An Empirical Comparative Study for Urban Regeneration: Measuring the Effectiveness of DSS and GIS Approaches

Alberto Calzada[1], Jun Liu[1], Hui Wang[1], Anil Kashyap[2]

[1]School of Computing and Mathematics, Faculty of Computing and Engineering, University of Ulster, Northern Ireland, UK

[2]School of the Art, Design and Built Environment, University of Ulster, Northern Ireland, UK

E-MAIL: Calzada-A@email.ulster.ac.uk, {J.Liu, H.Wang, A.Kashyap}@ulster.ac.uk

Abstract

Urban regeneration (UR) projects encompass complex decision-making processes that usually comprise a great amount of information collected from numerous data sources which may be uncertain, inconsistent or incomplete. Many stakeholders and other actors provide subjective judgments that need to be considered throughout the decision process. Furthermore, most factors involved in regeneration projects (i.e. indicators or alternatives) are geographically referenced, making spatial component a key input in the decision making process. Although there is a substantial body of literature regarding the combination of Geographic Information Systems (GIS) and Decision Support Systems (DSS) to tackle spatial decision problems, there is still a lack of empirical and comparative studies able to measure in real terms the results and effects when using both GIS and DSS together against the use of DSS or GIS technologies alone. This paper utilises, a belief rule-base inference methodology (RIMER) to support the decision-making procedure while handling the large and complex quantitative data along with qualitative information. This research paper considers a spatial analysis along with the RIMER approach for comprehensive analysis of input indicators. The initial finding of the research based on RIMER shows promising results in terms of flexibility, accuracy, and applicability based on some case studies relevant to urban regeneration decision-making problems. This empirical study indicate that RIMER-based DSS can provide a well-established base to implement further research in combination with different GIS methods to effectively handle the UR decision problem from an IT perspective, compared with GWR model in terms of flexibility, interpretation, accuracy, and applicability.

Keywords- decision-making; urban regeneration; GIS; spatial analysis; uncertainty; belief rule-base; GWR; decision support system; spatial decision making

1. Urban Regeneration and Deprivation Measures

Urban Regeneration (UR – also called urban renewal) is a crucial process carried out nowadays in cities worldwide to mitigate many socioeconomic and environmental issues affecting them. It is considered as a crucial process to (i) canalize and plan the effects of urban sprawl that is affecting cities worldwide, (ii) prevent uncontrolled spread of outskirts through green areas, (iii) improve the living conditions in neighbourhoods already deprived and (iv) recover brownfields back to beneficial use, among others (Yusuf et al., 2010; Winston, 2010; Juan et al., 2010). In this regard, the United Kingdom government is publicly dedicated to foster the UR practice to reduce these negative factors (UK Parliament, 2011; Waters et al., 2007; Hemphill et al, 2004). Consequently, the Belfast City Council includes UR as one of the pillars to boost sustainable development and improve the quality-of-life of its citizens (BCC, 2009).

In order to implement the policies established for UR and justify the master-plans designed to regenerate certain areas, a number of authorities through the UK have developed high-level indicators. The aim of these indicators is to measure and rank deprived areas within each circumscription. In the case of Northern Ireland, the Statistics and Research Agency (NISRA) has recently surveyed 582 electoral wards integrated throughout the territory. The data retrieved was organised as indicators containing general statistic figures. These indicators were then compiled in order to obtain a single Multiple Deprivation Measure (MDM) (NISRA, 2010)

These high-level indicators (like MDM) provide a general picture of the studied area. They represent useful information that is commonly used by authorities and policy-makers for decision support. However, keeping updated this general information is a complex procedure, since high-level indicators are a compilation of numerous single measurements that may vary continually and might be inaccurate or incomplete because data may be no longer available (NISRA, 2010).

