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Using Space Syntax For Estimation Of Potential Disaster Indirect Economic Losses

Abstract

The paper is aimed at estimation of indirect economic losses resulting from natural disasters. Generally, these losses are defined as interruptions in economic activities and are not related to the damaged enterprises. Even limited physical damage to property and infrastructure caused by natural disaster can produce chain reaction of losses in supply chain within a certain region.

The Space Syntax Methodology is developed and used for accessing the characteristics of buildings, cities or the surrounding space in general. Although the methodology was primarily developed as urban planning method, it was also applied in the field of social and economic networks. Various studies of poverty, crime, disaster management and real estate prices are based on this methodology.

The economic activities within a specific area are in a state of equilibrium before a disastrous event occurs. The disaster will change the spatial configuration (streets, buildings and infrastructure) causing negative effect on the economic networks and business opportunities. The main assumption of the research is that potential indirect losses could be estimated by comparing the Space Syntax characteristics before and after a disastrous event by measuring the deterioration of links between economic enterprises.

The methodology is applied in a practical study of urban area. OpenStreetMap data is used as road-centred map of the city of York. The Historical

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Flood Map of the UK Environment Agency is used to setup disaster event impact. The Angular Segment Analysis implemented in DepthmapX software is used as the main method for analysis.

The study of applicable network measures shows that Normalised Angular Choice can be used as criteria for selecting alternatives for minimizing indirect costs caused by road network damages. At the same time, this methodology cannot be used for monetizing indirect costs or identifying losses in different economic sectors. The study approach does not contradict the main theoretical approaches and it gives new opportunities for research on disasters recovery.

Keywords: *space syntax methodology, indirect economics looses*

1. Introduction

The consequences caused by disasters of natural or technogenic character can be manifold. The disaster may lead to loss of life, destruction of homes and critical infrastructure and even depopulation of areas where the risk of occurrence and repetition of disasters is high. Despite the wide variety of definitions for these effects in research studying the economic aspects of disaster impact, two main areas can be clearly identified – exploration and evaluation of the direct and indirect costs.

This study focuses on opportunities to reduce indirect costs caused by the violation and the change of conditions for the functioning of economic entities. The destruction of roads and industrial infrastructure, as well as the uncertainty caused by such extreme events may lead to a rise in production and transport costs, changes in demand, and the impact on businesses technologically related to the industries affected by the disaster.

Most often, the impact on the economy is examined using the methods of the Input-Output Models and Computable General Equilibrium. These studies do not include spatial dependencies. It could be argued, however, that the spatial element is included indirectly even in these methods. The increase in cost of production and delivery of products in related sectors, whether due to the use of bypass routes or to the use of new suppliers from unaffected areas, is the result of the new, changed by the disaster spatial characteristics. The same applies to the change in demand resulting from emergency events.

In this regard, changing the spatial and network connections proved essential to the level of indirect costs. Therefore, the use of a methodology capable to describe the change in the spatial relationships as a result of a disaster can provide a tool to identify and evaluate alternatives for reducing indirect costs.

Based on this idea, this study aims at using Space Syntax Methodology to assess the indirect costs caused by the disaster.

Space Syntax Methodology was developed initially for the spatial analysis of architectural projects, but very soon this methodology was implemented for the analysis of a number of social and economic phenomena. One of the main approaches of Space Syntax is the study of network connections between objects located in the space, which is another argument in favour of using this methodology.

In this regard, the article will investigate the possibilities for the application of Space Syntax Methodology to assess indirect costs arising from disasters. Selected methods and parameters for evaluation will be implemented and evaluated in the practical study of two major cases – impact study in an urban environment, and in the affected region as a whole.

One of the important aspects of the research is to assess the possibilities for application of the method not only in the planning stages of disaster protection, but also in the stage of recovery from their consequences.

2. Research of the costs caused by emergency events

Anticipating and assessing the losses associated with disasters of natural or technical nature is a prerequisite for managing the consequences of these events.

Drawing up a rational plan to reduce the damage is possible provided we have three things.

