Combining GIS with Fuzzy Logic and Scenario Planning to Deal with Demographic Change. A Case Study on Medical Supply in Rural Germany

Michael MÜLLER, Markus SCHAFFERT

Key words: Fuzzy logic, Geospatial Information, GIS, Medical supply, Scenario planning

SUMMARY

Demographic transition in rural Germany is often characterized by aging and population decline and poses challenges for all levels of administration. It leads to far-reaching consequences on the local level, for example with regard to the infrastructures of medical supply. Smart management of demographic change requires tools that can handle its spatial and temporal variability. Geographic Information Systems (GIS) are suitable as a basis for corresponding software solutions; at the same time, the extension of existing GIS functions is necessary. For demographic transition on the local level, especially uncertainties and fuzziness regarding future developments and incomplete data sets pose challenges that have to be taken into account. In this paper, we introduce fuzzy logic and scenario planning as a complement to GIS and present a case study to prove the applicability of a combined usage. The case study focuses on medical supply for the elderly in rural Bavaria. Three software packages were employed to support the implementation: QGIS, Parmenides EIDOS, and DEWIS.

Our results show that fuzzy logic, scenario planning and GIS can be applied jointly. We believe that the combined usage supports the inclusion of human decisions in GIS analyses in a more natural way by bringing human estimates and computational steps closer together. In our case study, however, the linkage between the individual software tools was loose. In the future, we want to integrate them more strongly and develop them into a spatial decision support system. A core challenge on the way to such a system is the identification of suitable operators, weightings and processing with fuzzy logic.

Combining GIS with Fuzzy Logic and Scenario Planning to Deal with Demographic Change. A Case Study on Medical Supply in Rural Germany

Michael MÜLLER, Markus SCHAFFERT

1. INTRODUCTION

The ongoing demographic change in Germany affects almost all areas of life and has far-reaching consequences, for example for the local medical infrastructure (cf. Swiaczny et al. 2010, Schöder et al. 2018, Tillmann et al. 2019). In order to deal adequately with demographic transition, it is necessary to develop tools that are able to cope with the distinct variability of demographic processes in space and time (Schaffert 2015, Wolff et al. 2022). Since many consequences of demographic change relate to space, the use of Geographical Information Systems (GIS) lends itself as a basis for such tools. However, in order to be able to use GIS properly in spatial planning in the context of demographic change, it is necessary to expand the functions of conventional GIS software (cf. Lechner et al. 2015, Schaefer et al. 2020).

In this paper, we present scenario planning and fuzzy logic as methods to complement GIS in dealing with demographic change and show advantages of such a mixed-methods approach using the example of a case study in the rural district (Landkreis) of Tirschenreuth in Bavaria (Germany). The case study focuses on medical supply for older people and respective facilities.

The implementation combines three different software packages: QGIS, Parmenides EIDOS and DEWIS. QGIS is an open source GIS. It serves as the basis for the management, processing and visualisation of geospatial data in our case study (https://qgis.org). DEWIS is the working title of a software that is being developed at Anhalt University of Applied Sciences (Benndorf et al. 2013). It allows fuzzy logic algorithms to be applied to such data. It extends the capabilities of QGIS for fuzzy logic calculation and offers further functions such as a model for population forecasts. While scenario planning can be seen as an entire informal planning process that is qualitatively led and often participatory in nature, individual steps within this process can be supported by software. One example for such a supporting tool is Parmenides EIDOS. It facilitates, for example, the visualisation of influencing factors and their weighting (see Figure 3), the checking for consistency of future developments or the identification of courses of action (https://www.parmenides-eidos.com/).

