

Web Processing - Standardised GIS Analyses for Cable Route Planning

SEBASTIAN HEIDEN, Harz University of Applied Sciences, Germany

The least cost paths for a power line from a power station at the cost to a power station further inland are calculated. Down-sampling and clipping are investigated as techniques to speed up the calculation. The path from the clipped cost raster is often the same as the original path. The speed-up of the clipping can not be known in advance.

CCS Concepts: • Computing methodologies → Modeling and simulation; • General and reference → Estimation.

Additional Key Words and Phrases: GIS, least cost path

ACM Reference Format:

Sebastian Heiden. 2022. Web Processing - Standardised GIS Analyses for Cable Route Planning. *J. ACM* 37, 4, Article 28 (February 2022), 7 pages. <https://doi.org/XXXXXX.XXXXXXX>

1 INTRODUCTION

The German power system is adding a lot of renewable energy sources in the north, because wind energy reaches its highest efficiency with high wind speeds. At the same time old power plants e.g. nuclear, hard coal and lignite are being phased out [1]. These older power plants were mainly located in southern and central Germany. The energy sink, industrial and private demand, is not shifting north. Therefore, the renewable energy has to be transported from north to south which increases the congestion in the power grid. The amount of offshore wind power, that the German energy system can use, can be greatly increased by adding new power lines [2].

However, it is not enough to find the shortest route when building new power lines. Other parameters have to be taken into consideration. As the steepness of a road or the soil, play an important role for the building cost of a road or pipeline [3]. When planning the additional routes for a power grid, further aspects such as legal regulations and acceptance by the local population have to be taken in consideration. Also technical aspects, as the effects on the grid stability are further points take into consideration [4].

Due to the increasing demand for renewable energy wind offshore wind turbines supply 5.5 % annual percentage in 2020 of the German energy mix [5].

Other methods such as multi-criteria decision analysis (MCDA) consider further aspects as stakeholder, experts, public and decision maker [6] (see section 5).

The least cost path algorithm is used to plan a possible route for a power line. The least cost path algorithm is a Dijkstra algorithm [7]

Author's address: Sebastian Heiden, u38439@hs-harz.de, Harz University of Applied Sciences, Friedrichstrasse 57-59, Wernigerode, Saxony-Anhalt, Germany, 38855.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

© 2022 Association for Computing Machinery.

0004-5411/2022/2-ART28 \$15.00

<https://doi.org/XXXXXX.XXXXXXX>

applied on a raster map. The vertices of the graph are the pixel centres, that are connected to the eight neighbouring pixel centres via the edges. This makes it possible to find routes on graphs that are not predefined, such as road networks. The weights of the edges are the local costs of travel from one pixel center to the neighbouring pixel center. The costs can be physical costs, such as the local slope, but also can be composed of other factors as the acceptance rate for the land usage of a given class. The Least Cost Path algorithm consists of at least two successive steps. 1) The first step is to aggregate the costs of travelling from the starting point to a given set of end points. This step generates the aggregated cost raster of travelling from the starting point to any point of the cost raster. 2) In the next step the backtracking, the route of the actual Least Cost Path is calculated. For each end point the path via the lowest cost neighbour is taken until the starting point is reached.

Some implementations switch the role of start and ending points, so that either many start points and one single end point, or one single end point and many end points can be used. In some implementation there is an extra step between 1) and 2) that calculates cost-weight direction raster, that encodes the direction of the shortest path to the starting point as integer values.

2 METHODS

We retrieve a set of different spacial data-sets from public sources as a basis for creating the cost raster. The study area are the counties of Cuxhaven and Osterholz in the state of Lower Saxony, Germany. Areas protected by different European and National conservation laws are provided by the German Environment Agency as Web Feature Service (wfs) [8].

The national land coverage (ATKIS) with a scale of 1:250000 are provided by the Federal Agency for Cartography and Geodesy [9]. The national power grid (tags: 'power': line) has been retrieved via OpenStreetMap [10]. Local data as houses at Level of Detail 1 are provided by the State Office for Geoinformation and Land Surveying of Lower Saxony [11]. In addition, local planning geodata for the land use are taken from 'Metropolplaner' (Planning data Lower Saxony & Bremen) [12].

PyWPS [13] is used to provide the least cost path algorithm as a Web Processing Service (wps) in combination with flask [14]. As client Birdy [15] connects to the wps, sends the cost raster and receives the resulting least cost path. The initial implementation of the Least Cost Path algorithm is based on the implementation for the QGIS-Plugin 'Least Cost Path' [16] in version 1.0.

The different layers of the different entities are optionally filtered, buffered and then rasterised. Filtering the layers of the files for special attributes enables further differentiation. For examples, it possible to differentiate between heath and uncultivated land in the land cover. Adding a buffer can be used either used to convert a line objects such as power grids and streets into a polygon with the correct physical width, or to add minimum distance from an existing of planned area to the new power grid. Each of these rasterised layers are given a weight, or cost which expresses the cost of using

land covered by this layer. The costs of all layers is aggregated with the maximum function. Thus, an area covered by several layers is uniformly used with the highest cost. Any place in the study area, that is not covered by any layer and thus does not yet have a weight, is given the default cost.