This research provides a comparison between two different computing approaches to estimate MDMs for UR. While the GWR method (GIS perspective) (Fotheringham et al, 1998) will be able to take advantage of the spatial relationships between data and exploit the non-stationary nature of spatial information, the RIMER+ method (DSS point of view) will focus on structuring the problem, assuming the heterogeneity, non-linearity, incompleteness and uncertainty nature of the information related to urban environment because of its complex and dynamic nature. To demonstrate so, this report presents an empirical study performed using real data to support regeneration alternatives based on deprivation measures of the Greater Belfast Region (GBA). Moreover, an initial attempt to combine the benefits of both fields of study into a single technology will be provided. This will be done by including spatial information from the GBA dataset within the RIMER+ decision process. This initial approach will throw key hints about how a complete an entire GIS-based decision model in further steps.

The results retrieved from these case studies will also help decision and policy makers in considering the key points of both approaches as an integral part of the decision process. The rest of this paper is organized as follows: Section 2 briefly presents the

GWR and RIMER+ methods and describes how regeneration initiatives can be approached from both perspectives; Section 3 presents two comparative case studies performed using the GWR technique and the RIMER+ method and discusses the performance of both systems in real UR scenarios. Finally, the conclusions retrieved from this research are summarized in Section 4.

2. Approaching Urban Regeneration from two Different Perspectives

This section briefly describes the selected DSS and GIS technologies (RIMER+ and GWR) to illustrate their potential applications in the field of decision-making for urban planning. Even if both RIMER+ and GWR have completely different basis, their benefits, drawbacks and results can be compared in terms of applicability, flexibility, interpretation and accuracy.

2.1. DSS Perspective: RIMER+ Approach for Urban Regeneration

The methodology referred to as a belief Rule-base Inference Methodology using the Evidential Reasoning approach – RIMER (Yang et al, 2006) has been designed in recognition of the need to handle uncertainty and heterogeneous information in human decision making. RIMER is a rule-based decision approach, whose rules are designed with belief degrees embedded in the entire consequent terms, forming belief rule-bases (BRBs). They are used to capture nonlinear causal relationships as well as uncertainty. The inference of the rule-based system is implemented using the evidential reasoning (ER) approach.

RIMER results have proved to be highly competitive solving decision problems applied to different areas, such as safety and risk analysis (Liu et al, 2004), oil pipe leak detection (Xu et al, 2007) and some other applications in engineering systems (Liu et al, 2008).

Recently, the BRB model has been extended to facilitate the more general application cases and more flexible and simple rule-base generation scheme. The belief rules were extended by embedding belief degrees in each antecedent term (Liu et al, 2012). Take for example the following extended belief rule:

IF “Crime” is {(High, 0.7), (Low, 0.3)} AND “Education” is {(Satisfactory, 0.5), (Poor, 0.2)} THEN “Deprivation” is {(High, 0.6), (Low, 0.4)} (1)

In (1), the “Education” antecedent has a belief degree of 50% for the “Satisfactory” term and 20% for the “Poor” one, leaving undefined the remaining 30%. Therefore, the missing 30% represents the incompleteness degree of the antecedent. The decision model which integrates these new extended BRBs with the evidential reasoning inference scheme has been named as RIMER+ (Liu et al, 2012).

To meet the aim of this particular research, the extended BRBs of RIMER+ can be used to integrate in the decision process some key elements of the UR problem: (i) nonlinear relationships between indicators (with IF-THEN rules; between its antecedents and the consequent), (ii) data heterogeneity (able to assume both quantitative and qualitative data parsing it as belief distribution), (iii) uncertainty related to multiple aspects of the urban environment (with beliefs), (iv) incompleteness in information (partially known beliefs in antecedents and/or consequents), (v) vagueness in stakeholders' opinions and policies (with linguistic terms). They also provide a flexible way to incorporate hybrid input information (both quantitative and qualitative) as well as an efficient rule generation scheme.