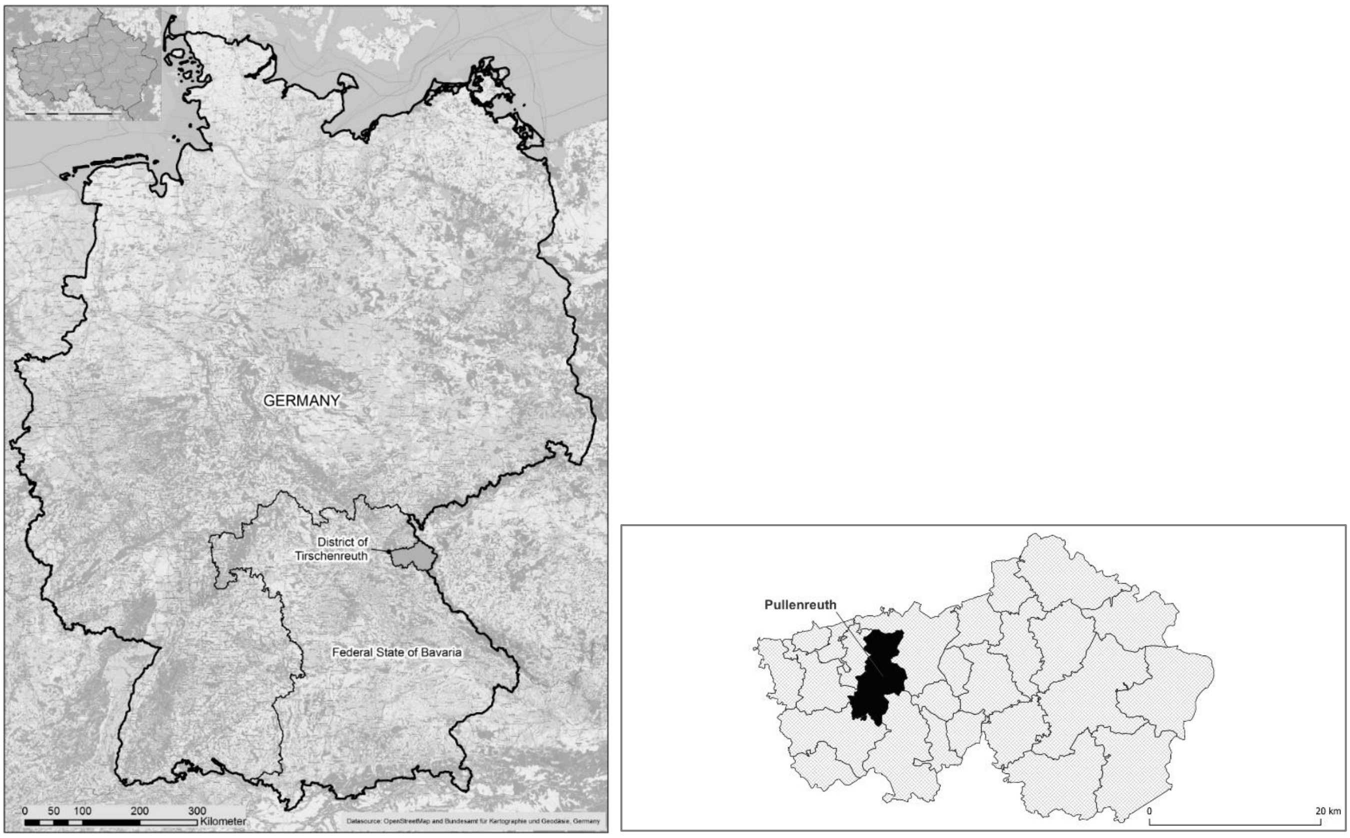

Figure 1 The research region – the district of Tirschenreuth – is located in North-East Bavaria in Germany. In a supplementary map (right), the administrative boundaries of all municipalities of the district of Tirschenreuth are depicted. It highlights Pullenreuth, since figure 5 and 6 centre on this village. The data of both maps come from Germany´s Federal Agency for Cartography and Geodesy and partly from the OpenStreetMap project (OSM 2023).

2. METHODOLOGY

Scenario planning

Scenario planning is a combination of methods with which future situations, so-called scenarios, can be generated in a structured and systematic way. Scenario planning predominantly follows a qualitative approach: For example, scenarios, by which we mean the concrete results of scenario planning, are often developed as purely textual descriptions of possible future developments and conditions (for instance Geldenhuys 2008, Schoemaker 2020, Walters 2021). To this end, the authors of the scenarios condense their ideas about different possible future developments according to their expertise in order to arrive at plausible and consistent representations of the future (often a trend scenario, a worst-case scenario and a best-case scenario, Schaffert 2015). The information that scenario authors draw on can come from a variety of sources, such as scientific studies, experts' experiences, or ideas and stories from old or young people. This information is often obtained in workshops of different types (with a view to repetition rate, number of participants or target groups).

