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Keywords:	Area deprivation, German Index of Multiple Deprivation, domains, weighting, mortality

Evaluation of alternative weighting approaches for the German Index of Multiple Deprivation

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ABSTRACT

Objectives:

This study aimed to assess the impact of using different weighting procedures for the German Index of Multiple Deprivation (GIMD) investigating their link to mortality rates.

Design and setting: In addition to the original (normative) weighting of the GIMD domains, four alternative weighting approaches were applied: equal weighting, linear regression, maximization algorithm and factor analysis. Correlation analyses to quantify the association between the differently weighted GIMD versions and mortality based on district-level official data from Germany in 2010 were applied (N=412 districts).

Outcome measures: Total mortality (all age groups) and premature mortality (< 65 years).

Results: All correlations of the GIMD versions with both total and premature mortality were highly significant ($p < 0.001$). The comparison of these associations using Williams's t-test for paired correlations showed significant differences, which proved to be small in respect to absolute values of Spearman's rho (total mortality: between 0.535 and 0.615; premature mortality: between 0.699 and 0.832).

Conclusions: The association between area deprivation and mortality proved to be stable, regardless of different weighting of the GIMD domains. The theory-based weighting of the GIMD should be maintained, due to the stability of the GIMD scores and the relationship to mortality.

Keywords: Area deprivation, German Index of Multiple Deprivation, domains, weighting, mortality

STRENGTHS AND LIMITATIONS OF THIS STUDY

- There is only limited literature on the application of different weighting approaches of deprivation indices – this study adds to that body of work.
- Our study provides an overview of established weighting approaches for deprivation indices used in Europe.
- We compare different weighting approaches for the domains of the German Index of Multiple Deprivation (GIMD) using also a greedy maximization algorithm.
- Limited selection of methods due to restricted data access at regional level.

INTRODUCTION

Indices of deprivation are increasingly being used to investigate health and, in some countries, as tools of public policy [1-5]. Therefore, it is important that these indices are transparent and rigorous in their construction so that confidence and understanding in their use are maintained.

In the 2000s, a series of deprivation indices with a multidimensional structure were introduced in the UK. These 'Indices of Multiple Deprivation' (IMDs) have been updated regularly ever since [6]. The domains of deprivation were identified from the literature and were a result of the availability of data at the time. A key aspect to consider when constructing such indices is the weighting and consolidation of the different deprivation domains that produce the final overall index.

Transparency and availability of data used in the indices mean that indicators and weightings can be adapted to particular demands by researchers. Adaptation may be needed, for example to prevent autocorrelation effects where a component of the index is also related to the independent variable under consideration.

An IMD for Germany has been developed based on the methodology according to Noble et al. [6]. It was first applied in the German federal state of Bavaria ('Bavarian Index of Multiple Deprivation', BIMD) and subsequently as a nationwide IMD ('German Index of Multiple Deprivation', GIMD) [7, 8]. For the construction of the German deprivation indices, domains from the British IMDs were partly used (e.g. income and employment), and additional domains for social capital and municipal revenue were introduced. The GIMD includes both aspects, material deprivation (e.g. income) as well as social deprivation (e.g. social capital).

The GIMD has been used repeatedly for analyses regarding the relationship between area deprivation and morbidity, mortality and health care provision in Germany, and a persistent positive association has been shown between area deprivation and health outcomes [9-11].

One crucial point in building IMDs involves the weighting of the different deprivation domains. So far, weightings of IMDs have been conducted mainly by analysing literature on multiple deprivation and based on expert consultation [12]. Regarding the domain weights of the English IMD, alternative empirical weightings were carried out by C. Dibben, which led to a recommendation of adjustment of the weights [13]. However, this did not yield an alteration in the weighting of subsequent IMDs, as user surveys 'did not reveal significant support for moving to new weights' [12], and consisted only of two different empirical methods.

Besides the IMDs in the UK and Germany, several alternative approaches to the development and weighting of deprivation indices have been developed in other European countries [14] as well as non-European countries [15, 16]. These approaches consist of a variety of (empirical) weighting approaches, which have not been applied to the British IMDs. However, it seems that almost all the approaches to weight deprivation indices are based on single methods, and sensitivity analysis regarding the application of different methods to a specific deprivation index has not been done. Additionally, literature regarding the application of different weighting procedures to a deprivation index is lacking. As the GIMD was weighted following the model of the British IMDs, we decided to examine several alternative weighting approaches for the domains of the GIMD by stepwise comparison:

1. From a literature review, we obtain an overview of weighting approaches for deprivation indices in Europe and select methods that can be used for alternative weighting approaches to the domains of the GIMD.

2. Regarding the weighting of the domains and the distribution of the GIMD scores, we analyse the results of the different weighting approaches and compare them with each other.

3. We compare the associations of these new versions of the GIMD with total mortality (all age groups) and premature mortality in Germany (< 65 years) in order to conduct a sensitivity analysis concerning the different approaches.

4. Finally, we identify the weighting set that maximizes the association between the GIMD and mortality.

A conceptual distinction between the different weighting methods was established with the identification of normative and empirically based approaches.

METHODS

Data for the statistical analysis

In order to construct different GIMD versions using alternative weighting approaches, we used regional data from the original GIMD from 2010 (GIMD 2010) for the domain and composite scores of the 412 districts in Germany [17]. For the construction of the original GIMD, Maier et al. standardized nine deprivation indicators and assigned them to seven deprivation domains, which represent different dimensions of deprivation: income, employment, education, environment, security, municipal revenue and social capital (Supplement 1). Each district is provided with a deprivation score for every single domain. The domain score is a statistical measure for the extent of area deprivation in a regional unit. The higher the deprivation within a district, the higher the domain score for the district. Subsequently, the domain scores are weighted based on a theoretical foundation and expert consultation and summed for an overall deprivation score for every district. For further details, see Maier et al. [7, 17].

Regarding an analysis of the relationship between area deprivation and both total mortality and premature mortality, we used raw mortality data and population data from 2010 at the district level, derived from the German Federal Statistical Office [18]. The districts were identified by official district code numbers. Using the mortality and population data, we indirectly calculated standardized mortality rates (SMRs) for both total mortality (SMR 'total') as well as premature mortality (SMR 'premature'). This was necessary to compare districts because of their highly varying population size [19].

Methods for the weighting and methods for the statistical analysis

Additional to the original weighting of the GIMD 2010, we decided to use four methods for the weighting of the GIMD domains found in a literature review (Table 1).

Table 1: Overview of identified weighting methods through a systematic literature review: characteristics and evaluation of the methods (abbreviations in brackets)

	Normative weighting of the domains/indicators			**Empirical weighting of the domains/indicators**					
Weighting methods	**Equal weighting of domains/indicators**	**Expert weighting of the domains/ indicators**	**Theory-based weighting of the domains**	**Logistic regression**	**Principal components analysis (PCA)**	**Bayesian factor analysis**	**Exploratory factor analysis (EFA)**	**Confirmatory factor analysis (CFA)**	**Revealed preferences**
Description and weighting of the indicators/ domains	- Equal weighting of the domains/ indicators	- Weighting of the domains/ indicators according to expert opinion	- Weighting of the domains: derived from research literature on multiple deprivation and social exclusion and by consultation process	- Deprivations: proxy as dependent, coefficients as relative weights of the domains	- Extraction of factors from indicators - Factors used as deprivation index/indices - Factor loadings as relative weights of the indicators			- Number of factors derived from research literature - Factor loadings as relative weights of the indicators	- Proportion of government spending allocated to each domain of the IMD was used to derive a set of weights
Construction index	Additive score of the equally weighted indicators or domains	Additive score of the weighted indicators or domains							
Selected advantages of the methods	- Simplest solution for aggregation of indicators to an overall score [20] - Equal relevance of all indicators/ domains	- Different weighting of the indicators, according to the individual relevance - Based on expert knowledge [20, 21]	- Weights derived from theory and research literature [6]	- Weights derived directly from the data [20] - Easy handling of the model and the coefficients [21]	- Weights derived directly from the data [20] - Easy handling, often used and robust approach [21-23]	- Weights derived directly from the data [20] - Suited for analysis of small area units [24]	- Statistical model - Derivation of number of factors by model fit [25] - Exploration of latent dimensions without foreknowledge [25]	- Dimensions of deprivation derived from theory and set a priori [23] - Measures of goodness of fit and error of model [25]	- Relative relevance of the domains, which influence public life, reflected by government spending [13]