First, assessment of the likely disastrous events for a region – what could possibly happen. Second, accurate physical models for the development of possible natural disasters have to be developed. Finally, an assessment of the economic implications of the impact of the disaster is made. Comparing alternatives for actions, we can choose the most suitable option for protection using two criteria – level of costs, and level of protection.

Taking advantage of this rational approach, however, we must take into account that in economic terms a disastrous event rarely affects only the area of direct impact. The destruction of one type of infrastructure can have economic impact over much wider area than the direct impact of the event. The destruction of a pipeline, a transmission line, a major road or bridge may lead to cessation of the economic activities or significantly increase the cost of production in other related economic activities.

The European Environment Agency (EEA) determines in a likewise way the pattern of reporting losses caused by disasters (De Groeve et al., 2015). The US Federal Emergency Management Agency of the United States estimates and records the cost similarly (FEMA, 2015). These two examples of similarity in assessing the losses can be easily explained and can even be supported by known differences with OECD methodological framework for assessing the impact of disasters (OECD, 2012). First, this framework evaluates events from the perspective of impact and correlation, and then analyzes them as financial impact and opportunities related to the prevention or elimination of consequences. Thus, the difference between direct and indirect losses is much smaller and is not as distinct as in the EEA and FEMA. The reason for the difference here lies in the function of various documents – cited EEA and FEMA documents aim at the assessment, accounting and reporting of costs associated with disasters, while OECD uses as a starting point the analysis and actions for risk management in all aspects and phases of disaster.

3. Theoretical approaches to assessing indirect losses

Such differences in the definition of indirect losses could be seen not only in practical guidance on cost analysis, but also in literature dealing with this issue. In the context of the Input-Output Models (IO) and Computable General Equilibrium (CGE), direct costs are those costs resulting from the impact of the event in a region, in industry, or directly affecting supply and demand, while indirect costs are interpreted as those caused in other related sectors or regions.

Evaluation of direct losses here can be done by defining the auxiliary concept vulnerability, which can be monetized[1] after taking into account the strength of the disaster impact. Establishing indirect costs is possible after tracking losses in other sectors, not on national, but rather on a regional scale, through the analysis of industry relations.

The CGE suggests that if an input for industry is not available or has reduced capabilities in a given region, it can easily be substituted with an input from another region.[2] Proponents of this method suggest that CGE is more accurate and flexible than I-O models as it can include variants of substitution of inputs and sources and more accurate indicators of supply and demand.[3] Both models are perhaps the most common and are implemented into FEMA's

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[1] This approach is used in practice. FEMA uses damage functions for vulnerability of the infrastructure to assess the direct costs of flooding (FEMA, 2014).

[2] Generally, the use of both models defines another type of costs – induced, reflecting additional household spending caused by the emergency event.

[3] To compare several method applications, see: Koks et al. (2015) and Clower (2005).

practice through HAZUS-MH model. There are a variety of options of use and application of these methods, but their main weakness is their static and their relatively limited ability to incorporate various industries.[4]

Another important methodological aspect for the evaluation of indirect costs is designed to investigate the losses from natural disasters and emergencies in terms of increase in transport and logistics costs. We can provisionally call it network estimation approach.

The basic idea of network approaches is that the research of destroyed links or links with reduced efficiency (industrial and space) can give a good enough idea of the estimated direct and indirect costs to the economy. In this regard, the basic concepts and parameters used to estimate costs are associated with research of networks and graph theory, such as robustness – the ability of the network to remain structurally unchanged under the influence (Sakakibara et al., 2004), resilience – the ability to provide a certain level of output under negative external impact and the possibility to recover after cessation of impact, and reliability – the probability of reaching the desired destination with a particular network configuration (Grubesic and Murray 2006).

The main objective of the assessment methods used is to establish the behaviour of network users when a change in its characteristics occurs. It could be argued that the theoretical orientation of the network approach helps to develop the approach for the Critical Infrastructure study. Generally speaking, it is this infrastructure whose damage will harm most seriously the economic system. This approach involves identifying the elements of the system (network) that are most relevant to its operation and action for its protection and rapid recovery (Schulz 2012, pp. 5–39).