Both RIMER and RIMER+ models allow the user to organize indicators in hierarchical structures. This characteristic is particularly important when dealing with semi-structured decision problems that comprise large amounts of information, like deprivation measures for UR (NISRA, 2010). Organizing indicators in hierarchies will also allow users to obtain partial results in each branch of the hierarchy. In this work, it will make possible to analyse deprivation indices for various sides of the problem, like crime, health or education deprivation measurements.

Moreover, in both models the inputs and outputs are represented as belief distributions, so they share most of the positive features of the extended BRBs. This feature allows the software tool which implements RIMER+ (Calzada et al, 2011) to retrieve easy-to-grasp inputs and outputs, with the values represented as belief degrees along with the uncertainty and incompleteness associated with them.

Finally, it is important to mention that the ER inference algorithm and the representation of information as BRBs allow the decision model to learn from any existing data source to retrieve reliable outputs. The case studies presented in Section 3 demonstrate how these powerful characteristics of RIMER+, along with the other features described in this Section; can help in approaching a complex decision problem like the MDM for UR.

2.2. GIS Perspective: GWR for Urban Regeneration

A completely different approach from that of the RIMER+ perspective is given by the GWR technique. Unlike RIMER+, the GWR technique is a GIS-based regression model whose principal idea is that a dependent variable can be estimated at any position in the study area given a set of independent variables, measured at known locations. GWR builds a regression equation for each sample data and then uses the spatial locations to estimate parameters at any location. In this context, the typical equation built by GWR in each sample data location (represented by a 2-dimensional vector u) would be:

$$y_i(\boldsymbol{u}) = \beta_{0i}(\boldsymbol{u}) + \beta_{1i}(\boldsymbol{u})x_{1i} + \beta_{2i}(\boldsymbol{u})x_{2i} + \cdots + \beta_{mi}(\boldsymbol{u})x_{mi} \quad (2)$$

Where y_i is the prediction of the dependent variable in the i^{th} sample of a set of n sample data, based on a model of m independent variables. The β values are the regression parameters built by GWR (with β_0 representing the intercept value) and the x values are the sample data measured at the u location.

To calibrate the model, GWR is based on Tobler's First Law of Geography, which states that observations located nearby will be more closely related than distant ones (Tobler, 1970). When estimating, GWR makes use of Tobler's idea by assigning greater weight to observations whose location is nearer to *u* than those which are further away (Charlton and Fotheringham, 2009). That is,

$$\hat{\beta}(\boldsymbol{u}) = (X^T W(\boldsymbol{u}) X)^{-1} X^T W(\boldsymbol{u}) y \quad (3)$$

Where $\hat{\beta}$ denotes an estimate of β and *W(u)* is a *n×n* matrix whose diagonal elements represent the geographical weighting of observed data in location *u* and the off-diagonal values remain zero. To meet Tobler's Law and assign weighting values to each location, the weight matrix is calculated at each point *u*, where regression parameters are estimated.

To compute the weight matrix, it is common to use Gaussian functions as kernels to represent the decreased-by-distance weighting values. These kernel functions can be fixed or adaptive (See Fotheringham et al, 1998 for further information) and they use a distance variable (normally defined as Euclidean distance) and a parameter named as bandwidth, which produces a decline of influence with distance. The bandwidth variable is important in terms of influencing the fit of the model, so it should be carefully adjusted *a priori* by the analyst. However, the GWR software tool provides two methods to determine the bandwidth value: the Cross Validation method and the AIC (Akaike Information Criterion) minimization (Akaike, 1974).

Due to the extensive use of spatial information in both building the regression model and estimation processes in a fairly simple mathematical framework, GWR has received considerable attention as an analytic technique in the field of spatial decision-making (Huang et al., 2010). Consequently, using GWR as an analytical method offers us the possibility of including spatial information of sample data within the decision making procedure for urban regeneration.

3. Case Studies

This section provides a numerical example to demonstrate the implementation and compare the different decision-making perspectives for urban planning. The following example is focused on prediction and analysis of the Northern Ireland Multiple Deprivation Measure (MDM) (NISRA, 2010).