Selected disadvantages of the methods	- Unintentional, implicit weighting of the domains of multiple deprivation possible (owing to the number of indicators included per dimension) [6]	- Arbitrary weighting possible, because of subjective decisions [20]	- Selected weights dependent on the quality of the research from the literature - Normative, subjective setting [21, 26]	- Derived coefficient dependent on the data quality - Removal or addition of variables can alter the coefficients significantly [20] - Large omitted variables, bias possible	- Descriptive data reduction of the variables [25] - All variables load on all factors [23] - Transferability to the population limited because of explanation of the sample variance [25]	- Derived coefficient dependent on the data quality - Reduction to one factor does not consider the multidimensionality of deprivation [23]	- Reliability is dependent on data quality - Restricted temporal comparability [20] - Different interpretability of the results, several decisions required [25]	- Elaborate procedure: theoretical knowledge and conceptualization required [25] - Several decisions required regarding covariance structure and the method of parameter estimation [25]	- Overlap of the spending for the domains possible, unambiguous allocation elaborate
Selected examples	[27]	[28]	[8, 12]	[13]	[29]	[24]	[30]	[31]	[13]

Besides the equal weighting of the domains, we used two commonly used empirical methods and an additional greedy algorithm method. The purpose of the empirical approaches was to extract relative weights for the domain scores from an empirical dataset. The extracted coefficients of the methods were used as relative weights for the domain scores, which should sum to 1 (or 100%), before the summation of the domains to an overall deprivation score.

1. Original weighting of the domains of the GIMD through theoretical foundation and expert opinion according to Maier et al. [8]. For weights used, see Supplement 1.

2. Equal weighting of the seven GIMD domains; thus, each domain weighted with 1/7. This approach was originally used for deprivation indices by Carstairs and Townsend [32, 33]. To date, this approach is still used for deprivation indices consisting of just single deprivation indicators [26, 33]. For this approach, an equal effect of all deprivation indicators is assumed. In our analysis, we transferred this approach to the domain level.

3. Weighting of the domains by the coefficients of a linear regression analysis with a proxy for deprivation ('available living space per inhabitant') as the dependent variable and the GIMD domains as the independent variables. We had to choose a dependent variable for the linear regression that had not been used for the construction of the GIMD domains and could be considered as an indicator of deprivation [13]. Townsend, Carstairs and Jarman considered overcrowding of living space as an indicator of deprivation [28, 32, 33]. We assumed that the availability of living space per inhabitant in an area could act as a proxy for area deprivation: the more deprived the area, the less living space is available per inhabitant [34-36]. For this approach, we calculated the absolute value of the regression coefficients and then used them as relative weights for the specific domains. Subsequently, the weighted domain scores were summed to an overall score. Linear models for the extraction of weights for a deprivation score have already been conducted in several studies [13, 37-38]. Because of the normal distribution of the dependent variable, we conducted an ordinary least square (OLS) regression.

4. Weighting of the GIMD domains using a greedy maximization algorithm [39]. This yields weights for the domains close to the maximum possible correlation between the GIMD 2010 and mortality as a relevant outcome of deprivation. The weighted domain scores of the GIMD were then added together to an overall index for both total mortality and premature mortality. This addition to the methods of the literature search aimed to extract weights for the maximum Spearman correlation between GIMD and mortality and can thus be seen as an outcome-specific approach with the independent variable mortality. Complete circularity was present because mortality had already been used for the extraction of the weights. In contrast, the other methods could be seen as general weighting approaches for deprivation indices.

5. Weighting of the domains according to the results of an exploratory factor analysis (EFA). We chose a principal axis factoring (PAF) approach for the extraction of the factors. PAF is a commonly used extraction method for factor analysis and requires no specific distribution of the entered variables. This non-parametric approach was necessary because of the exponentially transformed domains [25]. A priori, we specified the extraction of one factor (as a latent factor, measuring 'multiple deprivation') out of the seven domains. The absolute values of the factor loadings of the different domains were used as relative weights for the domains. Again, the weighted domains were added together to an overall deprivation score.

Correlation analysis and statistical software

Subsequently, we performed a sensitivity analysis of the newly weighted GIMD versions. We conducted correlation analyses in order to calculate the relationship between the different GIMD versions and both total as well as premature mortality (in terms of SMRs) and compared their results. For the analysis, we used Spearman's rank correlation coefficient (ρ) as a robust approach. This was required, in our opinion, as the GIMD score could be interpreted as an ordinal variable because of the ranking of the districts during the generation of the domain scores [7, 40]. Correlation analyses were each performed with a GIMD version and both total mortality and premature mortality. We also tested for significance of these bivariate correlation coefficients at an α-level of 5% [41]. For comparison of the bivariate correlations among each other, we performed t-tests for paired correlations. For this, we used Williams's t-test for the comparison of correlations out of dependent samples [42]. We compared two correlation coefficients in terms of both total and premature mortality at an α-level of 5%. For the statistical analysis, we used the Software R, version 3.2.3 [43].

Patient and Public Involvement

Patients and/or public were not involved in this study.

RESULTS

Population size of the districts and estimation of the SMRs

The size of the population of the 412 districts varied with median size of 139,188 inhabitants, IQR of 130,170 persons, minimum size of 33,944 and maximum size of 3,460,725 persons. Raw mortality of the 412 districts varied with median of 1,522 death cases, IQR of 1,347 cases, minimum of 413 cases and maximum of 32,234 cases. Qualifying date of the data was 31st December 2010. We estimated total mortality by calculating 'SMR_{total}' for the districts with a mean of 1.0175 (standard error (SE): 0.004) and premature mortality '$SMR_{premature}$' with a mean of 1.0165 (SE: 0.004). For details on the calculation of the SMRs, see Supplement 2.

Weights of the domains of the alternative approaches

An overview of the identified weighting methods for deprivation indices is given in Table 1. Alongside a description of the weighting and the construction of the deprivation indices, we offered selected advantages and disadvantages of the methods. This was completed with selected examples. From this table, we chose four approaches additional to the original weighting of the GIMD.

We found considerable differences between the domain weights resulting from the different approaches (Table 2).

Table 2: Weighting of the domains of the GIMD[1] through different weighting approaches, values in percentage points

Deprivation domains/ methods of domain weighting of the GIMD[1]	Income	Employment	Education	Municipal revenue	Social capital	Environment	Security
Original weighting	25.00	25.00	15.00	15.00	10.00	5.00	5.00
Equal weighting	14.29	14.29	14.29	14.29	14.29	14.29	14.29
Linear regression	4.47	21.68	15.42	30.25	11.45	14.65	2.09
Maximization algorithm (total mortality)	18.23	20.67	1.04	21.90	28.26	4.62	5.28
Maximization algorithm (premature mortality)	18.85	48.93	0.31	15.98	10.73	0.50	4.70
Factor analysis	23.09	18.99	8.97	21.72	20.08	5.86	1.28

[1] **GIMD:** German Index of Multiple Deprivation;

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and mortality;

Factor analysis: Weighting of the domains with loadings from principal axis factoring .

The weights for employment deprivation showed the largest variation with a range of 34 percentage points. The other deprivation domains showed a dispersion of at least 14 percentage points. Educational deprivation within the maximization algorithm and income deprivation within the linear regression showed very small weights compared with the weights of the original GIMD 2010. Municipal revenue deprivation resulted in a weight twice as high as the original weight within the linear regression. Concerning the algorithm, the weight for social capital deprivation was three times the original weight. Concerning premature mortality, the weight for employment deprivation was twice as high as the original weight for the GIMD. Deprivation domains for social capital and district income showed constantly higher weights for the empirical approaches compared with the two normative methods. The different GIMD versions revealed different distributions of the overall deprivation scores (Table 3).

Table 3: Descriptive results of the weighted indices, information on GIMD[1] scores

	Original weighting	Equal weighting	Linear regression	Maximization algorithm SMR[2] 'total' (SMR[2] 'premature')	Factor analysis
Number of districts	412	412	412	412 (412)	412
Mean	21.81	21.81	21.81	21.81 (21.81)	21.81
Median	18.80	19.97	19.34	17.05 (16.49)	18.17
Standard deviation	12.73	10.34	10.98	15.61 (17.09)	14.24
Variance	162.03	106.98	120.65	243.63 (292.03)	202.89
Minimum	2.04	2.29	2.11	1.48 (0.92)	1.33
Maximum	70.98	55.69	67.67	85.91 (91.14)	79.86

[1]**GIMD:** German Index of Multiple Deprivation

[2] **SMR**: Standardized mortality ratio

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and both total mortality (SMR 'total') and premature mortality (SMR 'premature' in brackets);

Factor analysis: Weighting of the domains with loadings from principal axis factoring.