The costs have been grouped into different levels (see table 1), starting from *preferential* areas with very low costs, via *no restrictions*, which is the default, used when no other layers are covering the local area, to *restricted*, *strongly restricted* and *prohibited* areas with high costs. These higher costs resemble the degree to which a place with this cost should be avoided, while routing the path. The ratio of the higher costs to the lower costs directly translates into the additional detour in pixels the algorithm is willing to go. Thus, as *prohibited* areas describe a legal obligation, not to use these areas or only to the utmost minimum, the weight that resembles the costs for these types of areas, has to be especially high.

All these layers are provided as vectors. The Least Cost Path algorithm uses raster data. Rasterisation transforms a vector into a raster. Rasterisation can be done in two different ways. In both ways, the rasterisation can be imaged, as the old vector is superimposed on the new raster grid with the new given resolution and the new affine transformation and the coordinate reference system of the vector. Both rasterisation techniques differ in the selection of the pixel, that describe the original polygon. The pixels can be selected, if either the centre of that pixel is overlapped by the geo-object, or any part of the pixel is overlaid. The version with any part overlapped is called all touched True. The version where an overlapped pixel centre is required is called all touched False. All touched False is considered the default (see figure 1).

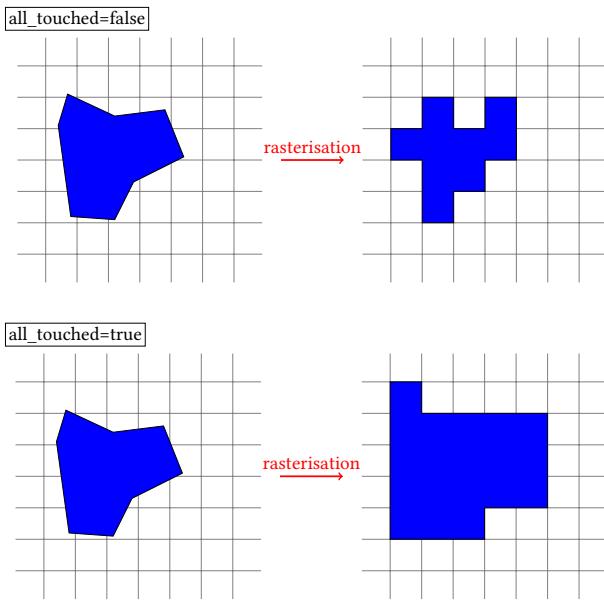


Fig. 1. Graphical example for rasterizing a vector (left blue), to a raster (right blue) with either all-touched False (above), or all touched True (below).

Table 1. Used levels of costs, the applied numerical equivalent and example layer this cost have been used for.

Cost Level	Cost	Example
Prohibited	500	Conversation areas as National Parks, Buildings
strongly Restricted	10	Conversation areas as Bird Reserve
Restricted	5	Protected Landscape Area, Industrial Areas, motorway, railway
No Restriction	0.5	Default
Preferential	0.1	Power Grid, Motorway and Railway Buffers

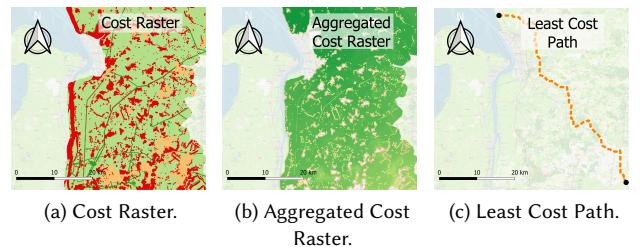


Fig. 2. Figures of Cost raster and the resulting aggregated Costs and the least cost path for a resolution of 50 m.

The complete list of layers and their processing, can be found in **Supplement S1**.

All three steps of the generation of the least cost path: generation of the cost raster, aggregation and backtracking is shown with an example for a starting cost raster of 50 m resolution and a rasterisation with all touched False (see 2).

The chosen implementation applies early stopping. Therefore, the costs for points that are not needed to try to connect to the end point are not aggregated. After finding an aggregated cost for every end point, the aggregation stops and the backtracking starts. Because the path ends at a power transformer, which is a building type, the paths ends at in a *Prohibited* area. Therefore, areas even further away from the starting point have been explored first.

3 RESULTS

In this chapter we want to show the different cost rasters, that were created from the same set of layers at different resolutions. The Least Cost Path is estimated from this set of rasters. In the last step the Least Cost Path is computed from the lower resolution rasters and compared with the Least Cost Paths computed from a high resolution raster.