In contrast to simulations that result from mathematical modelling, scenarios as an outcome of scenario planning clearly take into account the eventuality of breaks in trends, even if the reason for the break seems to be unlikely at the moment. This approach makes scenario planning robust in dealing with the future and thus does not run the risk of merely reproducing today's knowledge and conventions. This flexibility helped scenario planning, which originally was developed by Herman Kahn in the 1940s for military purposes, to achieve a breakthrough in strategic corporate management as well as in environmental and natural sciences (Van der Heijden 2005, Rialland & Wold 2009). Today, scenario planning is also widely used in spatial planning, where it can be utilized as a supplement for computational models, such as population projections. In German urban and regional planning, however, the method is often only applied in the context of research projects or one-off participation formats, for example to jointly develop a city vision. One reason for this is that scenario planning, which is usually carried out in this field in workshops, is too time-consuming for permanent use (Schaffert 2015).

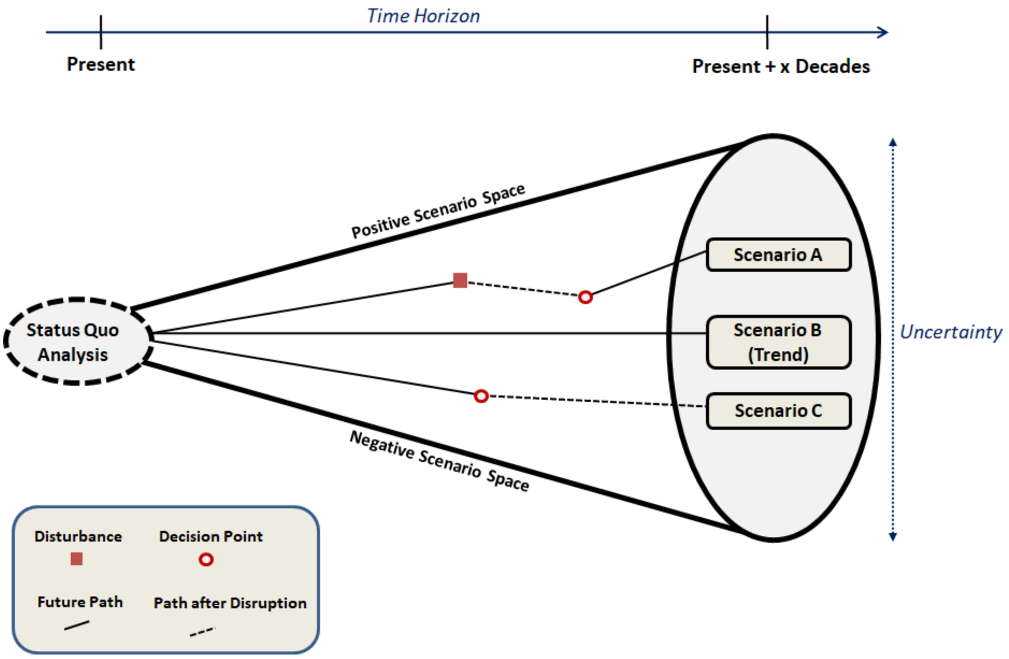

Figure 2 The basic idea of scenario planning can be illustrated using the analogy to a funnel: Scenario planning begins with determining the topic and space under examination and analyses the current status quo, including past developments. Starting from the present, a corridor is defined within which future developments can take place (Negative and Positive Scenario Space). The further one moves from the present towards the future, the more the influence of today's constellations decreases, uncertainty grows and the corridor of conceivable developments opens up in a funnel shape. Different development paths lead to differing visions of the futures.