Assumptions for the linear regression were generally met, and the model had significant explanatory power (adj. $R^2 = 0.33$). Five of the seven domains showed a significant effect on the deprivation proxy. Heterogeneity was present; thus, we presented robust standard errors (Supplement 3). The factor analysis generally had significant explanatory power (Chi-square: 584.65, $p < 0.0001$) and showed moderate reliability (Tucker–Lewis index = 0.50) (Supplement 4).

Results of the statistical analysis

Correlation analysis between the differently weighted deprivation indices and mortality showed different results (Table 4).

Table 4: Spearman's rank correlation coefficients for the association between the versions of the GIMD[1] and both premature and total mortality.

Methods of the domain weighting of the GIMD[1]	Total mortality (SMR[2] 'total')	Premature mortality (SMR[2] 'premature')
Original weighting	0.578*** [0.506, 0.642]	0.767*** [0.718, 0.808]
Equal weighting	0.535*** [0.459, 0.604]	0.699*** [0.641, 0.750]
Linear regression	0.564*** [0.492, 0.629]	0.738*** [0.685, 0.784]
Maximization algorithm	0.615*** [0.547, 0.676]	0.832*** [0.794, 0.864]
Factor analysis	0.598*** [0.529, 0.661]	0.772*** [0.724, 0.813]

*** $p < 0.001$, bootstrapped (10,000 fold), 95% confidence intervals in square brackets

[1] **GIMD:** German Index of Multiple Deprivation

[2] **SMR**: Standardized mortality ratio

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and mortality;

Factor analysis: Weighting of the domains with loadings from principal axis factoring.

Deprivation indices, domains weighted by the maximization algorithm, showed the maximum correlation with total mortality (ρ = 0.615) and premature mortality (ρ = 0.832). Correlations between the original GIMD and both total and premature mortality were ρ = 0.578 and 0.767 respectively. Correlations between the equally weighted GIMD and mortality were the lowest with ρ = 0.535 and 0.699. All correlations were significant concerning both total and premature mortality ($p < 0.001$). Additionally, bivariate correlations between all indices were significant (ρ between 0.86 and 0.98).

Pairwise comparisons of the correlation coefficients with Williams's t-tests showed a differentiated result (see Table 5).

Table 5: Test[1] of the differences in the Spearman correlation coefficients for the relationship of the GIMD[2] versions and both total and premature mortality

Total mortality	Original weighting	Equal weighting	Linear regression	Maximization algorithm	Factor analysis
Original weighting	0	0.043** [0.015, 0.074]	0.014$^{n.s.}$ [-0.006, 0.034]	–0.037*** [-0.060, -0.016]	–0.020** [-0.038, -0.005]
Equal weighting	–0.043** [-0.074, -0.015]	0	–0.029* [-0.059, -0.001]	–0.080*** [-0.122, -0.041]	–0.063*** [-0.105, -0.025]
Linear regression	–0.014$^{n.s.}$ [-0.034, 0.006]	0.029* [0.001, 0.059]	0	–0.051*** [-0.080, -0.024]	-0.034** [-0.059, -0.011]
Maximization algorithm	0.037*** [0.016, 0.060]	0.080*** [0.041, 0.122]	0.051*** [0.024, 0.080]	0	0.016** [0.003, 0.031]
Factor analysis	0.020** [0.005, 0.038]	0.063*** [0.025 , 0.105]	0.034** [0.011, 0.059]	–0.016 ** [-0.031, -0.003]	0
Premature mortality					
Original weighting	0	0.068*** [0.044, 0.097]	0.028*** [0.012, 0.049]	–0.065*** [-0.093, - 0.043]	–0.005$^{n.s.}$ [-0.021, 0.019]
Equal weighting	–0.068*** [-0.097, -0.044]	0	–0.040***	–0.133*** [-0.174, -0.098]	–0.073*** [0.110, -0.040]
Linear regression	–0.028*** [-0.049, -0.012]	–0.040***	0	–0.094 *** [-0.128, -0.066]	–0.034*** [-0.014, -0.057]
Maximization algorithm	0.065*** [0.043, 0.093]	0.133*** [0.098, 0.174]	0.094*** [0.066, 0.128]	0	0.060*** [0.037, 0.088]
Factor analysis	0.005$^{n.s.}$ [-0.019, 0.021]	0.073*** [0.040, 0.110]	0.034*** [0.014, 0.057]	–0. 060*** [-0.088, -0.037]	0

*** p < 0.001; ** p < 0.01; * p < 0.05; n.s. not significant, 95% confidence intervals in square brackets

[1] Test of the significance of the differences with Williams's t-test for paired correlations

[2] **GIMD:** German Index of Multiple Deprivation

Original weighting: Spearman correlation between GIMD (weighting according to Maier et al. [8]) and both total and premature mortality;

Equal weighting: Spearman correlation between GIMD (domains equally weighted) and both total and premature mortality;

Linear regression: Spearman correlation between GIMD (weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables) and both total and premature mortality;

Maximization algorithm: Spearman correlation between GIMD (weighting of the domains for the maximum Spearman correlation between overall index and mortality) and both total and premature mortality;

Factor analysis: Spearman correlation between GIMD (weighting of the domains with loadings from principal axis factoring) and both total and premature mortality.

Almost every pairwise difference in the correlation coefficients was significant at the 5% α-level. One exception was the difference in the coefficients between the original GIMD and the GIMD weighted by linear regression concerning total mortality. The other deviation was the difference between the original GIMD and the GIMD weighted by factor analysis concerning premature mortality. The difference was not significant, neither one-sided nor two-sided. Maximum correlation coefficients of the GIMD, weighted by the algorithm, differed significantly from all the correlation coefficients of the other methods regarding both total and premature mortality.

DISCUSSION

The central objective of the study was to explore whether alternative weighting approaches had an influence on the relationship between area deprivation and mortality when applied to the GIMD. Thereby, different weighting methods were selected if they were, on the one hand, applicable to the domain-based construction of the GIMD and, on the other hand, seemed feasible in the course of an application of a multi-methodical approach. The four different methods were applied to the weighting of the domains of the GIMD 2010. The selected approaches and the original method were compared concerning both the weighting of the domains of the GIMD and the relationship between GIMD and mortality.

There was little evidence in the literature concerning the application of different weighting methods for multidimensional deprivation indices. However, a summary of different weighting approaches and their classification was presented by Noble et al [6]. They briefly assessed the specific procedures of the methods (e.g. empirical approaches) and were in favour of a weighting driven by literature considerations on multiple deprivation. Regarding the application of empirical weighting approaches for the English IMD 2004, we want to emphasize Dibben's work [13]. He recommended new weights for the domains of the IMD, as the empirical weighting approaches indicated a higher weighting of the health domain and a lower weighting of the employment domain. However, this suggested swapping of weights was not eventually applied to the subsequent versions of the English IMD. The maintenance of the weights was justified by a consultation of IMD users and stable results of the IMD with either existing or suggested weights [12].

In this study, we pursued a multi-methodical approach for the weighting of the GIMD, including empirical methods. Owing to the different inherent intentions of the selected methods, we integrated the approaches as follows:

1. Normative approaches: The original weighting of the domains according to Maier et al. through theory and experts' opinion. We used the term 'normative' because weights for the domains must be selected a priori subjectively before they can be validated with data.

2. *Specific empirical approaches*: Concerning the maximization algorithm with the dependent variable mortality, a weighting of the domains has been sought that was in line with the relationship between area deprivation and both total mortality and premature mortality and should maximize the correlation between them.

3. General empirical approaches: In contrast to the specific empirical approaches, the weighting of the domains was realized according to the results of a linear regression model or according to a factor analysis to generate generally applicable indices, which can also be used for the analysis of other health outcomes.