3.1 Cost Raster

The cost raster contains all the costs for the geographical region of the study area. The different cost layers in the study area are aggregated by the maximum function. If the resolution is higher than the object size, then the effect of the rasterisation with all touched True or False is limited. For all touched True any part of the pixel that is covered by the object, will attribute that whole pixel to the

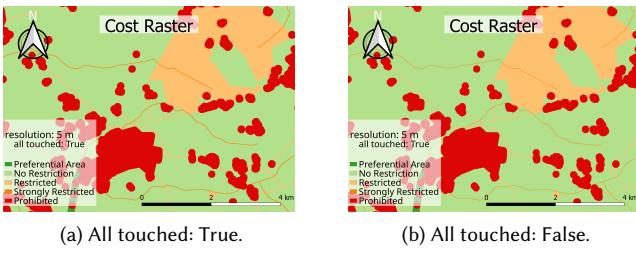


Fig. 3. Figures of the cost raster. Contrasting the for different values in all touched at a resolution of 5 m.

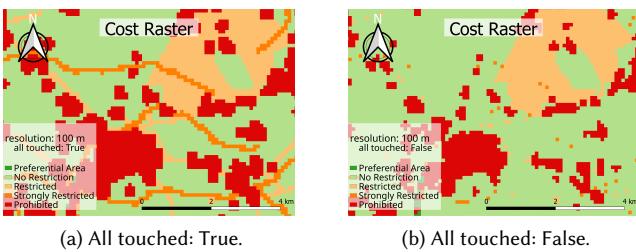


Fig. 4. Figures of the cost raster. Contrasting the for different values in all touched at a resolution of 100 m.

object. This makes the object appear a halve a pixel size larger in all directs. As can be seen in figure 3, which shows a detailed view of the costs for the village of Beverstedt. The rasterisation with all touched false will be a better description of the real size of the object, for high resolution.

In contrast, if the resolution is smaller, than the object-size this behaviour changes. In general, while the area, of the pixel increases for all touched True, the area for which the cost is overestimated also increases. As the pixel size for all touched False increases, not only does the overestimated area increases, but in addition the object is less probable situated in the centre of the pixel. Therefore, object is sampled at random. Hence, all touched false leads to a loss of information for smaller objects. Since the default cost is much smaller than the average cost, this method underestimates the cost. The figure 4 shows, that for the resolution of 100 m, that larger objects are still included in the map, but appear to be larger. But smaller objects, such as roads, are not fully or randomly included. Thus, with having larger areas and more objects, with higher costs, all touched True rasterisation might more likely lead to longer roots and more likely to block the direct spatial path.

3.2 Least Cost Paths

For each resolution the Least Cost Paths were estimated from the all_touched False and all_touched True rasters.

For the study, a start point were chosen at a transformer about 6 km north of the container terminal Bremerhaven and an end point at a transformer in the southeast of the Osterholz county.

Put this part into Discussion?

Put this part into Discussion?

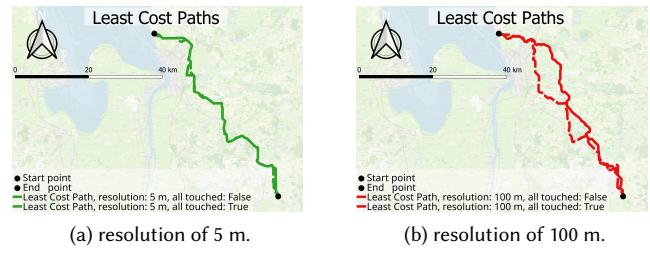


Fig. 5. Figures of the least cost paths. Contrasting the paths for different resolutions. Paths computed from all touched false raster are indicated by dashed lines. Results from all touched True are indicated by continuous lines. Higher resolutions are indicated by the color green, lower resolutions by the color red. Using OpenStreetMaps as base map.

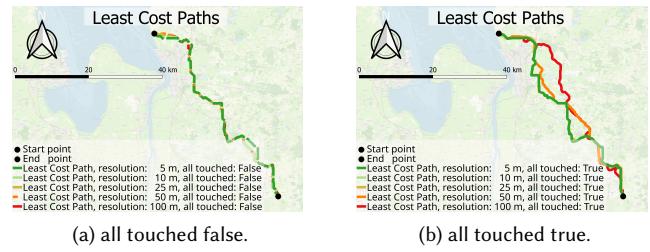


Fig. 6. Figures of the least cost paths. Contrasting the changes of the least cost paths for the different results, depending on the parameter all_touched. Paths computed from all touched false raster are indicated by dashed lines. Results from all touched true are indicated by continuous lines. Higher resolutions are indicated by the color green, lower resolutions by the color red. Using OpenStreetMaps as base map.