3.1. Problem Description

The MDM aims at informing policy and targeting areas of need in Northern Ireland (NISRA, 2010). These objectives are common in prior decision-making processes for UR, where it is essential to (1) advise policy-makers with real field data summarized as statistic figures and (2) identify disadvantaged areas where regeneration is needed the most (Lombardi et al, 2010; Winston, 2010). In this regard, the MDM can be used as a powerful high-level indicator to support/oppose UR decision alternatives and to justify future regeneration projects. However, for future UR projects, values in numerous indicators of the MDM might have changed or be currently missing or not available – like the case of Northern Ireland MDM revision (NISRA, 2010). It may also happen that a particular regeneration project is programmed in an area not included in the MDM index where only limited information is available, so prediction analysis to estimate the MDM value would be needed.

To overcome these issues and still provide reliable decision support information for UR through MDM, this study performed a comparative analysis to investigate the performance of both GWR and RIMER+ approaches when estimating MDM indexes in different urban areas. It will help in evaluating the performance of both methods before extrapolating them to approach a wider UR domain. In this regard, the following example demonstrates the benefits and drawbacks of both perspectives as decision support and analysis approaches for UR.

3.2. Implementation

From the 582 electoral wards of Northern Ireland analysed by NISRA to develop the MDM (NISRA, 2010), this study focused on the 51 urban-type wards that comprise the Greater Belfast Area (GBA). Figure 1 represents the area of study within Northern Ireland. To simplify the study and create indicators for the empirical tests, a selection of the 31 most relevant indicators from the MDM index was performed. Then, using the same data, the different approaches were implemented to estimate MDM indices.

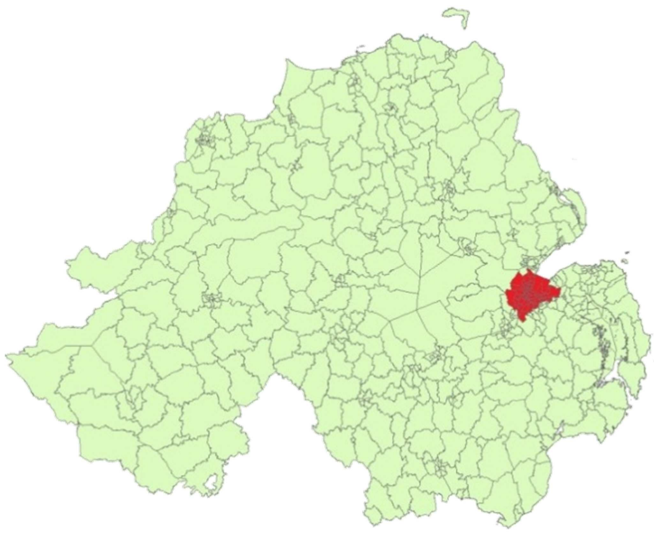

Figure 1. The Greater Belfast Area of study (red) within Northern Ireland

Using the 51 wards included in the GBA, two comparative case studies are presented in this paper to assess the performance of the different methodologies. The aim of both studies will be to estimate the MDM for the GBA wards. Figure 2 illustrates the MDM values in the GBA, which go from 4.57 for the least deprived area to 78.58 for the most deprived one.

First, a 10-fold Cross-Validation test was performed using the same data for both RIMER+ and GWR methodologies and then a series of tests to estimate 3 of the wards of the Pottinger District Electoral Area in East Belfast were carried out, using the remaining 48 wards of the GBA as sample data to train the different models.