In summary, we can say that the use of network models for the study of indirect costs and economic impact of the direct costs is possible and often used in the literature. The main measures in this approach can be defined as parameters of the network and space (regions) of disaster. The underlying assumption is that the increased distance, the degree of destruction of relationships and alternatives for connecting objects determine the behaviour of consumers and producers.

Ensuring the stable operation of the spatial network of connections and the reduction of the time for reconstruction of damaged parts are of utmost importance to reduce indirect costs. At the same time, it could be argued with reasonable confidence that the above mentioned methods are not in use, and probably would not be practicable to analyze specific events and establish

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[4] Some microeconomic methods to estimate costs could be mentioned, such as the method of Hedonic Regression, evaluating losses as a result of disaster inconveniences, but their use is far more limited. David (1985) and Don (1987).

alternatives for recovery after the event. Methods to assess indirect costs are used in the risk assessment and planning of prevention and rehabilitation activities prior to the emergency.

4. Space Syntax Methodology – Overview

Space Syntax is a methodology designed for the analysis of space from an architectural point of view but in its evolution it has focused on human, social and economic aspects of the environment. According to Space Syntax Network "Space Syntax was pioneered in the 1970s by Prof Bill Hillier, Prof Julienne Hanson and colleagues at The Bartlett, University College London". One of the most famous publications promoting this method is the book "The Social Logic of Space" published in 1984 by Bill Hiller and Julienne Hanson, (Hillier and Hanson 1984) which aroused the interest of the scientific community and facilitates the development of the theory and its use in numerous studies and applications. Some of the main applications of Space Syntax are the study of movement patterns, urban security applications, crime, integration, segregation and cultural development.

Space Syntax is used for analysis of disasters and emergency situations, mainly for analysis of escape routes, deployment of rescue teams, etc[5]. We should point out in particular the publication of J. Gil and P. Steinbach "From flood risk to indirect flood impact" (Gil and Steinbach 2008), which explores the possibilities of analyzing the indirect consequences of floods and uses some of the indicators of Space Syntax for their establishment. The article and the present study are close both in their objective and approach to drafting the spatial pattern of emergencies; however, the authors of the article focus on examining the general parameters of the network and aim "to evaluate performance changes to the urban structure and activities". This study uses and tests different parameters and its aim is not network analysis as a whole, but it rather seeks a rational method of selection between alternatives for sequence of network recovery.

Space Syntax distinguishes several basic methods of analysis – isovist and VGA, convex, axial and segment analysis. This study uses only segment analysis.

[5] For comparison of selected studies see Castillo (2013, pp. 3–5)

5. Segment analysis and measures

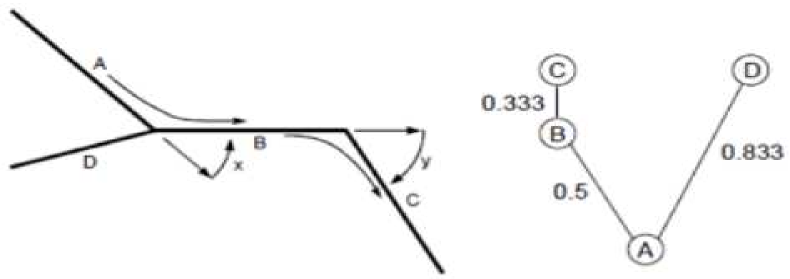
In order to explain the main measure used in this study – Normlised Angular Choice (NACH) first we have to explain two other measures used in calculation of NACH – Depth and Choice.