Fuzzy Logic

In the traditional set theory by Cantor there are only two possibilities of true statements respectively logic states: either the statement is true or it is not correct and consequently false (Eiden 2002). However, there are situations in which more than one thinkable solution seems to be right. Drawing on Łukasiewicz´s work (three-value logic) Zadeh arrived at the conclusion that one could use the state between false and true (resp. zero and one) as well (Zadeh 1965). However, he did not only extent the model of the traditional set theory, but also developed a complete fuzzy set theory with all the necessary mathematical relations and possibilities of computation for fuzzy logic (Kruse et al. 1995). Since the beginning of this century, fuzzy logic has been used in many areas, even outside its original application domain (control engineering). Today, for example, it has already been used to deal with demographic change (cf. Müller 2010, Grekousis et al. 2013, Naumann & Nadler 2022).

GIS analyses and database queries usually work with exact threshold values. In the real world, however, thresholds are often not in discrete dimensions. These analyses therefore produce exact results that do not reflect the complexity and nuances of reality. This leads to challenges and rises uncertainty especially when several factors – in the field of medical supply the factors age, place of residence and distance to doctors are worth mentioning – are linked and processed.
The example of a reachability calculation with the parameters "distance in metres" (from point A to B) and "age in years" (person's age) illustrates this: In an ordinary GIS-based walkability calculation, exact threshold values need to be defined, for instance 300 metres (distance) and 70 years (age). A combination of boundary values, for example "301 metres and 69 years", can then no longer be considered straightforwardly. However, it makes sense to include adjacent values as well. A vigorous senior of 75 years might regard facilities in 750 metres' distance as "within easy walking distance" and for a younger person due to health restrictions, shorter distances can already be challenging. If the assessments of all seniors involved in a particular area are not known in relation to the range of the destinations, the use of fuzzy logic lends itself. Fuzzy logic is based on fuzzy sets. Here, the set is not defined by the objects that are (or are not) elements of this set, but by the degree to which they belong to it. Consequently, in fuzzy logic, adjacent values can be included in the calculation to a certain extent. Fuzzy logic transfers numbers by the aid of membership functions and extends the model by linguistic variables, capable to cover adjacent values. One element is related to a certain set by membership functions. The degree of membership (between zero and one) steers how intensive this element is part of the set. Linguistic expressions offer an approach to the interpretation of fuzzy phrasing such as "the medical facility is near" instead of "the distance to the medical facility amounts to 239 metres".

Fuzzy logic follows a basic course:

1. Data input and fuzzyfication: This is the transfer of crisp data inputs into fuzzy sets using membership functions. Linguistic variables of a parameter facilitate the relation to a class with this operation. The parameter "distance" can be divided into "near", "medium" and "far", for example.
2. Inference: This is the logic (in case of the fuzzy logic: approximated) reasoning by “if-then”-rules in corresponding set operations. The individual “if-then”-rules are united in a so-called rule-base.
3. Defuzzyfication: This term describes the transformation of fuzzy inference-results back into crisp data.

A central aspect of fuzzy logic is the linking of individual "if-then" sentences with the help of operators. Such operators have the disadvantage that they cannot fully represent the flowing range of transitions of membership functions. Therefore, we have supplemented the basic functions with a compensatory operator (using *fuzzy*AND, cf. Jaanineh and Maijohann, 1996).

3. COMBINATION OF METHODS – CASE STUDY IN THE RURAL DISTRICT (LANDKREIS) OF TIRSCHENREUTH

Scenario planning and fuzzy logic show promising qualities that, in combination with GIS, prove useful for a handling of the spatial dimension of demographic change and medical supply at the local level. This statement appears convincing, at least in theory. A case study was used to test whether this statements also keeps its promise in practice.

While a direct link, for example in the form of an interface, between scenario software tools and GIS has not yet been realised, scenario planning software with fuzzy logic extensions already exists. For example, the software Szeno-Plan (Szeno-Plan 2012: 26) uses fuzzy logic to find out probabilities of occurrence and to calculate the influence of descriptors. A descriptor is a describing parameter (for example the level of education) of a concrete topic. Each descriptor has one or several distinctions (for example a high or low level of education). Different scenario planning software packages, for example the comparatively complex EIDOS (Parmenides Eidos 2023), do not have this functionality, but derive their advantage from other fields. Supported by EIDOS, we developed medical supply scenarios for the district of Tirschenreuth in a first step. We used this software as part of a scenario planning exercise that involved expert knowledge and workshops with students and identified drivers of the future development (Figure 3). The workshops were designed so that students could validate and add to a predefined list of possible drivers and roughly weight them. The consistency of the resulting future manifestations was then worked out and ensured with the support of the software.