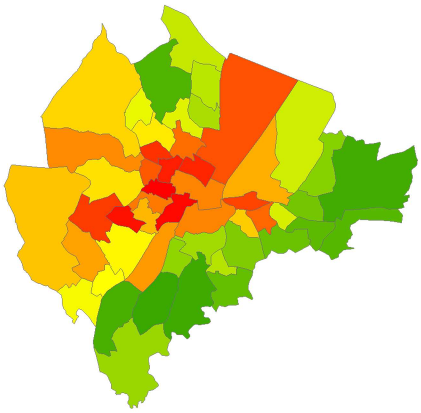

Figure 2. MDM values to be estimated in the Greater Belfast Area

(Red tones represent most deprived areas while green-coloured areas are less deprived)

Following subsections describe how each case study was performed taking advantage of the characteristics of each method, using the data from the 31 indicators as well as the spatial information to estimate the MDM indices.

3.3. Case Study 1: RIMER+ and GWR Empirical Comparison

To define indicators for GWR and RIMER software systems (Calzada et al, 2011), a selection of the 31 most relevant variables from the MDM index was performed. Based on data of each ward, the numeric values were mapped as linguistic terms for the RIMER system. Then, for each of these 31 indicators, 5 generic linguistic terms were defined as Utility Functions (Yang, 2001). The generic linguistic terms defined in this study were: *"VL"*, *"L"*, *"M"*, *"H"* and *"VH"* (from *"very low"*, *"low"*, *"medium"*, *"high"* and *"very high"*). The values for the *"VL"* and *"VH"* terms correspond to the minimum and maximum values of the indicator in the MDM dataset, respectively. The value of the *"M"* linguistic term was the average of the indicator and for the *"L"* and *"H"* terms were assigned the values in-between the average and the minimum or maximum, respectively.

Once the indicators were defined, they were structured in a hierarchy in the RIMER software tool, following the definition of the MDM index. Therefore, the indicators were clustered in six groups, depending on their nature: (i) Crime; (ii) Education; (iii) Health; (iv) Living Environment; (v) Income; and (vi) Employment. These high-level indicators correspond with the six main sections of the MDM hierarchy, and the RIMER system will allow obtaining deprivation scores for each side of the decision problem. Therefore, thanks to the values retrieved in these indicators, users would be able to know how the performance of each ward is regarding some specific issue, like education, income or health. Table 1 lists the 31 indicators included in this study and grouped in the 6 categories aforementioned.

For the GWR method, a previous analysis to obtain the coordinates of each ward centroid had to be carried out in a GIS software application. Then, these spatial coordinates were included in a file along with the indicator's value for each ward and imported into the GWR software tool. It is important to note that GWR is unable to organise indicators in hierarchies, so no partial results in each branch can be obtained from the GWR analysis.

The comparative results of the 10-fold cross validation analysis performed in the 51 wards of Belfast show that although the RIMER+ performance is positive in terms of accuracy, the GWR methodology is still more accurate. The R^2 value for the RIMER+ approach is 0.9756 and the average error (average of differences between the predicted and real values) is 4.094, while the R^2 value in the GWR method is 0.9901, with an average error of 2.276. Figure 3 summarises the individual results for each one of the 51 wards retrieved from this test.

Table 1. Indicators used in this study

Category	**Indicators included**
Crime	"Total Offences", "Offences against person", "Burglary", "Theft" and "Criminal Damage"
Education	"Degree level or higher", "School leavers gained 5 or more GCSEs at grade C", "School leavers continued to higher education" and "School leavers continued to further education"
Health	"Deaths", "Standard mortality ratio for all", "Standard mortality ratio for aged 75 and under", "%People with long-term illness", "%Population provided unpaid care", "%People stated good health" and "%Children registered with a dentist"
Living Environment	"%Persons under 16", "%Persons aged 60 and over", "%Catholic background", "%Protestant background", "%Persons 16 and over single", "%Births of unmarried mothers", "Lone pensioner households" and "Lone parents households with children".
Income	"Aged 18-59 claiming support", "Aged 16+ claiming house benefit" and "Aged 16-59/64 incapacity"
Employment	"%Active", "%Inactive", "%Unemployed" and "%Long-term Unemployed"