As a description of space Space Syntax Analysis (SSA) uses connection between void spaces in configuration of environment. These connections forms axial maps – network of lines and vertices, which differs in many aspects from centreline network of so called "natural street" or road networks. The axial map – lines and vertices and related dual graph can be used for calculation of angular and topological measures of the environment. Creation of axial map is not a usual task and requires information for buildings, void spaces and street network.[6]

SSA was further developed and enriched after some discussion and critiques (Batty 2004; Cutini et al., 2004; Dalton 2001; Jiang and Claramunt 2004) with Angular Segment Analysis (or just Segment Analysis). Turner defines this analysis in brief as follows: "In essence, the analysis breaks axial lines into segments, and then records the sum of the angles turned from the starting segment to any other segment within the system […] This angular sum is treated as "the cost" of a putative journey through the graph, and from it a shortest (that is, least cost) path from one segment to another across the system can be calculated" (Turner 2005, p. 146).

In this regard each street segment is identified as the interjunction between two intersection points of street network. Figure 1. presents such kind of intersection of three segments and graph description of their relations. Names of segments are used as vertices and weighted angles are used as graph edges.

Figure 1. Segment map and its associated graph



Source: (Turner, 2005, p. 147).

[6] Special software and applications are developed for automatisation as Axwoman and AxialGen developed by B. Jiang.

In segment analysis the *connectivity* is defined as cumulative turn angle to other lines. If we set 180° as cumulative weight 2, then 45° will have cumulative weight of 0.5, then angular connectivity of B will be equivalent of sum of weighted angels between A and B and B and C (x+y) or 0.833.

Step depth is defined as the shortest angular path from the selected segment to all other segments within the network. Then (syntactic) *step depth* from A to B is 0.5. Respectively *total depth* (or Total Angular Depth) is considered as cumulative total of the shortest angular paths to all segments within network. In case of Figure 1. The TAD is equal to sum of step depth to A (0.5), to C (0.833) and to D (0.833). TAD for network as whole is defined in SSA Methodology handbook as follows:

"Two open spaces, i and j, are said to be at depth d_{ij} if the least number of syntactic steps needed to reach one vertex from the other is d_{ij}. The sum of all depths from a given origin is computed as Total Depth:

$$\mathrm{TAD} = \sum_{j=1}^{n-1} d_{ij}, \quad i \neq j \tag{1}$$

The Choice in SSA terms corresponds to the graph's theory term Betweeness Centrality. Turner explains it as: "Choice works as follows: for all pairs of possible origin and destination locations, shortest path routes from one to other are constructed. Whenever a node is passed through on a path from origin to destination, its choice value is incremented. Thus frequently used nodes take high values and while those that fall on fewer paths take low values" (Turner 2001, p. 147). The Choice as measure also shows the potential for selection of the segment within network paths.

It should be noted that in segment analysis metric measures can be used as radius for calculating above mentioned parameters. In addition, Turner compared road map and axial map properties and their significance for exploratory analysis. Findings of this comparisons shows that road-centre map and segment analysis can be used in SSA. This is the reason to use in current research the OpenStreetMap data as segment map. Segment analysis and calculation of all angular weighted measures is implemented in DepthmapX software. The last version of the software – DepthmapXnet was used in current research.

Developing further the methodology of Space Syntax Yang (and Hill) proposed few normalised measures. Normalised Angular Choice (NACH) is among them. Authors describe the normalisation of choice as cost-benefit principle regarding total depth: "This would seem to have the effect of measuring choice in a cost-benefit way […]: so much choice, but at such and such a cost in angular depth; or, so much through-movement, but at such and such a cost in angularly getting there" (Hillier et al., 2012, p. 160). Therefore the greater value of NACH means better options for travelling from the selected segment.

NACH give also the possibility to compare different networks – the measure has been proven to be independent of the city networks size. It is calculated by the following formula.[7]

$$NACH(x) = \frac{\log\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\sigma(i,x,j) + 1\right)}{\log\left(\sum_{i=1}^{n}d_{\theta}(x,i) + 3\right)}, (i \neq x \neq j) \quad (2)$$

where $(i,x,j) = \begin{cases} 1 \text{ if the shortest path from i to j passes through x} \\ 0 \text{ otherwise} \end{cases}$

and d_{θ} is the length of a geodesic (shortest path) between vertix x and i

Considering NACH from indirect losses and disaster relief point of view, the measure is very useful. It directly corresponds to selection of best option for travelling within network, which means less transportation costs. The NACH independence from size gives also opportunity to find best ways within changed (or separated on several parts) from disaster road network. Therefore connecting segments (roads) with highest NACH have to be the first priority within disaster relief and will guarantee minimization of losses due to road network failures.