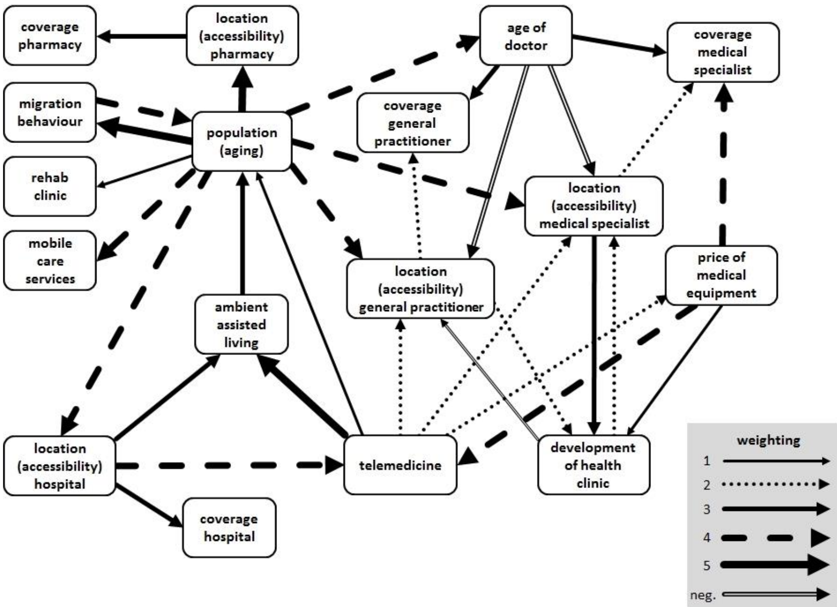

Figure 3 shows drivers of the future development of medical supply. The arrows imply the positive and negative relations (weights) between the drivers. The consistency checks of future values of the drivers were carried out with EIDOS. For reasons of clarity, not all factors are shown in the figure.

Furthermore, we identified decision points and disturbances, such as hospital or school closures, and corresponding answers like an increase in out-migration or in the usage of telemedicine in the municipalities. In a second step, these findings were incorporated into QGIS and potential spatial effects of the driver's development on Pullenreuth and the surrounding municipalities were assessed and examined. For this purpose, questions such as, "which medical office among several will be closed (in a negative scenario)?" were asked and answered in the manner of a planning game.
In a third step, maps (in the form of individual GIS layers) were created, for example for the locations of medical offices, the road network and the homes of older people. In addition, we extrapolated the age of the residents at the housing addresses into the future using the DEWIS population forecast module. The programme takes the population register of all municipalities of the district of Tirschenreuth as data basis and applies the cohort component method to these data (cf. Schaffert, & Höcht 2018: 430). To this end, the future population is calculated on the basis of the current population structure (and its development in the past), taking into account "deaths", "births", "inflows" and "outflows". The concept and functioning of the programme are described in Benndorf et al. (2013). Based on the current residential addresses and the projected age of the residents, the reachability of medical facilities was calculated. The data set we used for these analyses came from the Association of Statutory Health Insurance Physicians Bavaria (doctors' offices – the destination of the reachability calculation), the municipalities of the district of Tirschenreuth (age at residential addresses – the start points of the reachability calculation), and from the open data project OpenStreetMap (road network connecting start points and destinations).

Then, using DEWIS, the layers were mathematically combined by Fuzzy logic, applying the minimum function of the AND-linkage according to Mamdani (fuzzy logic algorithm, c.f. Müller 2010, Figure 4).