Assessment of the alternative weighting approaches

The high weighting of the deprivation domains income and employment of 50% altogether within the original GIMD was confirmed by the empirical weighting of the factor analysis approximately, as well as the weighting of the environment deprivation domain. Educational deprivation was weighted considerably lower by the factor analysis and algorithm than by the original GIMD. Deprivation domains for district income and social capital were constantly weighted much higher by the empirical approaches than by the approach of the original GIMD. The shift in the weighting of the domains can be explained by the data dependency of the empirical approaches and should be reviewed using alternative data. Should the higher weighting of the district income and social capital domains be confirmed, an adjustment in the domain weights could be considered. Perhaps those context variables have a higher relevance concerning area deprivation than expected by Maier et al. [8].

The low weighting of the deprivation domains of income by the linear regression and education by the maximization algorithm can barely be reconciled with existing evidence regarding the positive relationship of these two deprivation domains and mortality [44, 45]. The high weighting of the employment deprivation domain (49%) by the algorithm, concerning mortality, could reflect the high relevance of unemployment relating to premature mortality.

Relationship of the GIMD versions and mortality

Throughout the analysis, we could not find a weighting method that could be seen as superior compared with the other approaches or could even be recommended as a gold standard. Even though almost all GIMD weighting approaches differed significantly in their correlation with mortality, using only significance as a method of evaluation for the approaches seemed inappropriate. The correlation coefficient between the different GIMD versions was already very high ($\rho > 0.89$), so that even small non-relevant differences could have produced significant results. All correlations of the GIMD versions with mortality were highly significant and showed rather small differences in respect to absolute values (ρ between 0.54 and 0.62). Since we conducted multiple paired t-tests, type-1 error inflation was present. In an additional analysis we corrected for multiple testing with Benjamini et al. adjustment [46]. When we corrected for the correlation of the GIMD versions with mortality, the significance of the results did not change (Table 4). When we corrected for the multiple comparison of the difference of the correlation between the GIMD-versions (Table 5), there was a slight difference present in the significance (Supplement 5).

The empirical weighting of the GIMD by an exploratory factor analysis represented an adequate alternative to the theory-based weighting of the domains, on account of the simple operability and the highly significant association of this GIMD version with mortality. Thereby, a general applicability of the GIMD for the analysis of implications for other health outcomes can be ensured, and the results of different datasets can be compared by model fit measures [25]. Despite the significant correlation, the application of equal weighting of the domains could be considered as obsolete, as this would produce an implicit weighting of the domains depending on the availability of indicators for each domain [6].

Strengths and limitations of the study

Using a multi-methodological strategy, we were able to cover a broad bandwidth of weighting approaches. As there seems to be no gold standard for weighting of deprivation indices, we recommend that sensitivity testing of the GIMD is particularly important. An equal weighting as well as an exploratory factor analysis for the weighting of multiple deprivation domains were carried out in this study for the first time. A factor analysis of the IMD domains was advised by Deas et al. [26], but has not been implemented to date. Furthermore, we provided an outcome-specific weighting approach in the form of a greedy maximization algorithm: this method produced a domain weighting of the GIMD that maximized a specific measure concerning one health outcome (in this case, the correlation between GIMD and mortality). A transfer of the algorithm to other areas of interest is possible without difficulty but should be used mainly for orientation, which is possible concerning a selected measure, given a dataset.

Limitations of the study concerned the selection of weighting methods such as the revealed preferences or Bayesian factor analysis (cf. Table 1), which resulted from restricted data access at a regional level. Empirical methods are always data dependent and are restricted concerning a possible comparison over time, especially with the use of cross-sectional data. This could be addressed by using longitudinal data and would enable us to measure 'between variation' (i.e. over different locations) to 'within variation' (i.e. the same location over time).

Using correlation coefficients to evaluate the association between different GIMD versions and mortality does not necessarily imply a causal association between area deprivation and mortality. Additionally, overfitting is present by using the greedy algorithm as a weighting approach, since it already yields the weights for the maximum correlation between the GIMD and mortality. However, there is reliability of using the GIMD to evaluate total and premature mortality, since the correlation between the GIMD and mortality is very stable over time (GIMD scores from 2006 and 2010 yield very similar correlations with mortality). Another point was the lack of literature regarding the application of different weighting procedures. This limitation could partly be counterbalanced with the input of expert interviews. With regard to the linear regression, the selection of the deprivation proxy should be reconsidered ex post, as the use of the deprivation measure regarding living space per inhabitant showed a rather weak (yet significant) positive correlation with overall deprivation (ρ = 0.35). This could be explained by the idea that, in less deprived cities such as Hamburg and Munich, there can be – in general – less available living space because of a very competitive housing market. So, there could be a partial negative correlation between deprivation regarding available living space and overall deprivation in some areas. Unfortunately, multidimensional proxies at district level were not available for Germany. We tested other measures like the overall Gross Domestic Product (GDP) per district and the GDP per employed persons per district. They had a similar or lower correlation with the original GIMD as the living space variable, but using them had some major drawbacks. We understand, that the use of a one-dimensional proxy is a limitation in our work. However, given the very restricted variety of appropriate variables at the district level in Germany, the selection of this proxy was a pragmatic approach to test a weighting approach based on a linear regression.

Conclusion

The variation in the domain weights of the GIMD did not have a large measurable impact on the relationship between area deprivation and mortality. The correlation between the GIMD and both total mortality and premature mortality proved to be very stable, regardless of the application of the different weighting approaches and the resulting different sets of domain weights. The GIMD versions produced relatively stable results with regard to the central distribution measures of the overall scores (Table 3).

The theory-based weighting of Maier et al. can be interpreted ex post as more conservative than the empirical weighting approaches, as the weighting of the income and employment domains is relatively strong at 50% in contrast to the empirical methods. Nevertheless, a theory-based selection of domains seems to be more meaningful than an empirically based selection because the results of the empirical methods are restricted, as discussed above. The stability with respect to the scores and the relationship to mortality support this advice. A modelling of the GIMD with a confirmatory factor analysis could be considered as a promising empirical approach with the prospect of temporal comparability in future studies.

Competing interests

No competing interests to declare.

Data sharing statement

Extra data regarding the GIMD is available by emailing Werner Maier (werner.maier@helmholtz-muenchen.de).

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Contributorship statement

FS and WM designed the study. FS performed the analysis and wrote the initial version of the manuscript. CK gave statistical advice, provided the greedy maximization algorithm and gave support preparing the manuscript. WM provided the German Index of Multiple Deprivation (GIMD), supervised the study and gave support preparing the manuscript. JF advised on deprivation indices and gave support preparing the manuscript. All authors read and approved the final manuscript.

What is already known on this subject

Indices of Multiple Deprivation are weighted according to theoretical deliberations about deprivation and expert consultations. Several alternative weighting methods for deprivation indices are available. However, evidence is scarce regarding the comparison of these weighting approaches.

What this study adds

- **Different weighting approaches were applied to the domains of the German Index of Multiple Deprivation (GIMD). The resulting GIMD versions were compared regarding to the domain weights and the association of these indices with mortality.**
- **The association of the differently weighted GIMD versions with mortality proved to be very stable, regardless of the weighting approach. However, theory-based weighting of the domains provides a good standard.**

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SUPPLEMENT

Supplement 1: Weighting of the domains and use of indicators from the 'German Index of Multiple Deprivation' (GIMD).

Domains	**Domain weight (%)**	**Indicators (reference)**
Income deprivation	25	- Total earnings (Number of Taxpayers)
Employment deprivation	25	- Total number of unemployed (Population, 15 to 65 years)
Educational deprivation	15	- Persons without vocational training (Employees subject to social security contributions at the place of residence)
Municipal revenue deprivation	15	- Tax revenue of municipalities (Total population)
Social capital deprivation	10	- Migration balance* (Total population) - Electoral participation in % (Federal parliament)
Environment deprivation	5	- Commercial, industrial and traffic areas ** (Total area)
Security deprivation	5	- Number of road accidents(Total population) - Number of crimes(Total population)

* People moving into a municipality or a district minus people leaving a municipality or a district.

** Indicator for soil sealing.

Supplement 2: Calculation of the standardized mortality rates (SMR):

1. SMR 'total mortaltiy' per district = total deaths per district / expected total deaths per district

2. Expected total deaths per district = total population size per district * total mortality rate per 100,000 per district / 100,000

3. Total mortality rate per 100,000 per district = total deaths per district/total population size per district*100,000

4. SMR 'premature mortaltiy' per district = premature (before 65 years) deaths per district / expected premature (before 65 years) deaths per district

5. Expected premature deaths per district = premature population size per district * premature mortality rate per 100,000 per district / 100,000

6. Premature mortality rate per 100,000 per district = premature deaths per district/premature population size per district*100,000

Supplement 3: Results of a linear regression: Outcome: deprivation proxy, Covariables: domains of the GIMD10.