6. Definitions, losses and measures

For the purposes of this study, we will assume that direct costs incurred by the disaster include all necessary costs of repairing the damage to the concrete damaged objects. Indirect costs will be considered those caused in related industries that are not affected by the disaster, but suffer from supply chain disruptions, increased production costs or changes in consumption.

Limited to the spatial features associated with the changes incurred by the disaster in the area, we can use the indicator of Total Angular Depth (TAD). Let us assume that the road network is divided into one or more subnets by the disaster. We can recalculate TAD for each subnet.

The lower level of Depth in the network means that all other segments are closer and therefore there are more alternatives for reaching more nodes. In this case, we will assume with sufficient level of certainty that connecting the points

[7] For full mathematical explanation see Appendix 2, Hillier et al. (2012) pp. 191–193.

with the lowest level of TAD in subnets will create the most alternatives to reach as many points as possible. In other words, we will recover better and faster all other network parameters. At the same time, it is not certain that the longest route, the longest street, will ensure the shortcut to all points. The topological index TAD does not guarantee it. In this case depth should be considered from another point of view – that of the radial shortest paths. Thus, we will get the best alternatives if we use NACH "cost benefit" indicator. In terms of restoration of the network and providing the best alternatives for travel using NACH, we will contact these places on the network that have the best ratio of depth/shortcuts.

7. Algorithm and data

Taking into account all of the above, we can define the algorithm for research. We need to create the environment for the event, which requires:

1. Information on the region infrastructure – streets, buildings, land, and a description of the functions of buildings and streets;
2. The spatial model of the event – affected area and intensity of the impact;
3. Determination of damaged infrastructure.

Once we have created the scene of the disaster, we can calculate TAD and NACH for the changed street network and determine the points and roads with the highest level of NACH. The proposal for the best alternative for restoring connections can be made after further analysis of the affected infrastructure.

Being aware of the number of affected routes between the two points that need to be connected, we could choose the shortest repair works needed to connect the two selected points.

For the purposes of this study, the city of York in England was chosen as the scene of the event for several reasons. First, its street network is of medium size - neither too large to impede the calculation of the indicators, nor too small in order to have a variety of connection types. York is a typical centre-oriented European city with a ring road.

Initially, GIS data for real flooding in York provided by Copernicus Monitoring Service of the European Commission were selected as a disaster model; however, once it was established that they did not contain data on the scale of the infrastructure destruction, the Historic Flood Map of the UK Environment Agency[8] was chosen, since it provides a georeferencing record of all floods registered in England from 1946 to date.

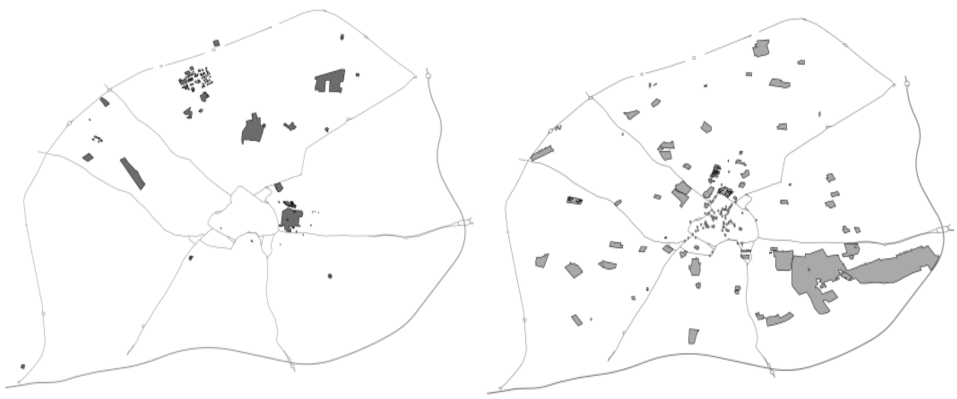
[8] Data.gov.uk, Historic Flood Map – Datasets.