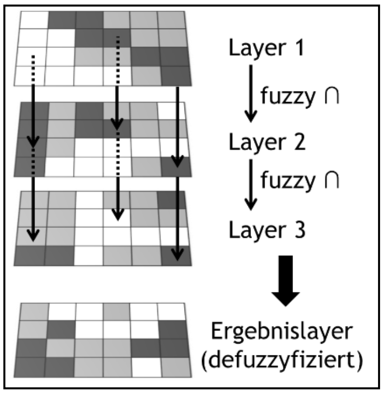

Figure 4 shows the principle of relating two or more layers with fuzzy logic in a GIS (Schaffert et al. 2011). Raster layers were chosen for illustrative purposes. DEWIS also allows working with vector geometries, and in the case study we used vector data. In this way, age and the values of the reachability calculation for all residential addresses (points) were linked via fuzzy logic.

The settings of the membership functions were first chosen according to insights gained from literature research and then were gradually improved. We drew on information from the previous scenario planning exercises for this purpose. The defuzzified results were subsequently visualized in QGIS (Figure 6).

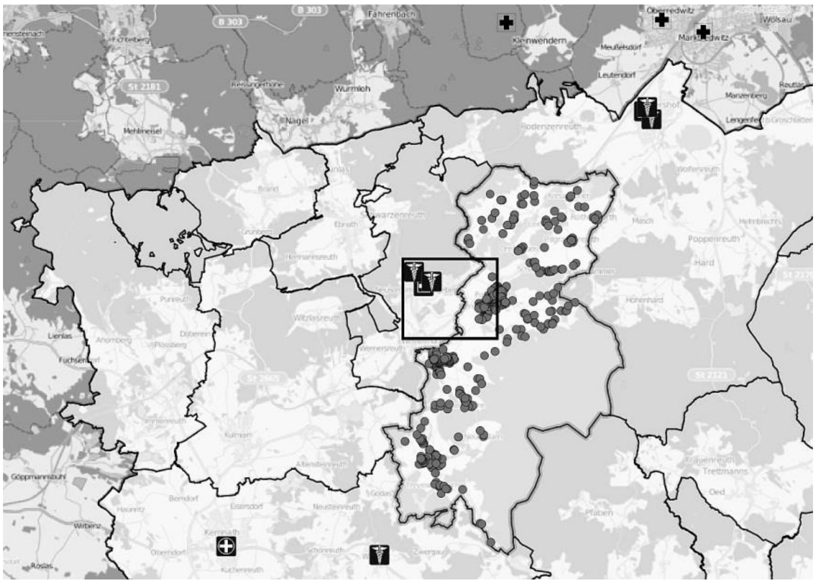

Figure 5 shows the residential addresses (points) in the village of Pullenreuth. The rectangular signatures outside of Pullenreuth represent the location of available medical facilities. Signatures with white crosses stand for hospitals, black crosses for medical institutions, which are somewhat less well equipped than hospitals. The signature with the rod of Asclepius denotes the general practitioners' offices.

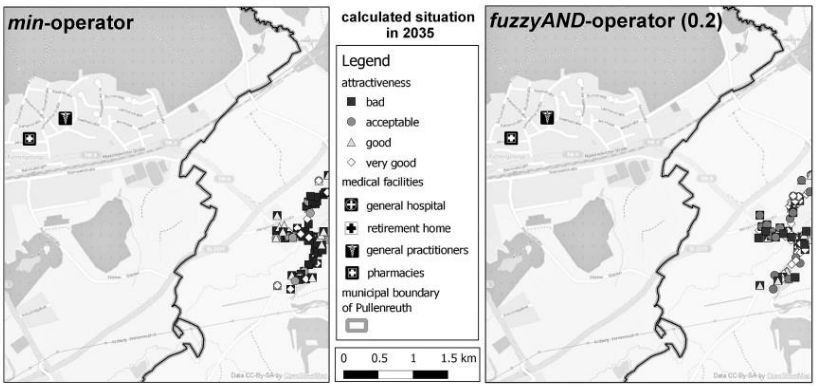

Figure 6 shows a reachability scenario for medical facilities in the year 2035 depending on the age (at each residential address) at that time by using the *min*- and *fuzzy*AND operator (λ=0.2). We systematically adjusted and falsified the results due to privacy reasons in both maps.