Although the GWR process to some extent improves the accuracy of RIMER+, the methodology of the latest is capable of covering a larger problem domain by including: (i) non-linear, (ii) heterogeneous, (iii) vague, (iv) incomplete and (v) uncertain information within its decision process. In this regard, recent studies have tested and demonstrated the positive performance of RIMER+ under extremely uncertain situations (Calzada et al, 2012). RIMER+ is therefore a more flexible method, able to include more real-case elements in the decision process rather than only numerical figures. It also provides more options to represent the relationships between indicators instead of linear equations only. These features of RIMER+ will be essential when further approaching urban planning and regeneration projects from a computing perspective, since using just GIS-based technology use to fall short in providing decision support capabilities (Nyerges T.L. and Jankowski P., 2010, pp. 7-8).

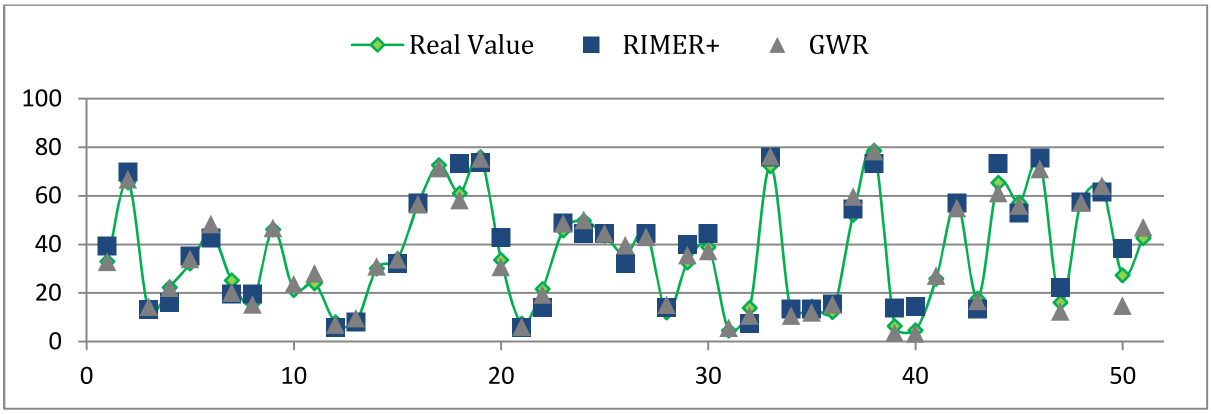

Figure 3. 10-fold Cross Validation results predicting MDM in the GBA

However, it is clear that the spatial component makes a difference in the estimating procedure. To verify this fact, a second comparative study was performed by embedding spatial information within the RIMER+ methodology.

3.4. Case Study 2: RIMER+ adjusted with Spatial Data

To demonstrate the positive influence of spatial information within the decision process and improve the RIMER+ performance in terms of accuracy, an attempt to embed spatial data within the RIMER+ decision process was carried out. In this second study, out of the 51 wards included in the GBA, 3 of the wards of the Pottinger District Electoral Area in East Belfast were selected to be estimated. Therefore, the remaining 48 wards of the GBA were used as sample data to train the different approaches. Figure 2 represents the area of study.

RIMER+ provides mechanisms to weight both indicators and belief rules. Therefore, the adjustment of the RIMER+ model to include spatial information was design based in rule weighting. Distances were normalised to a 0 to 1 interval to be directly assigned as a rule weight (note that each belief rule in the RIMER+ system represents the information of a sample data, which in this case is ward of the GBA). In this sense, the weight for each belief rule was calculated in a similar way than in the GWR method: using a function representing the decrease-by-distance importance of each sample data and scoring with higher weights to rules which are located nearby.

Although this way of embedding spatial information in the RIMER+ method is still primitive and may be further developed; it already retrieves positive results and overcomes the results of using the RIMER+ method alone. Table 2 summarises these results and Figure 5 represent the error of the 3 approaches graphically. Therefore, it can be concluded that adding spatial information to a decision model can definitely make a difference and enhance the decision support of the system.