The distance of Least Cost Paths of the all touched false to the paths of the all touched true raster is calculated by the mean minimum distance. For each vertex P_i in the path L_1 the minimum distance between the vertex and the path L_2 is calculated and then the minimum distances are averaged (see equation 1).

$$d_{mean} = \frac{1}{|L_1|} \sum_{i=1}^n d_{min}(P_i, L_2) \Big| P_i \in L_1 \quad (1)$$

This equation is used, to measure the degree of similarity between the paths.

Table 2 shows the distance between the two paths decreases with increasing resolution. In addition, this tendency is depicted in figure 5 for the calculated cost paths of 5 m and 100 m resolutions.

At the same time, the differences in the aggregated costs per resolution remain almost constant. On one hand it can be seen, that the all_touched False underestimates the costs and that this tendency scales linearly with the resolution. On the other hand, the all_touched True least cost overestimates the aggregated costs on a linear scale of the resolution.

When estimating distance between the Least Costs Paths from all_touched True rasterisation and all_touched False at the same

Table 2. Least cost paths as length for the different resolution of the raster, including the mean minimum distance and the maximum minimum distance and the agg. costs. From the agg. costs the differences of the agg. costs and the agg. costs per resolution are given.

res /m	$l_{al=f}/m$	$l_{al=t}/m$	d_{mean}/m	d_{max}/m	agg. cost _{al=f}	agg. cost _{al=t}	Δ costs	agg. costs _{al=f/m}	agg. costs _{al=t/m}
5	76136.3	78002.0	126.0	1065.0	18665.9	19616.8	-850.00	93329.6	97584.8
10	75430.1	77936.6	277.9	1590.0	8931.2	9731.2	-799.95	89312.5	97311.8
25	75422.9	78422.9	313.8	1621.2	3354.9	3872.7	-517.78	83871.7	96816.4
50	76135.0	70620.0	1140.0	4950.0	1409.0	2300.1	-891.05	70451.2	115003.7
100	76283.8	74120.7	1946.4	6016.6	640.5	1572.3	-931.70	64051.6	167226.8

resolution the mean minimum distance between the 100 m resolution paths is 1946.41 m and between the 5 m resolution paths is 126.04 m. The similarity for the all touched False paths is higher, than for the all touched true raster. The distance for the 100 m path to the 5 m resolution path is 243.42 m for all touched false and 2109.44 m for all touched true.

When comparing the similarity between the all touched false paths themselves and the similarity between the all touched false rasters to the all touched true rasters of the same resolution: The similarity in between the all all_touched False paths is higher than, than for most paths of same resolution. Namely except for the highest resolution.

This behaviour is shown in figure 6. On a more detailed level, it can be seen, that the paths of all_touched False also converge directly to the all touched True paths, but the extent is smaller. The length of the paths only differs by a maximum of about 10 %. On the other hand, side the length of the paths can increase, because with more vertices are used with higher resolution.

The zonal stat (see table 3) for a buffer of 100 m (5 m) around the path has been used, to estimate the percentage of each costs levels around the path. When using all_touched True rasterisation at higher resolution, the tendency is to use a higher percentage of the *Preferential Level* and less of the *NoRestriction Level*. The ratio of the 100 m buffered Least Cost Path, strongly shifted to Levels lower costs.

There is no strong tendency for the all_touched False least cost paths.

3.3 Execution time

In theory, the execution time increases with the square of the resolution, because higher resolutions result in a higher number of pixels and thus data points the aggregated costs needs to be calculated for. A full logarithmic fit for several repetitions of the execution shows, that the execution time scales with power of 2.1997 ± 0.007 of the inverse resolution.

The total execution time consists of two parts. The aggregation of the costs and the back tracking of the least cost to find the path.

3.4 Faster Processing of the Cost Path Algorithm

The first step is to optimise the computational speed, by a reduced area. Another method, is to improve the prediction of the medium resolution itself and thus reduce the need for a computation in higher resolution.

3.4.1 Compare least cost paths, for overlay of both rasterisations.

For the example paths shown, all touched true rasterisation overestimates the true costs and all touched true underestimates them.

A weighted average of the costs could therefore be a more accurate measure and make estimated medium resolution Least Cost Path more similar, to high resolution paths. As all example show, the weighting should favour the all touched false raster. The best weight should be the percentage of the pixels, which is covered by the object, but this can not be calculated in this work. An alternative would be to compute the cost raster at a high resolution and reproject them to a medium resolution by a (linear) interpolation of the weights.

This will speed-up the aggregation. The time needed for the back tracking stays unchanged.