The map in Figure 6 shows the categorized results obtained by using the *min*-operator and *fuzzy*AND for relating reachability and age. The *min*-operator links reachability and age without giving preference to one of these two topics by a certain weighting. In contrast, the *fuzzy*AND linkage allows for a weighting. Accordingly, the *fuzzy*AND linkage produces results that differ from those of the min-operator: the application of *fuzzyAND* suggests a slightly better situation for the residents (in this map section).

4. CONCLUSION AND OUTLOOK

The quality of the result in fuzzy logic is strongly influenced by the choice of operators, tresholds or weights. This applies to fuzzy logic in general (Bill 2010) and was also evident in the case study presented. Therefore, further knowledge must be gained from additional studies in test regions that use different operator settings and weightings in the context of demographic transition.

Despite this challenge, the advantages of the mixed methods approach outweigh the disadvantages. For example, by embedding fuzzy logic and GIS in scenario planning, spatial images of the future can be efficiently built. Thus, the participants of a scenario workshop can nominate parameters, put them up for discussion and suggest a weighting of the parameters in a dialogue. This information can then become input values for fuzzy logic-based calculations and weightings. The results of the computation can be brought back to the workshop afterwards, where they can be discussed, questioned or validated. Maps and other geospatial information are particularly suitable as a basis for discussion because they speak a language that is understood by many people (even with different professional backgrounds) and can also present complex spatial interrelationships in an easily understandable way (Lung-Amam, & Dawkins 2020, Schaffert et al. 2020). In this way, parts of scenario planning in a spatial planning context can be operationalized with the help of software. This in turn opens up possibilities for making the use of scenario planning in urban and regional planning more efficient in the future.

In the case study, we linked the individual software tools QGIS, DEWIS and EIDOS comparatively loosely. In the future, we want to make the combination more direct and develop a more integrated tool in the sense of a spatial decision support system.

ACKNOWLEDGEMENT

The article was authored in the project RAFVINIERT – Raumintelligenz für die integrierte Versorgung von Seniorinnen und Senioren in ländlichen Quartieren (Spatial Intelligence for the Integrated Supply of Senior Citizens in Rural Neighbourhoods), funded by the Carl Zeiss Foundation. The case study results presented were partly carried out in earlier years, before the project was launched. The software DEWIS in its basic form was developed at Anhalt University of Applied Sciences.

REFERENCES

Benndorf, F., Bergfeld, A., Schaffert, M., Koppers, L., 2013, Schlussbericht des BMBF-Forschungsprojekts „DemoGI – Geoinformatik-Methoden und -Werkzeuge zur Analyse, Anpassung und Bewältigung des demographischen Wandels“. Dessau-Roßlau.

Bill, R., 2010, Grundlagen der Geo-Informationssysteme. vol. 5, Wichmann, Berlin.

Eiden, W., 2002, Präzise Unschärfe. Informationsmodellierung durch Fuzzy-Mengen. Ibidem-Verlag. Stuttgart

Geldenhuys, C. A., 2008, A change navigation-based scenario planning process: an afrocentric, developing country perspective, Ph.D.-Thesis, University of Johannesburg.

Grekousis, G., Manetos, P., & Photis, Y. N., 2013, Modeling urban evolution using neural networks, fuzzy logic and GIS: The case of the Athens metropolitan area. Cities, 30, 193-203.

Jaanineh, G. and Maijohann, M., 1996, Fuzzy-Logik und Fuzzy-Control. Vogel Verlag, Würzburg

Kruse, R., Gebhardt, J. Klawonn, F., 1994, Foundations of fuzzy systems. Reprinted. Wiley. Chichester.

Lechner, A. M., Harris, R. M., Doerr, V., Doerr, E., Drielsma, M., & Lefroy, E. C., 2015, From static connectivity modelling to scenario-based planning at local and regional scales. Journal for Nature Conservation, 28, 78-88.

Lung-Amam, W. S., & Dawkins, C. (2020). The power of participatory story mapping: Advancing equitable development in disadvantaged neighbourhoods. Community development journal, 55(3), 473-495.

Müller, M., 2010, Entwicklung und Bewertung eines Java-basierten Fuzzy-Logik Tools. Diploma thesis Hochschule Coburg. Coburg.