The choice of this fictional disaster makes it possible to "destroy" a large part of the infrastructure and to demonstrate in a better way the "division" of the transport network. For lack of any other information, all streets and roads in the affected area are considered to be equally affected – i.e. dysfunctional in need of restoration. Data on the road network and infrastructure are produced by query tools for OpenStreetMap data,[9] which is of excellent quality and volume in England. QGIS was used to set up the scene of the event, while the Space Syntax parameters were calculated with open source software developed by the authors of the methodology – DepthmapXnet.

8. Disaster Scene Setup and Analysis

Initially, after determining the region of York, we can make a series of maps that will show the spatial distribution of economically important city facilities – industrial buildings and areas, schools, banks, restaurants, shops, etc. As Figure 2. shows, the industrial zone is located north-northeast of the city by the River Ouse, while services, historical sites and administrative buildings are concentrated in the centre and in the eastern part.

Figure 2. Industrial zones and amenities[10]



Source: author's query of OpenStreetMap.

[9] OSM tools osmconver and osmfilter was used

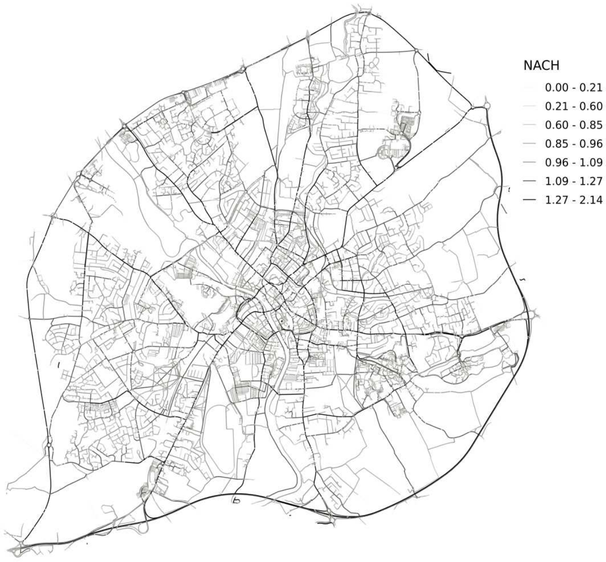
[10] The query for amenities consists of following tags: school, shop, restaurant, college, university, hospital, bar, doctor.

Figure 3. presents the calculated parameters TAD and Figure 4 – calculated NACH regarding the city road network with the help of DepthmapXnet.

Figure 3. Total Depth for streets, the city of York

Source: author's own calculations and mappings.

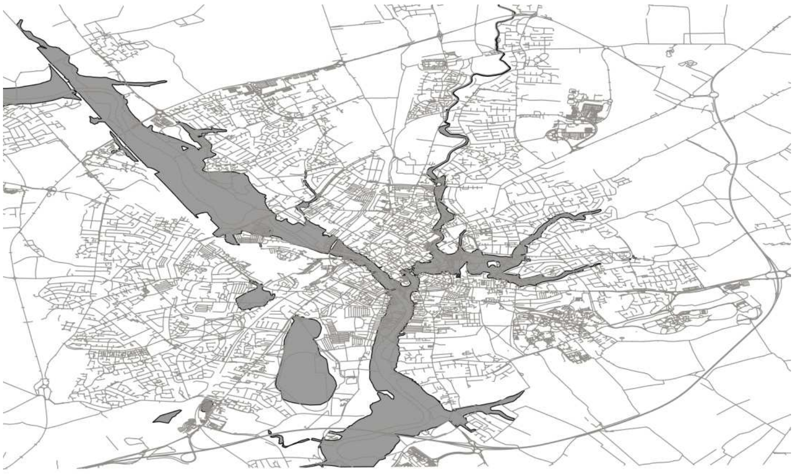
Figure 4. NACH for street network, the city of York



Source: author's own calculations and mappings.