Deprivation of living space = Income + Employment + Education + Municipal Income + Social Capital + Environment + Security

Coefficients (Robust Standard Errors in Parenthesis)	
Income	0.014
	(0.051)
Employment	0.067*
	(0.029)
Education	-0.048*
	(0.023)
Municipal income	-0.094***
	(0.025)
Social capital	0.035**
	(0.014)
Environment	0.045***
	(0.011)
Security	-0.006
	(0.008)
--	
Model	
R-squared = 0.34	
adj. R-squared = 0.33	
F = 30.01	
p < 0.001	
Log-likelihood = -1050.76	
Deviance = 3959.74	
AIC = 2117.52	
BIC = 2149.69	
N = 412	

**** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s. not significant*

Source: R-Output, regression results conducted with R-package 'stargazer' [47].
→ All domains have a significant effect on the proxy, except security and Income
→ Overall model explains the variance of living space deprivation significantly, $R^2 = 0.34$

Supplement 4: Results of an exploratory factor analysis of the deprivation domains with the extraction of one factor, method = principal axis factor analysis.

Standardized loadings	Factor 1	Communality (u^2)	Specific variance ($1– u^2$)
Income	0.92	0.85	0.15
Employment	0.76	0.58	0.42
Education	–0.36	0.13	0.87
Municipal income	0.87	0.75	0.25
Social capital	0.80	0.64	0.36
Environment	-0.23	0.06	0.94
Security	-0.05	0.01	0.99

Model	Factor 1
Variance, explained by the factor (SS loadings)	3.01
Proportion of total variance	0.43

Model fit measures	
Root mean square of the residuals (RMSR)	0.17
Likelihood chi square	584.65 ($p < 0.001$)
Tucker–Lewis index of factoring reliability	0.50
RMSEA index (confidence interval)	0.32 ([0.30; 0.34])
BIC	500.35

Source: Tables output from R and own presentation

Supplement 5: Corrected Test[1] of the differences in the Spearman correlation coefficients for the relationship of the GIMD[2] versions and both total and premature mortality.

Total mortality (all age groups)	Original weighting	Equal weighting	Linear regression	Maximization algorithm	Factor analysis
Original weighting	0	0.043*	0.014$^{n.s.}$	–0.037**	–0.020*
Equal weighting	–0.043*	0	–0.029*	–0.080***	–0.064**
Linear regression	–0.014$^{n.s.}$	0.029*	0	–0.051 ***	–0.034*
Maximization algorithm	0.037**	0.080**	0.051**	0	0.016*
Factor analysis	0.020*	0.064**	0.034*	–0.016 *	0
Premature mortality (< 65 years)					
Original weighting	0	0.068***	0.028***	–0.065***	–0.005$^{n.s.}$
Equal weighting	–0.068***	0	–0.040**	–0.133***	–0.073***
Linear regression	–0.028***	–0.040**	0	–0.094 ***	–0.034***
Maximization algorithm	0.065***	0.133***	0.094 ***	0	0.060***
Factor analysis	0.005$^{n.s.}$	0.073***	0.034***	–0. 060***	0

*** p < 0.001; ** p < 0.01; * p < 0.05; n.s. not significant

[1] Test of the significance of the differences with Williams's t-test for paired correlations

[2] **GIMD:** German Index of Multiple Deprivation

Original weighting: Spearman correlation between GIMD (weighting according to Maier et al. [8]) and both total and premature mortality;

Equal weighting: Spearman correlation between GIMD (domains equally weighted) and both total and premature mortality;

Linear regression: Spearman correlation between GIMD (weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables) and both total and premature mortality;

Maximization algorithm: Spearman correlation between GIMD (weighting of the domains for the maximum Spearman correlation between overall index and mortality) and both total and premature mortality;

Factor analysis: Spearman correlation between GIMD (weighting of the domains with loadings from principal axis factoring) and both total and premature mortality.

Supplement 6: Working steps of the greedy weighting algorithm.

- The vector P containing the greedy solution of the non-normalized weighted sum in each step is initialized with zero elements.
- All column weights and the total number of weights are also initialized to zero. In each iteration, first, the total number of weights is incremented.
- Then, all sums of P with a column of X are normalized by the total number of weights and evaluated separately on the evaluation metric (correlation).
- The column corresponding to the highest value is assigned one weight factor and added to P. This procedure is repeated 100 times.
- The algorithm returns a vector of length N, with the number of columns of X, containing weights for each column, summing to 1.

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Do alternative weighting approaches for an Index of Multiple Deprivation change the association with mortality? A sensitivity analysis from Germany.

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Do alternative weighting approaches for an Index of Multiple Deprivation change the association with mortality? A sensitivity analysis from Germany.

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ABSTRACT

Objectives:

This study aimed to assess the impact of using different weighting procedures for the German Index of Multiple Deprivation (GIMD) investigating their link to mortality rates.

Design and setting: In addition to the original (normative) weighting of the GIMD domains, four alternative weighting approaches were applied: equal weighting, linear regression, maximization algorithm and factor analysis. Correlation analyses to quantify the association between the differently weighted GIMD versions and mortality based on district-level official data from Germany in 2010 were applied (N=412 districts).

Outcome measures: Total mortality (all age groups) and premature mortality (< 65 years).

Results: All correlations of the GIMD versions with both total and premature mortality were highly significant ($p < 0.001$). The comparison of these associations using Williams's t-test for paired correlations showed significant differences, which proved to be small in respect to absolute values of Spearman's rho (total mortality: between 0.535 and 0.615; premature mortality: between 0.699 and 0.832).

Conclusions: The association between area deprivation and mortality proved to be stable, regardless of different weighting of the GIMD domains. The theory-based weighting of the GIMD should be maintained, due to the stability of the GIMD scores and the relationship to mortality.

Keywords: Area deprivation, German Index of Multiple Deprivation, domains, weighting, mortality

STRENGTHS AND LIMITATIONS OF THIS STUDY

- There is only limited literature on the application of different weighting approaches of deprivation indices – this study adds to that body of work.
- Our study provides an overview of established weighting approaches for deprivation indices used in Europe.
- Sensitivity testing of deprivation indices is particularly important as there seems to be no gold standard.
- We compare a broad range of normative and empirical weighting approaches for the domains of an Index of Multiple Deprivation.
- Limitations of the study concern the selection of weighting methods resulting from restricted data access at regional level.

INTRODUCTION

Indices of deprivation are increasingly being used to investigate health and, in some countries, as tools of public policy [1-5]. Therefore, it is important that these indices are transparent and rigorous in their construction so that confidence and understanding in their use are maintained.

In the 2000s, a series of deprivation indices with a multidimensional structure were introduced in the UK. These 'Indices of Multiple Deprivation' (IMDs) have been updated regularly ever since [6]. The domains of deprivation were identified from the literature and were a result of the availability of data at the time. A key aspect to consider when constructing such indices is the weighting and consolidation of the different deprivation domains that produce the final overall index.

Transparency and availability of data used in the indices mean that indicators and weightings can be adapted to particular demands by researchers. Adaptation may be needed, for example to prevent autocorrelation effects where a component of the index is also related to the independent variable under consideration.

An IMD for Germany has been developed based on the methodology according to Noble et al. [6]. It was first applied in the German federal state of Bavaria ('Bavarian Index of Multiple Deprivation', BIMD) and subsequently as a nationwide IMD ('German Index of Multiple Deprivation', GIMD) [7, 8]. For the construction of the German deprivation indices, domains from the British IMDs were partly used (e.g. income and employment), and additional domains for social capital and municipal revenue were introduced. The GIMD includes both aspects, material deprivation (e.g. income) as well as social deprivation (e.g. social capital).

The GIMD has been used repeatedly for analyses regarding the relationship between area deprivation and morbidity, mortality and health care provision in Germany, and a persistent positive association has been shown between area deprivation and health outcomes [9-11].

One crucial point in building IMDs involves the weighting of the different deprivation domains. So far, weightings of IMDs have been conducted mainly by analysing literature on multiple deprivation and based on expert consultation [12]. Regarding the domain weights of the English IMD, alternative empirical weightings were carried out by C. Dibben, which led to a recommendation of adjustment of the weights [13]. However, this did not yield an alteration in the weighting of subsequent IMDs, as user surveys 'did not reveal significant support for moving to new weights' [12], and consisted only of two different empirical methods.