The optimal ratio of overlaying all touched false and all touched true cost raster for 10 m resolution is estimated via similarity of the resulting Least Cost Path to the path of the original high Resolution raster. The mean distance of Least Cost Paths for different ratio is estimated to the path from the all touched false raster of the higher (5 m) resolution. Table 4 shows, that the distance decreases, with increasing ratio (1:1, 2:1, 4:1) and after this optimum is reached, increases with increasing ratio (8:1, 16:1 and so on). Comparing the similarity of the paths from the rasters of the different ratios to normal paths with 10 m resolution, paths with a higher ratio of all touched true is nearer to the all touched true paths. Paths with a ratio in favour of all touched false are much closer to the all touched false paths.

move to discussion/conclusion
move to planning;

3.4.2 Compare least cost paths, for down sampled cost paths.

As an alternative to the superposition of the all touched true and false rasters for the same resolution, the all touched false raster is down-sampling to 10 m, 25 m, 50 m and 100 m (with bi-linear) interpolation. With this method, smaller structures can still be fully seen in the cost raster, although the resolution is reduced. The distances of the paths that are computed from the bi-linear down sampled raster to the path of the original 5 m resolution (all touched false) shows (see table 5), that only down-sampling to a resolution of 10 m, produces a path that is relatively close the high resolution path.

The opposite is true for the lower resolution raster which is more similar to paths computed from the all touched true cost raster. Every path from a down sampled raster is more similar to a path computed from an all touched true raster, than an all touched false raster, although the all touched false raster of the 5 m resolution was used for down sampling.

interpretation all touched true and down-sampling, both show

Table 3. resolution (r) of Category percentages of each least cost path for a buff of 100 m (5 m) around the least cost path.

res /m	all touched	rPreferential%	rNoRestriction%	rRestricted%	rstronglyRestricted%	rProhibited%
5	False	4.7 (5.4)	58.7 (58.9)	8.8 (8.4)	0.7 (0.7)	27.1 (26.7)
10	False	19.6 (33.5)	68.5 (64.5)	1.0 (0.8)	0.8 (0.3)	10.1 (0.9)
25	False	19.2 (34.2)	68.9 (64.9)	1.0 (0.2)	0.7 (0.1)	9.7 (0.6)
50	False	20.4 (33.2)	68.0 (66.2)	0.9 (0.1)	0.7 (0.0)	10.1 (0.5)
100	False	21.1 (30.7)	69.1 (68.8)	1.1 (0.0)	0.7 (0.0)	7.9 (0.4)
5	True	18.9 (28.5)	67.3 (66.4)	1.3 (1.6)	1.0 (0.5)	11.5 (3.0)
10	True	18.9 (33.7)	66.6 (63.4)	1.6 (1.4)	1.4 (0.6)	11.5 (1.0)
25	True	18.7 (31.9)	65.5 (65.5)	2.0 (1.3)	2.5 (0.7)	11.4 (0.6)
50	True	9.1 (13.0)	75.7 (83.0)	3.9 (2.0)	4.2 (1.6)	7.1 (0.4)
100	True	7.0 (10.1)	73.8 (81.9)	5.5 (3.9)	8.5 (3.6)	5.2 (0.4)

Table 4. Length of the path computed from the overlaying of all touched false and true raster and the mean distance of the paths to the paths calculated from the all touched false 5 m resolution and all touched false and true raster of 10 m resolution.

r	d _{5 al=f} /m	d _{10 al=f} /m	d _{10 al=t} /m
1:1	119.6	285.5	47.2
2:1	97.1	263.5	74.2
4:1	40.1	206.4	100.2
8:1	41.7	169.0	137.3
16:1	56.7	153.3	152.72
32:1	56.7	145.6	162.1
64:1	163.5	10.6	272.4

Table 5. Length of the path computed from the bi-linear down sampled raster and the mean distance of the paths from the down sampled raster to the paths calculated from the all touched true and all touched false raster of the same resolution as the down sampled raster.

res /m	1 /m	d _{5 m} /m	d _{al=f} /m	d _{al=t} /m
10	75980.6	59.3	219.4	143.6
25	70205.3	385.8	558.1	432.8
50	69217.9	730.8	693.4	255.7
100	66667.9	1681.3	1605.6	400.6

3.4.3 *Restrict search to a buffered around the least cost paths.* Construct a polygon from the two Least Cost Paths (all touched true and all touched false of the same resolution). Buffer the polygon with twice the maximum minimum path distance (see equation 2).

$$d_{max} = \max\left(\sum_{i=1}^n d_{min}(p_i, L_2)\right) | p_i \in L_1 \quad (2)$$

This provided the possibility to run a 2.5 m resolution cost raster and clip it to the extent of the polygon. This clipped 2.5 m raster for all touched true changed the path only slightly change.

The all touched False raster, on the other hand, leads to a completely new previously unused subroutine at the end of the path. Due to the low resolution a small path became passable. This small path is a power line next to road between protected landscape areas. The road and the protected landscape area are both *restricted* areas, while the power line is *preferred*. This shows, that the way the cost

raster is created in the first place can play a crucial role, in the end result. So that a nuance, can cause a detour. When this behaviour occurs, the polygon may not include the Least Cost Path. This polygon should therefore be overlapped with a polygon around the shortest path.

move
dis-
cus-
sion

3.4.4 *Examine the proposed solutions.* To broaden the view and verify the result, e.g. start and end points, four different routes should be found using the above strategies. Two routes should be found form the start point to two new points in the south east of the investigated area and two routes should be found from the north and north east of the study area to the end point.