The Figure 3. shows low TAD in centre and in the North East, which corresponds to locations shown in Figure 2. Figure 4 shows the flooded area in York recorded after 1946 by the Historic Map Flood, as well as possible damage to the road infrastructure.

Figure 4. Full road network and flooded areas



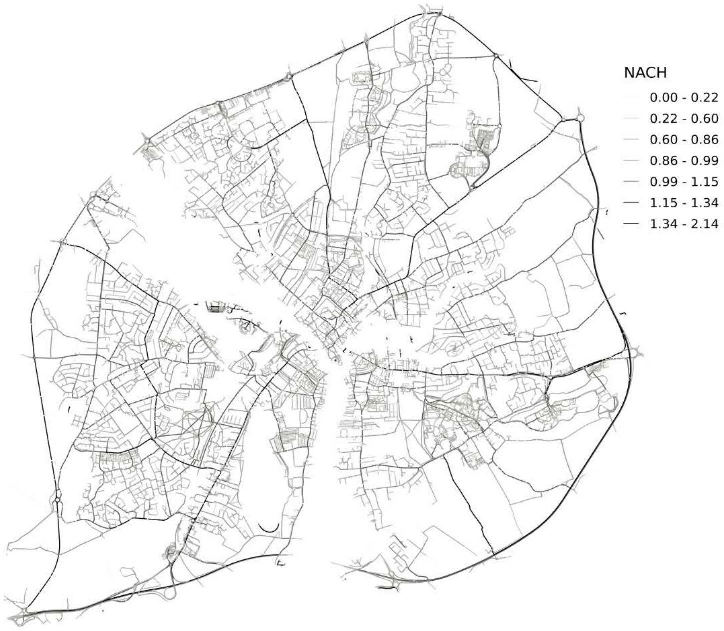
Source: author's own mappings.

Figure 5. shows the calculated TAD and Figure 6. – calculated NACH for each of the two subnets "created" by the flood. It is evident that TAD declines in value for western network and increases in eastern part.

Figure 5. Total Depth for streets after the "event"

Source: author's own calculations and mappings.

Figure 6. NACH for streets after the "event"



Source: author's own calculations and mappings.

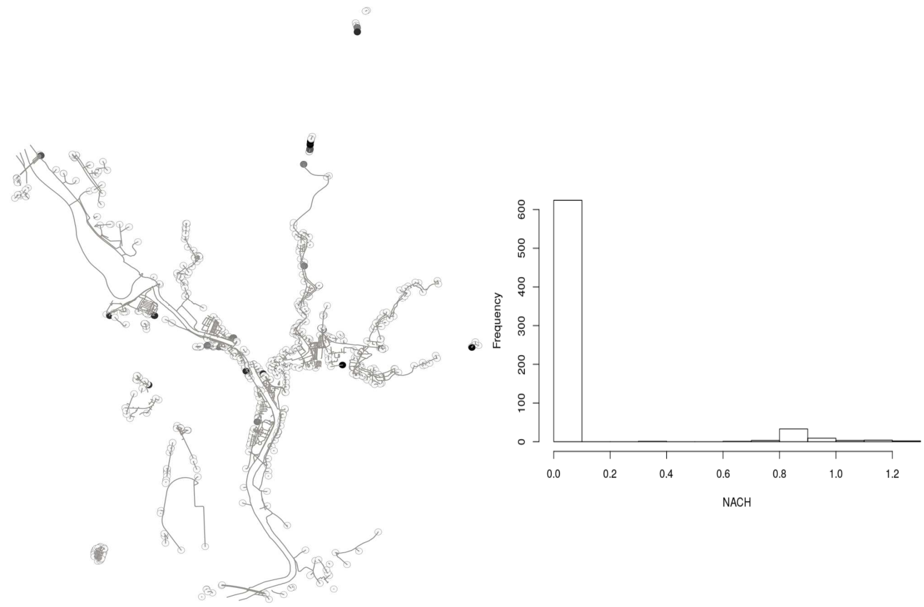
If such a significant in size event occurs, the indirect costs will be enormous for the research area due to the interrupted connection between industries concentrated in the central and northern region by the River Ouse, and those located in the western part of the city.