Besides the IMDs in the UK and Germany, several alternative approaches to the development and weighting of deprivation indices have been developed in other European countries [14] as well as non-European countries [15, 16]. These approaches consist of a variety of (empirical) weighting approaches, which have not been applied to the British IMDs. However, it seems that almost all the approaches to weight deprivation indices are based on single methods, and sensitivity analysis regarding the application of different methods to a specific deprivation index has not been done. Additionally, literature regarding the application of different weighting procedures to a deprivation index is lacking.

As the GIMD was weighted by experts following the model of the British IMDs, we conducted a sensitivity analysis for the domain weighting of the GIMD following the example of Dibben et al. [13]. The aim of this study was to test the stability of the GIMD to different weighting approaches by conducting correlation analyses with mortality as a key health outcome. We decided to examine several alternative weighting approaches for the domains of the GIMD by stepwise comparison:

1. From a literature review, we obtain an overview of weighting approaches for deprivation indices in Europe and select methods that can be used for alternative weighting approaches to the domains of the GIMD.

2. Regarding the weighting of the domains and the distribution of the GIMD scores, we analyse the results of the different weighting approaches and compare them with each other.

3. We compare the associations of these new versions of the GIMD with total mortality (all age groups) and premature mortality in Germany (< 65 years) in order to conduct a sensitivity analysis concerning the different approaches.

4. Finally, we identify the weighting set that maximizes the association between the GIMD and mortality.

A conceptual distinction between the different weighting methods was established with the identification of normative and empirically based approaches.

METHODS

Data for the statistical analysis

In order to construct different GIMD versions using alternative weighting approaches, we used regional data from the original GIMD from 2010 (GIMD 2010) for the domain and composite scores of the 412 districts in Germany [17]. For the construction of the original GIMD, Maier et al. standardized nine deprivation indicators and assigned them to seven deprivation domains, which represent different dimensions of deprivation: income, employment, education, environment, security, municipal revenue and social capital (Supplement 1). Each district is provided with a deprivation score for every single domain. The domain score is a statistical measure for the extent of area deprivation in a regional unit. The higher the deprivation within a district, the higher the domain score for the district. Subsequently, the domain scores are weighted based on a theoretical foundation and expert consultation and summed for an overall deprivation score for every district. For further details, see Maier et al. [7, 17].

Regarding an analysis of the relationship between area deprivation and both total mortality and premature mortality, we used raw mortality data and population data from 2010 at the district level, derived from the German Federal Statistical Office [18]. The districts were identified by official district code numbers. Using the mortality and population data, we indirectly calculated standardized mortality rates (SMRs) for both total mortality (SMR ‘total’) as well as premature mortality (SMR ‘premature’). This was necessary to compare districts because of their highly varying population size [19]. For details on the calculation of the SMR see Supplement 2.

We used the variable 'available living space per inhabitant' from the German Federal Statistical Office from 2010 [18] as a proxy of deprivation. We reversed the polarity of its values and thus make it more comparable to the GIMD scores.

Methods for the weighting and methods for the statistical analysis

Additional to the original weighting of the GIMD 2010, we decided to use four methods for the weighting of the GIMD domains found in a literature review (Table 1). We searched relevant literature in the databases PubMed and Embase [e.g., keywords used in PubMed: (deprivation OR deprived) AND (index OR indices) AND (area* OR region* OR neighborhood OR neighbourhood), limits: English OR German OR French OR Italian OR Spanish.]

Table 1: Overview of identified weighting methods through a literature review: characteristics and evaluation of the methods (abbreviations in brackets)

	Normative weighting of the domains/indicators			Empirical weighting of the domains/indicators					
Weighting methods	**Equal weighting of domains/indicators**	**Expert weighting of the domains/ indicators**	**Theory-based weighting of the domains**	**Logistic regression**	**Principal components analysis (PCA)**	**Bayesian factor analysis**	**Exploratory factor analysis (EFA)**	**Confirmatory factor analysis (CFA)**	**Revealed preferences**
Description and weighting of the indicators/ domains	- Equal weighting of the domains/ indicators	- Weighting of the domains/ indicators according to expert opinion	- Weighting of the domains: derived from research literature on multiple deprivation and social exclusion and by consultation process	- Deprivations: proxy as dependent, coefficients as relative weights of the domains	- Extraction of factors from indicators - Factors used as deprivation index/indices - Factor loadings as relative weights of the indicators- - Assume the existence of an unmeasured unifying concept, but make no prior judgements as to what that is.			- Number of factors derived from research literature - Factor loadings as relative weights of the indicators	- Proportion of government spending allocated to each domain of the IMD was used to derive a set of weights
Construction index	Additive score of the equally weighted indicators or domains	Additive score of the weighted indicators or domains							
Selected advantages of the methods	- Simplest solution for aggregation of indicators to an overall score [20] - Equal relevance of all indicators/ domains	- Different weighting of the indicators, according to the individual relevance - Based on expert knowledge [20, 21]	- Weights derived from theory and research literature [6]	- Derives outcome specific weights from the data [20] - Easy handling of the model and the coefficients [21]	- Weights derived directly from the data [20] - Easy handling, often used and robust approach [21-23]	- Weights derived directly from the data [20] - Suited for analysis of small area units [24]	- Statistical model - Derivation of number of factors by model fit [25] - Exploration of latent dimensions without foreknowledge [25]	- Dimensions of deprivation derived from theory and set a priori [23] - Measures of goodness of fit and error of model [25]	- Relative relevance of the domains, which influence public life, reflected by government spending [13]

Selected disadvantages of the methods	- Unintentional, implicit weighting of the domains of multiple deprivation possible (owing to the number of indicators included per dimension) [6]	- Arbitrary weighting possible, because of subjective decisions [20]	- Selected weights dependent on the quality of the research from the literature - Normative, subjective setting [21, 26]	- Derived coefficient dependent on the data quality - Removal or addition of variables can alter the coefficients significantly [20] - Large omitted variables, bias possible	- Descriptive data reduction of the variables [25] - All variables load on all factors [23] - Transferability to the population limited because of explanation of the sample variance [25] - Reduction to one factor does not consider the multidimensionality of deprivation [23]	- At least weakly informative prior information is required - Computationally more expensive - Reduction to one factor does not consider the multidimensionality of deprivation [23]	- Restricted temporal comparability [20] - Different interpretability of the results, several decisions required [25] - Reduction to one factor does not consider the multidimensionality of deprivation [23]	- Elaborate procedure: theoretical knowledge and conceptualization required [25] - Several decisions required regarding covariance structure and the method of parameter estimation [25] - Reduction to one factor does not consider the multidimensionality of deprivation [23]	- Overlap of the spending for the domains possible, unambiguous allocation elaborate
Selected examples	[27]	[28]	[8, 12]	[13]	[29]	[24]	[30]	[31]	[13]

Besides the equal weighting of the domains, we used two commonly used empirical methods and an additional greedy maximization algorithm method. The purpose of the empirical approaches was to extract relative weights for the domain scores from an empirical dataset. The extracted coefficients of the methods were used as relative weights for the domain scores, which should sum to 1 (or 100%), before the summation of the domains to an overall deprivation score.

1. Original weighting of the domains of the GIMD through theoretical foundation and expert opinion according to Maier et al. [8]. For weights used, see Supplement 1.

2. Equal weighting of the seven GIMD domains; thus, each domain weighted with 1/7. This approach was originally used for deprivation indices by Carstairs and Townsend [32, 33]. To date, this approach is still used for deprivation indices consisting of just single deprivation indicators [26, 33]. For this approach, an equal importance of all deprivation indicators is assumed. In our analysis, we transferred this approach to the domain level.

3. Weighting of the domains by the coefficients of a linear regression analysis with a proxy for deprivation ('available living space per inhabitant') as the dependent variable and the GIMD domains as the independent variables. We had to choose a dependent variable for the linear regression that had not been used for the construction of the GIMD domains and could be considered as an indicator of deprivation [13]. Townsend, Carstairs and Jarman considered overcrowding of living space as an indicator of deprivation [28, 32, 33]. We assumed that the availability of living space per inhabitant in an area could act as a proxy for area deprivation: the more deprived the area, the less living space is available per inhabitant [34-36]. For this approach, we calculated the absolute value of the regression coefficients and then used them as relative weights for the specific domains. Subsequently, the weighted domain scores were summed to an overall score. Linear models for the extraction of weights for a deprivation score have already been conducted in several studies [13, 37-38]. Because of the normal distribution of the dependent variable, we conducted an ordinary least square (OLS) regression.