For three of the four routes, the Least Cost Path estimation from the clipped raster, was able to calculated exactly the same result. For the fourth path, the Least Cost Path from the 5 m resolution raster was clipped out by the buffer around the 50 m resolution paths. The speed up from the clipping of the higher resolution raster depends on the number of pixels that, have been clipped.

Bi-linear down sampling the of the high resolution raster to a medium resolution, did not result in any benefits compared to an original medium resolution raster. The aggregated cost per resolution of the Least Cost Path from the down-sampled raster is higher, than that from the higher resolution 5 m raster and the normal medium resolution 10 m raster. In addition, the distance from these paths to the high resolution path is greater, than the distance from the original 10 m resolution path to the 5 m resolution path (see table 6).

interpretation
Why is the down-sampling result so different?
Don't know

4 DISCUSSION

In theory, the need for computing time increases with the resolution as power of two. Similarly, the use of main memory increases. This again limits the number data points, that can be processed and resolution, and probably causes difference in increase of computation time from power of 2 to a power of 2.2, because additional slower ram moduls have been used for the aggregation of higher resolution.

On the other hand, the similarity to higher resolutions only scales linear with the resolution. Thus, there is a diminishing return of smaller errors, compared to compute time and resources used.

Table 6. Length of the path, the resolution corrected costs and the mean distance to the path created from the 5 m resolution all touched false raster for the four control routes, for the reference path of constructed from the 5 m and 10 m raster and the down 5 m to 10 m down sampled raster and the 5 m clipped raster.

Route	Method	<i>length/m</i>	<i>costs_{al=f}</i>	<i>d_{mean} /m</i>
P1-E	5 m	107889.6	208547.8	
	Clipped	107889.6	208547.8	0.0
	Down	96754.2	212911.0	628.1
	10 m	107232.9	203010.2	103.5
P2-E	5 m	103706.4	155567.9	
	Clipped	103706.4	155567.9	0.0
	Down	92403.3	158238.6	639.9
	10 m	104249.9	149899.7	177.7
S-P3	5 m	102187.1	34503.8	
	Clipped	90377.1	37926.1	4465.4
	Down	94125.6	37574.9	742.4
	10 m	102461.6	32446.0	81.2
S-P4	5 m	96449.2	33865.5	
	Clipped	96449.2	33865.5	0.0
	Down	87861.1	36462.7	796.4
	10 m	96739.5	31899.3	83.5

Therefore, this work attempts a) to reduce the computation power needed and b) reduce the deviation for a given resolution compared to a higher resolution raster.

For a), to reduce the computational complexity, clipping of the high resolution has been applied, to reduce the search space of the aggregation. While this method reduces the computation time and memory usage, the backtracking part stays unchanged.

For b), two methods have been used to increase the similarity of the paths computed from the medium resolution raster, to the path of the highest resolution raster. These methods are used as surrogates for the more complex calculation of the Least Cost Path with the higher resolution. In the first method a bi-linear downsampling of the higher resolution raster has been applied and in the second method, the all touched false and true raster where averaged in different ratios, to compute the optimum weighted cost raster. While the second method of using an averaged raster, a higher similarity to the path from the highest resolution raster, the downsampling method is simpler and does not need to be optimised for the given cost. This disadvantage could be reduced by normalising the costs.

This early stopping may result in suboptimal paths around the end points for some edge cases, where the connection via another neighbour might be more optimal.

The set of rules that are used create the cost raster, includes a rule to create buffer around buildings which is set to the level *prohibited* areas. In all touched false rasters. The resolution of the medium level raster needs to be high enough to show every detail. At least in the magnitude of the minimum object size plus twice its buffer. This is true for the 10 m resolution raster and less true for the 25 m resolution raster that misses some details for roads for all touched false raster. Other details such as rivers and houses, are already included in the lower resolution raster, due to larger buffers. The

Least Cost Path algorithm searches for an optimal path as a line. As lines do not have a width, the route found might contain bottlenecks, that have a smaller width than the object that should be placed there. Therefore, the used resolution should not be smaller than, the width of the object that should be placed. This can be avoided by downsampling, but by weighting the medium resolution all touched true or false rasters.

This paper examines the effect of computational costs and deviation of the results, is examined for a very limited set of points. Also, only the cost of finding the Least Cost Path from a single start point, to a single end point has been considered. If multiple endpoints are used, the computational cost for the aggregated cost raster has only to be paid once.

If multiple paths are calculated from a single raster, the speed-up benefit is reduced. Especially, pre-calculation on medium resolution raster and clipping around a buffering of the resulting medium resolution paths becomes less effective. As the number of paths increases, fewer pixels are clipped. The Least Cost Path algorithm does only select the single most cost-effective path. Therefore, paths of similar, but slightly higher costs remain unknown. In additional, slight variations on the costs rasters can lead to very different paths, although the costs will not change much. An end-user may be interested in selecting a path from a set of similar aggregated costs and applying their own evaluation criteria. This can be achieved a by adjusting the backtracking and return polygons, or by applying perturbation on the costs.