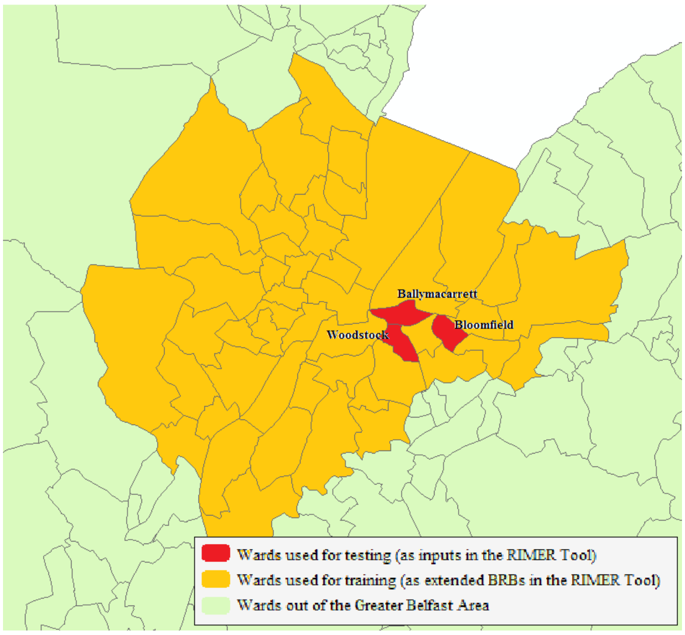

Figure 4. Training and testing wards used for Case Study 2

Table 2. Results of Case Study 2

Ward Name	**Real MDM Values**	**RIMER+ Result**	**Adjusted RIMER+**	**GWR result**
Ballymacarrett	63.75	62.99	62.52	73.8
Bloomfield	27.43	44.94	43.65	13.16
Woodstock	42.67	56.04	53.65	51.59

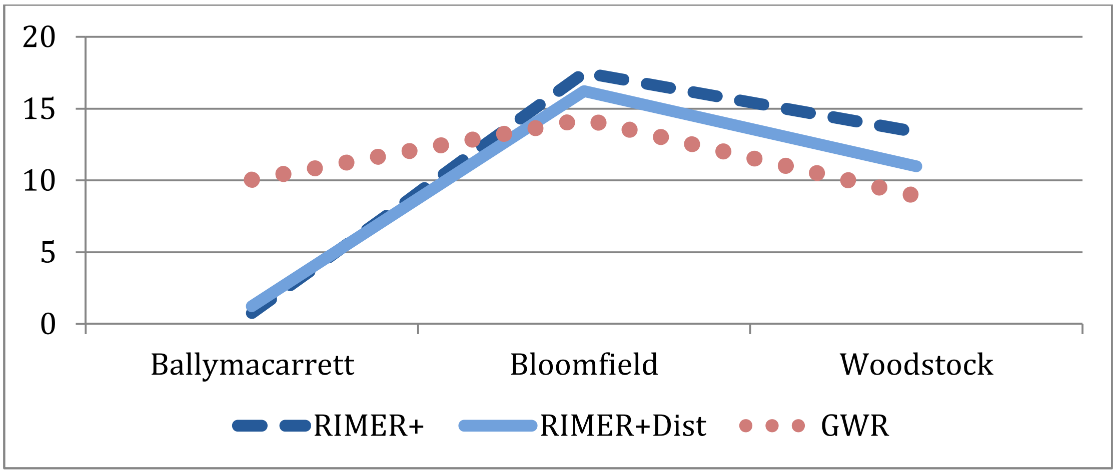

Figure 5. Error representation of the 3 methods used in Case Study 2

As we can see in Figure 5, the results of the adjusted RIMER+ approach in Bloomfield and Woodstock wards were closer to the GWR ones than those using RIMER+ alone (without spatial information in the decision process). This is a key finding to support a further research in this direction because involving spatial data along with all the positive features of a complete decision support model like RIMER+ can make a difference when approaching decision problems located in real environments, like the case studies presented here.

