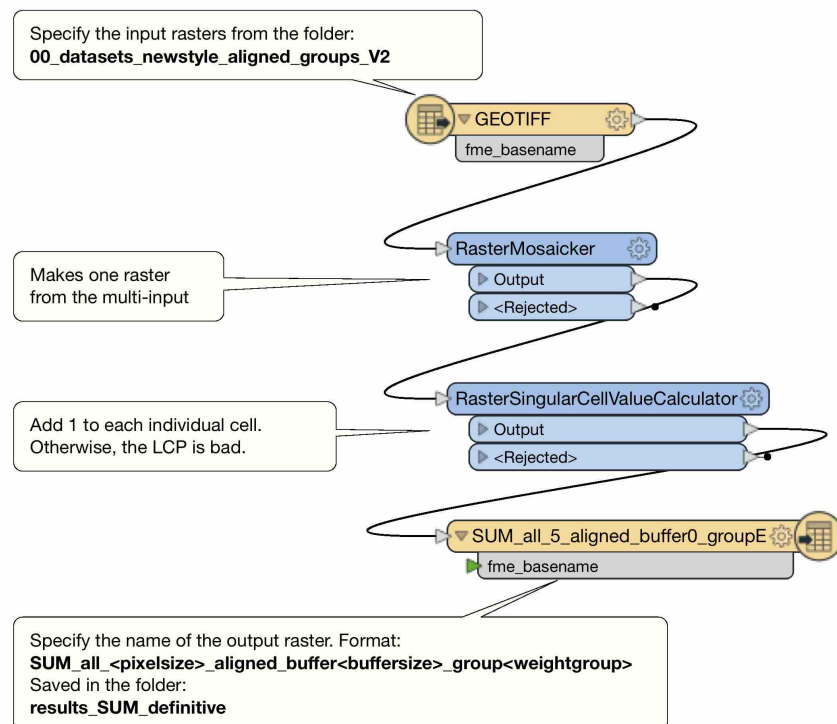
/Users/Niek/Documents/Master_EIP/EIP_thesis/Thesis/research/FME_workbenches/Raster_to_weig
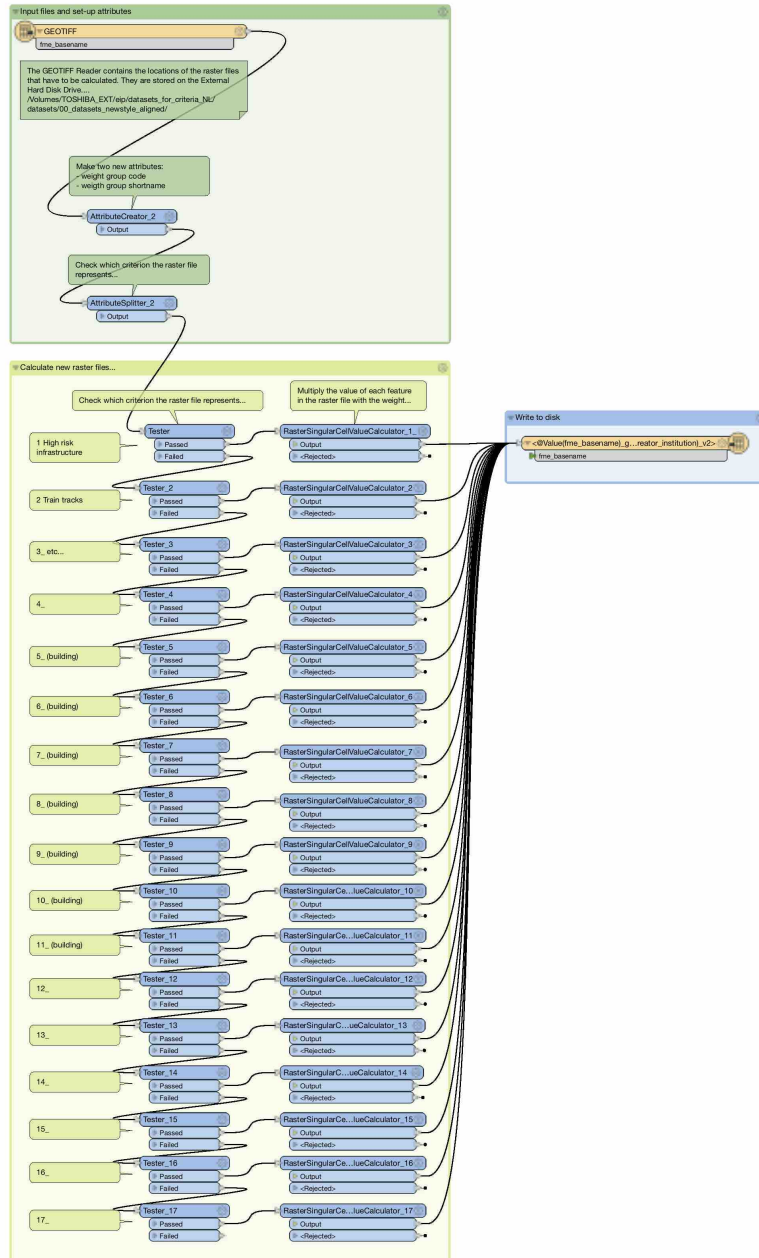


**(a)**

**Figure D.2:** Workbench for calculating weighted raster layers (FME)

/Users/Niek/Documents/Master_EIP/EIP_thesis/Thesis/research/FME_workbenches/Weighted_rast

Specify the input rasters from the folder:
**00_datasets_newstyle_aligned_groups_V2**

GEOTIFF
fme_basename

RasterMosaicker
Output
<Rejected>

Makes one raster
from the multi-input

RasterSingularCellValueCalculator
Output
<Rejected>

Add 1 to each individual cell.
Otherwise, the LCP is bad.

SUM_all_5_aligned_buffer0_groupE
fme_basename

Specify the name of the output raster. Format:
**SUM_all_<pixelsize>_aligned_buffer<buffersize>_group<weightgroup>**
Saved in the folder:
**results_SUM_definitive**

(a)

**Figure D.3:** Workbench for calculating Cost Surface maps from individual layers (FME)