In this work, the intermediate cost raster layers are aggregated using the maximum function. Another possible aggregation function is the sum or average. Each aggregation function can be justified, by a different interpretation of the cost and its scale.

When the *prohibited* level is used as the highest level, then summing the two highest levels would result in a new highest level. Also, the maximum function does not interfere with the nodata value. Although this can be done by a nansum- / nanmean-function, if the nodata value is set to *not a number* during the aggregation. The disadvantage of aggregation with the maximum function is, that this aggregation is unable to distinguish between nuances of different overlapping intermediate costs. On sum or average aggregated rasters, one can distinguish between, different sublevels.

The fact that all touched false rasters produce more similar results than high resolution raster, is probably due to the fact, that the default level is relatively low. As the default level increases, the effect would probably be reduced for low resolution rasters. For high resolution raster, the effect would still be present, because the fact, that the raster pixel centre is used for sampling, reflects the original geometry better.

This effect of the similar aggregated costs per resolution could also be seen in the test paths, even when the paths varied greatly with the change in resolution or algorithm. This could be an indication of an even spatial distribution of the costs.

The all touched true cost raster shows every detail, but the sampling with all touched true increases the size of the features. The fact that the aggregated costs per resolution for all touched true rasters overestimate the costs when computing the path from a low resolution raster, might be due to the fact, that the values of

the costs are not uniformly distributed, but that the high costs are much more frequent, because the costs are exponential scaled.

5 RELATED WORKS

The different models of the power system, that are used in the expert system range from not modelling the grid at all to models that include Kirchhoffs laws [6]. The calculation of a power system is complex, because changing one edge changes the flow in all parts of grid and the actual grid data are confidential [6]. Some models consider not only the grid of one nation, but consider neighbouring states or the whole European power system [20]. Older national power grid models are e.g. are optimising the well fare, but economic modelling is not sufficient for planning modern routes, as the aspect of environmental sustainability, security of supply and the public acceptance play an increasingly important role [17] in modern planning.

In contrast to a GIS analysis, these other factors can be studied done with a multi-criteria decision analysis (MCDA) [6]. Stakeholders as decision makers can be included and combined with an expert system [6].

The uncertainties associated with MCDA data uncertainties, preferential uncertainties and model uncertainties are investigated by a with a sensitivity analysis [6] or simulation [18]. Both inter- and intra-criteria preferential uncertainties [19] can be considered.

6 CONCLUSION

The cost of computing of the Least Cost Path scales with the square of the resolution. The difference between the aggregated costs of the paths per resolution computed from the all touched false raster and the all touched true raster only shows a linear decrease. Therefore, the gain in accuracy per compute time decreases. The presented methods have attempted to circumvent this bottleneck. When these strategies are applied to a medium resolution raster, the compute time for high resolution results can successfully be reduced, without compromising the run time for worse distances to the least cost path from the high resolution raster. The paths can change significantly even for a small change in total cost. Therefore, to develop an alternative backtracking algorithm, that generates a corridor of costs might be a good strategy, to offer alternative paths and at the same time show variations between these paths. An alternative for future methods, would be to specify a range of costs and compute the aggregation of the costs and superimpose these aggregations and compute the path by backtracking from the superimposed cost raster. This again increases the computation time.

In an actual search for Least Cost Path search, a survey could be used as a method to estimate the costs. If the sample size of the survey is large enough, the weights could take into account local differences in relative acceptance.

Only changes in the algorithm have been applied in the search for acceleration. Therefore, other methods such as just-in-time compilation have not been tested.