Figure 5 also shows the surprisingly not-so-good results of GWR compared other methods for the Ballymacarrett ward. This is so because Ballymacarrett deprivation index is the highest of its area, having a larger MDM than all its neighbours, as shown in Figure 6.

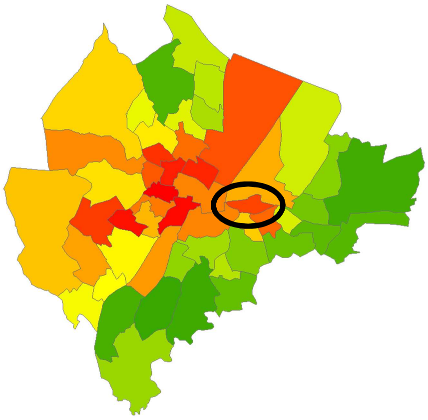

Figure 6. Location of the Ballymacarrett ward in the GBA.
Its MDM value is a local peak in East Belfast

Therefore, to deal with such irregularities and other uncertainties and still provide reliable decision support (like RIMER+ approaches for Ballymacarrett) it is needed a comprehensive decision support model able to learn from existing non-spatial data as well as incorporate valuable spatial information instead of relying on spatial information only.

3.5. Findings

The RIMER+ method provided the flexibility in terms of (i) data heterogeneity, (ii) vagueness in policies/opinions, (iii) non-linear relationships between indicators, (iv) incompleteness and (v) uncertainty required to approach such complex decision problems. However, it lacks of a comprehensive mechanism to include spatial information within its decision support, which is one of the strongest features included in the GWR method.

When implementing both methods to predict multiple deprivation measures in the Greater Belfast Area using real data from the city of Belfast, the results reflected the importance of acknowledging the spatial component within the decision support process, since the results of GWR were slightly more precise than those from RIMER+ in these simple studies. However, for more complex real-world decision problems, GWR has a great lack in terms of flexibility and applicability, since it can deal only with numerical data and creates a series of linear regression models. Although these models are able to represent data's non-stationary nature, they are unable to represent the vagueness, heterogeneous and uncertain nature of the urban environment. Therefore, a decision problem focused on a certain urban area will have to be cut down before being approached with GWR, having a great risk of oversimplifying it.

Hence, in this field of study it is then considered as essential to critically evaluate the benefits and drawbacks from both perspectives. This assessment is crucial in order to combine the advantages of both techniques into a single methodology able to deal with regeneration projects in a flexible and accurate manner. To meet this aim, a first approach including spatial information within RIMER+ was also presented. This study demonstrates how the use of spatial information enhances the accuracy of the decision support estimations and still benefit of its many advantages. Therefore, this research may open many possibilities in this fundamental field of study to computationally aid real-case regeneration processes.

5. Conclusions

This study presented the application for the UR decision problem of both GWR and RIMER+ approaches as an exemplar for the GIS and DSS points of view, respectively. The empirical results, based on real world data, demonstrated the positive performance of the two methods even when only few sample data is available. The comparative analysis of the procedures and results may establish the basis for further research to combine the benefits of each perspective into a single decision model.

Urban regeneration decision makers and their efforts to measure deprivation indices provided an exemplar of a particularly complex work environment, where decision support is increasingly needed. Estimating multiple deprivation measures in different urban areas can be used as a crucial starting point for regeneration initiatives. In this regard, the results obtained in this paper are expected to be extrapolated to a wider UR domain in order to approach and combine more accurately different aspects of the decision procedure. This research will also be essential to further analyse the UR problem and therefore provide a broader picture of the needs for an optimal urban regeneration.

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