Naumann, L. L., & Nadler, M., 2022, GIS-basierte multidimensionale Verfahren zur optimalen Baulandentwicklung im Städtebau anhand des Beispiels des innerstädtischen Projekts Holsten-Areal in Hamburg. Raumforschung und Raumordnung/Spatial Research and Planning, 80(2), 202-218.

OSM – OpenStreetMap, https://www.openstreetmap.org (accessed 14.02.2023). Parmenides EIDOS, https://www.parmenides-eidos.com/eidos9/us/ (accessed 14.02.2023).

Patras, F., & Patras, F., 2020, Cantor and Set Theory. The Essence of Numbers, 91-99.

Rialland, A., Wold, K. E., 2009, Future Studies, Foresight and Scenarios as basis for better strategic decision, IGLO-MP2020 Working Paper 10-2009, online: http://www.iglo-mp2020.no/publications/IGLO_WP2009-10_Scenarios.pdf

Schaffert, M., Müller, M., & Benndorf, F., 2011, Kommunen im Zeichen des demografischen Wandels. Planungsunterstützung durch kombinierte Nutzung von Melderegister und Geobasisdaten. Angewandte Geoinformatik, 503-512.

Schaffert, M., 2015, Scenario Planning as a Tool for Handling Demographic Change in Rural German Municipalities. Research Collection, 195.

Schaffert, M., Becker, T., Steensen, T., & Wenger, F. C., 2020, Qualitative GIS to Support Sustainable Regional Branding and Transition in Northern Germany. In: Methods and Concepts of Land Management: Diversity, Changes and New Approaches (European Academy for Land Use and Develoment).

Schaffert, M., & Höcht, V., 2018, Geokodierte Meldedaten als Basis bedarfsgerechter Planungen in ländlichen Gemeinden und Regionen. Raumforschung und Raumordnung | Spatial Research and Planning, 76(5), 421-435.

Schaefer, M., Thinh, N. X., & Greiving, S., 2020,. How can climate resilience be measured and visualized? Assessing a vague concept using GIS-based fuzzy logic. Sustainability, 12(2), 635.

Schoemaker, P. J., 2020, How historical analysis can enrich scenario planning. Futures & Foresight Science, 2(3-4), e35.

Soria-Lara, J. A., Ariza-Álvarez, A., Aguilera-Benavente, F., Cascajo, R., Arce-Ruiz, R. M., López, C., & Gómez-Delgado, M., 2021, Participatory visioning for building disruptive future scenarios for transport and land use planning. Journal of Transport Geography, 90, 102907.

Schröder, L., Flägel, K., Goetz, K., & Steinhäuser, J. (2018). Mobility concepts and access to health care in a rural district in Germany: a mixed methods approach. BMC Family Practice, 19, 1-10.

Swiaczny, F., Graze, P., & Schlömer, C., 2008, Spatial impacts of demographic change in Germany. Zeitschrift für Bevölkerungswissenschaft, 33(2), 181-205.
Szeno-Plan Benutzerhandbuch Version 4.2.6, SINUS Software und Consulting GmbH, Braunschweig. http://www.sinus-online.com/szeno-plan-top.html
Tillmann, J., Just, J., Schnakenberg, R., Weckbecker, K., Weltermann, B., & Münster, E., 2019, Challenges in diagnosing dementia in patients with a migrant background-a cross-sectional study among German general practitioners. BMC family practice, 20(1), 1-10.
QGIS, https://www.qgis.org (accessed 14.02.2023).
Van der Heijden, K., 2005, Scenarios: the art of strategic conversation. John Wiley & Sons.
Walters, E. L., 2021, Considering uncertain futures in shrinking regions: Inventing, reinventing, and responding to narratives through scenario planning, Doctoral dissertation).
Wolff, M., Haase, A., Leibert, T., & Cunningham Sabot, E., 2022, Calm ocean or stormy sea? Tracing 30 years of demographic spatial development in Germany. Cybergeo: European Journal of Geography.
Zadeh, L. A., 1965, Fuzzy Sets. In: Information and Control 8, pp. 338-353. Academic Press, New York & London.

CONTACTS

Markus Schaffert

Hochschule Mainz, i3mainz
Lucy-Hillebrand-Str. 2
55128 Mainz, Germany