4. Weighting of the GIMD domains using a greedy maximization algorithm [Kurz C, Maier W, Rink C. A greedy stacking algorithm for model ensembling and domain weighting. Working paper. 2019]. This yields weights for the domains close to the maximum possible correlation between the GIMD 2010 and mortality as a relevant outcome of deprivation (Supplement 3). The weighted domain scores of the GIMD were then added together to an overall index for both total mortality and premature mortality. This addition to the methods of the literature search aimed to extract weights for the maximum Spearman correlation between GIMD and mortality and can thus be seen as an outcome-specific approach with the independent variable mortality. Complete circularity was present because mortality had already been used for the extraction of the weights. In contrast, the other methods could be seen as general weighting approaches for deprivation indices.

5. Weighting of the domains according to the results of an exploratory factor analysis (EFA). We chose a principal axis factoring (PAF) approach for the extraction of the factors. PAF is a commonly used extraction method for factor analysis and requires no specific distribution of the entered variables. This non-parametric approach was necessary because of the exponentially transformed domains [25]. A priori, we specified the extraction of one factor (as a latent factor, measuring ‘multiple deprivation’) out of the seven domains. The absolute values of the factor loadings of the different domains were used as relative weights for the domains. Again, the weighted domains were added together to an overall deprivation score.

Correlation analysis and statistical software

Subsequently, we performed a sensitivity analysis of the newly weighted GIMD versions. We conducted correlation analyses in order to calculate the relationship between the different GIMD versions and both total as well as premature mortality (in terms of SMRs) and compared their results. For the analysis, we used Spearman's rank correlation coefficient (ρ) as a robust approach. This was required, in our opinion, as the GIMD score could be interpreted as an ordinal variable because of the ranking of the districts during the generation of the domain scores [7, 39]. Correlation analyses were each performed with a GIMD version and both total mortality and premature mortality. We also tested for significance of these bivariate correlation coefficients at an α-level of 5% [40]. For comparison of the bivariate correlations among each other, we performed t-tests for paired correlations. For this, we used Williams's t-test for the comparison of correlations out of dependent samples [41]. We compared two correlation coefficients in terms of both total and premature mortality at an α-level of 5%. For the statistical analysis, we used the Software R, version 3.2.3 [42].

Patient and Public Involvement

Patients and/or public were not involved in this study.

RESULTS

Population size of the districts and estimation of the SMRs

The size of the population of the 412 districts varied with median size of 139,188 inhabitants, IQR of 130,170 persons, minimum size of 33,944 and maximum size of 3,460,725 persons. Raw mortality of the 412 districts varied with median of 1,522 death cases, IQR of 1,347 cases, minimum of 413 cases and maximum of 32,234 cases. Qualifying date of the data was 31st December 2010. We estimated total mortality by calculating 'SMR_{total}' for the districts with a mean of 1.0175 (standard error (SE): 0.004) and premature mortality '$SMR_{premature}$' with a mean of 1.0165 (SE: 0.004).

Weights of the domains of the alternative approaches

An overview of the identified weighting methods for deprivation indices is given in Table 1. Alongside a description of the weighting and the construction of the deprivation indices, we offered selected advantages and disadvantages of the methods. This was completed with selected examples. From this table, we chose four approaches additional to the original weighting of the GIMD.

We found considerable differences between the domain weights resulting from the different approaches (Table 2).

Table 2: Weighting of the domains of the GIMD[1] through different weighting approaches, values in percentage points

Deprivation domains/ methods of domain weighting of the GIMD[1]	Income	Employment	Education	Municipal revenue	Social capital	Environment	Security
Original weighting	25.00	25.00	15.00	15.00	10.00	5.00	5.00
Equal weighting	14.29	14.29	14.29	14.29	14.29	14.29	14.29
Linear regression	4.47	21.68	15.42	30.25	11.45	14.65	2.09
Maximization algorithm (total mortality)	18.23	20.67	1.04	21.90	28.26	4.62	5.28
Maximization algorithm (premature mortality)	18.85	48.93	0.31	15.98	10.73	0.50	4.70
Factor analysis	23.09	18.99	8.97	21.72	20.08	5.86	1.28

[1] **GIMD:** German Index of Multiple Deprivation;

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and mortality;

Factor analysis: Weighting of the domains with loadings from principal axis factoring .

The weights for employment deprivation showed the largest variation with a range of 34 percentage points. The other deprivation domains showed a range of at least 13 percentage points. Educational deprivation within the maximization algorithm and income deprivation within the linear regression showed very small weights compared with the weights of the original GIMD 2010. Municipal revenue deprivation resulted in a weight twice as high as the original weight within the linear regression. Concerning the algorithm, the weight for social capital deprivation was three times the original weight. Concerning premature mortality, the weight for employment deprivation was twice as high as the original weight for the GIMD. Deprivation domains for social capital and district income showed constantly higher weights for the empirical approaches compared with the two normative methods. The different GIMD versions revealed different distributions of the overall deprivation scores (Table 3).

Table 3: Descriptive results of the weighted indices, information on GIMD[1] scores

	Original weighting	Equal weighting	Linear regression	Maximization algorithm SMR[2] 'total' (SMR[2] 'premature')	Factor analysis
Number of districts	412	412	412	412 (412)	412
Mean	21.81	21.81	21.81	21.81 (21.81)	21.81
Median	18.80	19.97	19.34	17.05 (16.49)	18.17
Standard deviation	12.73	10.34	10.98	15.61 (17.09)	14.24
Minimum	2.04	2.29	2.11	1.48 (0.92)	1.33
Maximum	70.98	55.69	67.67	85.91 (91.14)	79.86

[1]**GIMD:** German Index of Multiple Deprivation

[2] **SMR**: Standardized mortality ratio

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and both total mortality (SMR 'total') and premature mortality (SMR 'premature' in brackets);

Factor analysis: Weighting of the domains with loadings from principal axis factoring.

Assumptions for the linear regression were generally met, and the model had significant explanatory power (adj. $R^2 = 0.33$). Five of the seven domains showed a significant effect on the deprivation proxy. Heterogeneity was present; thus, we presented robust standard errors. Additionally, we provided tests of the assumptions of the linear regression model. (Supplement 4). The factor analysis generally had significant explanatory power (Chi-square: 584.65, $p < 0.0001$), but showed low reliability (Tucker–Lewis index = 0.50) and a RMSEA of 0.32 with tight confidence intervals (0.30- 0.34) indicated that this one factor was not a good fit to the data (Supplement 5).

Results of the statistical analysis

Correlation analysis between the differently weighted deprivation indices and mortality showed different results (Table 4).

Table 4: Spearman's rank correlation coefficients for the association between the versions of the GIMD[1] and both premature and total mortality.

Methods of the domain weighting of the GIMD[1]	Total mortality (SMR[2] 'total')	Premature mortality (SMR[2] 'premature')
Original weighting	0.578*** [0.506, 0.642]	0.767*** [0.718, 0.808]
Equal weighting	0.535*** [0.459, 0.604]	0.699*** [0.641, 0.750]
Linear regression	0.564*** [0.492, 0.629]	0.738*** [0.685, 0.784]
Maximization algorithm	0.615*** [0.547, 0.676]	0.832*** [0.794, 0.864]
Factor analysis	0.598*** [0.529, 0.661]	0.772*** [0.724, 0.813]

*** $p < 0.001$, bootstrapped (10,000 fold), 95% confidence intervals in square brackets

[1] **GIMD:** German Index of Multiple Deprivation

[2] **SMR**: Standardized mortality ratio

Original weighting: Weighting according to Maier et al. [8];

Equal weighting: Every domain gets equal weighting (1/7 = 0.1429);

Linear regression: Weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables;

Maximization algorithm: Weighting of the domains in order to achieve the maximum Spearman correlation between overall index and mortality;

Factor analysis: Weighting of the domains with loadings from principal axis factoring.