The ring road is also interrupted, which would significantly reduce the options for finding bypass routes and supply of goods and services in the region. At the same time, we can see that the calculation of both parameters retains high levels for the ring road, which is not contrary to expectations for higher connectivity of this road and shows the rationality of the use of Space Syntax for this analysis.

9. Complementary (subsequent) analysis

Figure 7 (a) shows the nearest points of subnets to the area of devastation. The graph in Figure (b) shows that out of over 680 possible points to start out repair works, only about 30 have high positive NACH values, which significantly reduces the number of suitable rational alternatives to start restoration activities. Let us recall that NACH can be seen as an indication that largely guarantees "the most effective" route in a network, and connecting two subnets in points with high NACH will lead to the best initial connection torn by the disaster.

Figure 7. (a) Points with positive and high NACH near damaged streets, (b) Histogram of NACH values for all points near damaged streets



(a) (b)

Source: author's own calculations and mappings.

After determining the most appropriate connection points we can do further analysis to ensure a rational way for their connection. Rationality can be seen in terms of the time required for connection, of network accessibility of restored roads, or of other important indicators considered by the city or region authorities, such as the location of important industries. All this will depend on the level of destroyed infrastructure.

Data is needed on the extent of destruction and hence the expected speed and costs of recovery. However, such information would be available if we use a physical model of the disaster to determine the expected intensity and scope of damage. During the event, it is also possible to give an expert estimate of destruction and the recovery rate and to use supplementary analysis for the method of connecting points.

10. Conclusions

In conclusion, we could claim that the study has achieved its aim. Space Syntax Methodology was applied to a possible emergency event to identify opportunities to reduce indirect costs associated with this event.

The methodology proved to be extremely useful in this direction, as some of its network (topology) and geometric parameters can directly affect the potential to reduce indirect costs. The study approach does not contradict the main theoretical approaches to identify indirect costs and it can be argued that it gives new opportunities for research.

It was demonstrated that Space Syntax can be applied to eliminate the effects of disasters providing rational alternatives to restore the road network in order to reduce indirect costs.

At the same time, this methodology can hardly be used for monetizing indirect costs or establishing losses in specific sectors. Using these parameters there is no way to accent monetary value of the potential for indirect costs. Although its application does not require particularly complex for finding and using information, resources for the calculation of indicators may be significant for larger networks.

Despite the above-mentioned weaknesses, the application of Space Syntax as a tool for identifying and selecting alternatives for recovery and reduction of indirect costs of disasters is worth being explored and developed.

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Streszczenie

WYKORZYSTANIA SYNTAKSU PRZESTRZENI DO SZACOWANIA POŚREDNICH STRAT EKONOMICZNYCH WYNIKAJĄCYCH Z KATASTROF EKOLOGICZNYCH

Referat ma na celu oszacowanie pośrednich strat ekonomicznych wynikających z klęsk żywiołowych. Generalnie, straty te są definiowane jako przerwa w działalności gospodarczej. Nawet ograniczone fizyczne uszkodzenie mienia i infrastruktury spowodowane przez klęski żywiołowe mogą powodować reakcję łańcuchową strat w łańcuchu dostaw w określonym regionie.

Metoda syntaksu przestrzeni jest rozwijana i wykorzystywana do uzyskania charakterystyki budynków, miast lub otaczającej przestrzeni. Chociaż metoda została opracowana przede wszystkim jako metoda planowania miejskiego, była również stosowana w dziedzinie sieci społecznych i gospodarczych.

Słowa kluczowe: *przestrzeń składni mrthodology, ekonomia pośrednie traci*