REFERENCES

- [1] EßER-FREY, Anke: *Analyzing the regional long-term development of the German power system using a nodal pricing approach*. <http://dx.doi.org/10.5445/IR-1000028367>. Version: 2012
- [2] LEUTHOLD, Florian U. ; RUMANTSEVA, Ina ; WEIGT, Hannes ; JESKE, Till ; HIRSCHHAUSEN, Christian von: Nodal Pricing in the German Electricity Sector - A Welfare Economics Analysis, with Particular Reference to Implementing Offshore Wind Capacities. In: *SSRN Electronic Journal* (2005). <http://dx.doi.org/10.2139/ssrn.113782>. – DOI 10.2139/ssrn.113782. – ISSN 1556-5068
- [3] SULEIMAN, Sani ; AGARWAL, V C. ; LAL, Deepak ; SUNSI, Aminuldeen: Optimal Route Location by Least Cost Path (LCP) Analysis using (GIS), A Case Study. In: *International Journal of Scientific Engineering and Technology Research* 4 (2015), Oktober, Nr. 44, S. 9621–9626
- [4] SCHÄFER, Benjamin ; PESCH, Thimo ; MANIK, Debsankha ; GOLLENSTEDE, Julian ; LIN, Guosong ; BECK, Hans-Peter ; WITTHAUT, Dirk ; TIMME, Marc: Understanding Braess' Paradox in power grids. In: *Nature Communications* 13 (2022), September, Nr. 1, 5396. <http://dx.doi.org/10.1038/s41467-022-32917-6>. – DOI 10.1038/s41467-022-32917-6. – ISSN 2041–1723. – Number: 1 Publisher: Nature Publishing Group
- [5] *Nettstromerzeugung in Deutschland 2020: erneuerbare Energien erstmals über 50 Prozent* - Fraunhofer ISE. <https://www.ise.fraunhofer.de/de/presse-und-medien/news/2020/nettstromerzeugung-in-deutschland-2021-erneuerbare-energien-erstmals-ueber-50-prozent.html>. Version: Januar 2021
- [6] BERTSCH, Valentin ; FICHTNER, Wolf: A participatory multi-criteria approach for power generation and transmission planning. In: *Annals of Operations Research* 245 (2016), Oktober, S. 177–207. <http://dx.doi.org/10.1007/s10479-015-1791-y>. – DOI 10.1007/s10479-015-1791-y
- [7] DIJKSTRA, E. W.: A note on two problems in connexion with graphs. In: *Numerische Mathematik* 1 (1959), Dezember, Nr. 1, 269–271. <http://dx.doi.org/10.1007/BF01386390>. – DOI 10.1007/BF01386390. – ISSN 0945-3245
- [8] *Schutzgebiete in Deutschland*. <https://geodienste.bfn.de/schutzgebiete?lang=de>. Version: 2015
- [9] *Digitales Landschaftsmodell 1:250 000 (Ebenen)*. <https://gdz.bkg.bund.de/index.php/default/open-data/digitales-landschaftsmodell-1-250-000-ebenen-dlm250-ebenen.html>. Version: 2021
- [10] BOEING, Geoff: OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. In: *Computers, Environment and Urban Systems* 65 (2017), September, 126–139. <http://dx.doi.org/10.1016/j.compenvurbsys.2017.05.004>. – ISSN 0198-9715
- [11] *OpenGeoData.NI*. <https://opengeoedata.lgl.niedersachsen.de/#lod1>. Version: 2022
- [12] *Metropolplaner*. <https://metropolplaner.de/metropolplaner/>. Version: 2022
- [13] Welcome to the PyWPS 4.3.dev0 documentation! — PyWPS 4.3.dev0 documentation. <https://pywps.readthedocs.io/en/latest/index.html>. Version: 2016
- [14] *Flask*. <https://palletsprojects.com/p/flask/>
- [15] *Birdy 0.8.1 documentation*. <https://birdy.readthedocs.io/en/latest/>
- [16] *LeastCostPath/dijkstra_algorithm.py at master · Gooong/LeastCostPath*. <https://github.com/Gooong/LeastCostPath>. Version: Dezember 2022
- [17] HAUFF, Jochen ; HEIDER, Conrad ; ARMS, Hanjo ; GERBER, Jochen ; SCHILLING, Martin: Gesellschaftliche Akzeptanz als Säule der energiepolitischen Zielsetzung. In: *ET, Energiewirtschaftliche Tagesfragen* 61 (2011), Oktober, Nr. 10, 85–87. <https://www.osti.gov/etdeweb/biblio/21522981>
- [18] BUTLER, John ; JIA, Jianmin ; DYER, James: Simulation techniques for the sensitivity analysis of multi-criteria decision models. In: *European Journal of Operational Research* 103 (1997), Dezember, Nr. 3, 531–546. [http://dx.doi.org/10.1016/S0377-2217\(96\)00307-4](http://dx.doi.org/10.1016/S0377-2217(96)00307-4). – DOI 10.1016/S0377-2217(96)00307-4. – ISSN 0377-2217
- [19] BERTSCH, Valentin ; TREITZ, Martin ; GELDERMANN, Jutta ; RENTZ, Otto: Sensitivity analyses in multi-attribute decision support for off-site nuclear emergency and recovery management. In: *International Journal of Energy Sector Management* 1 (2007), Mai, Nr. 4, S. 342–365. <http://dx.doi.org/10.1108/17506220710836075>. – DOI 10.1108/17506220710836075
- [20] DIETRICH, Kristin ; LEUTHOLD, Florian ; WEIGT, Hannes: Will the Market Get it Right? The Placing of New Power Plants in Germany. In: *Zeitschrift für Energiewirtschaft* 34 (2010), Dezember, Nr. 4, 255–265. <http://dx.doi.org/10.1007/s12398-010-0026-9>. – DOI 10.1007/s12398-010-0026-9. – ISSN 1866–2765

Received 14 March 2023