Deprivation indices, domains weighted by the maximization algorithm, showed the maximum correlation with total mortality (ρ = 0.615) and premature mortality (ρ = 0.832). Correlations between the original GIMD and both total and premature mortality were ρ = 0.578 and 0.767 respectively. Correlations between the equally weighted GIMD and mortality were the lowest with ρ = 0.535 and 0.699. All correlations were significant concerning both total and premature mortality ($p < 0.001$). Additionally, bivariate correlations between all indices were significant (ρ between 0.86 and 0.98).

Pairwise comparisons of the correlation coefficients with Williams's t-tests showed a differentiated result (see Supplement 6). Almost every pairwise difference in the correlation coefficients was significant at the 5% α-level. One exception was the difference in the coefficients between the original GIMD and the GIMD weighted by linear regression concerning total mortality. The other deviation was the difference between the original GIMD and the GIMD weighted by factor analysis concerning premature mortality. The difference was not significant, neither one-sided nor two-sided. Maximum correlation coefficients of the GIMD, weighted by the algorithm, differed significantly from all the correlation coefficients of the other methods regarding both total and premature mortality. When we corrected for the multiple comparison of the difference of the correlation between the GIMD versions, there was a slight difference present in the significances (Supplement 7).

DISCUSSION

The central objective of the study was to explore whether alternative weighting approaches had an influence on the relationship between area deprivation and mortality when applied to the GIMD. Thereby, different weighting methods were selected if they were, on the one hand, applicable to the domain-based construction of the GIMD and, on the other hand, seemed feasible in the course of an application of a multi-methodical approach. The four different methods were applied to the weighting of the domains of the GIMD 2010. The selected approaches and the original method were compared concerning both the weighting of the domains of the GIMD and the relationship between GIMD and mortality.

There was little evidence in the literature concerning the application of different weighting methods for multidimensional deprivation indices. However, a summary of different weighting approaches and their classification was presented by Noble et al [6]. They briefly assessed the specific procedures of the methods (e.g. empirical approaches) and were in favour of a weighting driven by literature considerations on multiple deprivation. Regarding the application of empirical weighting approaches for the English IMD 2004, we want to emphasize Dibben's work [13]. He recommended new weights for the domains of the IMD, as the empirical weighting approaches indicated a higher weighting of the health domain and a lower weighting of the employment domain. However, this suggested swapping of weights was not eventually applied to the subsequent versions of the English IMD. The maintenance of the weights was justified by a consultation of IMD users and stable results of the IMD with either existing or suggested weights [12].

In this study, we pursued a multi-methodical approach for the weighting of the GIMD, including empirical methods. Owing to the different inherent intentions of the selected methods, we integrated the approaches as follows:

1. Normative approaches: The original weighting of the domains according to Maier et al. through theory and experts' opinion. We used the term 'normative' because weights for the domains must be selected a priori subjectively before they can be validated with data.

2. *Specific empirical approaches*: Concerning the maximization algorithm with the dependent variable mortality, a weighting of the domains has been sought that was in line with the relationship between area deprivation and both total mortality and premature mortality and should maximize the correlation between them.

3. General empirical approaches: In contrast to the specific empirical approaches, the weighting of the domains was realized according to the results of a linear regression model or according to a factor analysis to generate generally applicable indices, which can also be used for the analysis of other health outcomes.

A further distinction of the methods can be made regarding their conceptual aspects. Factor analysis and PCA are unsupervised methods that require no prior judgements and construct deprivation solely based on the domain knowledge. On the other hand, linear regression and the maximization algorithm are supervised or predictive methods considering deprivation based on a specific proxy and assuming a relationship between this proxy and deprivation.

Assessment of the alternative weighting approaches

The high weighting of the deprivation domains income and employment of 50% altogether within the original GIMD was confirmed by the empirical weighting of the factor analysis approximately, as well as the weighting of the environment deprivation domain. Educational deprivation was weighted considerably lower by the factor analysis and algorithm than by the original GIMD. Deprivation domains for district income and social capital were constantly weighted much higher by the empirical approaches than by the approach of the original GIMD. The shift in the weighting of the domains can be explained by the data dependency of the empirical approaches and should be reviewed using alternative data. Should the higher weighting of the district income and social capital domains be confirmed, an adjustment in the domain weights could be considered. Perhaps those context variables have a higher relevance concerning area deprivation than expected by Maier et al. [8].

The low weighting of the deprivation domains of income by the linear regression and education by the maximization algorithm can barely be reconciled with existing evidence regarding the positive relationship of these two deprivation domains and mortality [43, 44]. The high weighting of the employment deprivation domain (49%) by the algorithm, concerning mortality, could reflect the high relevance of unemployment relating to premature mortality.

Relationship of the GIMD versions and mortality

Throughout the analysis, we could not find a weighting method that could be seen as superior compared with the other approaches or could even be recommended as a gold standard. Even though almost all GIMD weighting approaches differed significantly in their correlation with mortality, using only significance as a method of evaluation for the approaches seemed inappropriate. The correlation coefficient between the different GIMD versions was already very high ($\rho > 0.89$), so that even small non-relevant differences could have produced significant results. All correlations of the GIMD versions with mortality were highly significant and showed rather small differences in respect to absolute values (ρ between 0.54 and 0.62). Since we conducted multiple paired t-tests, type-1 error inflation was present. In an additional analysis we corrected for multiple testing with Benjamini et al. adjustment [45]. When we corrected for the correlation of the GIMD versions with mortality, the significance of the results did not change (Table 4). When we corrected for the multiple comparison of the difference of the correlation between the GIMD versions (Supplement 6), there was a slight difference present in the significance (Supplement 7).

The empirical weighting of the GIMD by an exploratory factor analysis represented an adequate alternative to the theory-based weighting of the domains, on account of the simple operability and the highly significant association of this GIMD version with mortality. Thereby, a general applicability of the GIMD for the analysis of implications for other health outcomes can be ensured, and the results of different datasets can be compared by model fit measures [25]. Despite the significant correlation, the application of equal weighting of the domains could be considered as obsolete, as this would produce an implicit weighting of the domains depending on the availability of indicators for each domain [6].

Strengths and limitations of the study

Using a multi-methodological strategy, we were able to cover a broad bandwidth of weighting approaches. As there seems to be no gold standard for weighting of deprivation indices, we recommend that sensitivity testing of the GIMD is particularly important. An equal weighting as well as an exploratory factor analysis for the weighting of multiple deprivation domains were carried out in this study for the first time. A factor analysis of the IMD domains was advised by Deas et al. [26], but has not been implemented to date. Furthermore, we provided an outcome-specific weighting approach in the form of a greedy maximization algorithm: this method produced a domain weighting of the GIMD that maximized a specific measure concerning one health outcome (in this case, the correlation between GIMD and mortality). A transfer of the algorithm to other areas of interest is possible without difficulty but should be used mainly for orientation, which is possible concerning a selected measure, given a dataset.

Limitations of the study concerned the selection of weighting methods such as the revealed preferences or Bayesian factor analysis (cf. Table 1), which resulted from restricted data access at a regional level. Empirical methods are always data dependent and are restricted concerning a possible comparison over time, especially with the use of cross-sectional data. This could be addressed by using longitudinal data and would enable us to measure 'between variation' (i.e. over different locations) to 'within variation' (i.e. the same location over time).

Using correlation coefficients to evaluate the association between different GIMD versions and mortality does not necessarily imply a causal association between area deprivation and mortality. Additionally, overfitting is present by using the greedy maximization algorithm as a weighting approach, since it already yields the weights for the maximum correlation between the GIMD and mortality. However, there is reliability of using the GIMD to evaluate total and premature mortality, since the correlation between the GIMD and mortality is very stable over time (GIMD scores from 2006 and 2010 yield very similar correlations with mortality).

Another point was the lack of literature regarding the application of different weighting procedures. This limitation could partly be counterbalanced with the input of expert interviews. With regard to the linear regression, the selection of the deprivation proxy should be reconsidered ex post, as the use of the deprivation measure regarding living space per inhabitant showed a rather weak (yet significant) positive correlation with overall deprivation ($\rho = 0.35$). This could be explained by the idea that, in less deprived cities such as Hamburg and Munich, there can be – in general – less available living space because of a very competitive housing market. So, there could be a partial negative correlation between deprivation regarding available living space and overall deprivation in some areas. Unfortunately, multidimensional proxies at district level were not available for Germany. We tested other measures like the overall Gross Domestic Product (GDP) per district and the GDP per employed persons per district. They had a similar or lower correlation with the original GIMD as the living space variable, but using them had some major drawbacks. We understand, that the use of a one-dimensional proxy is a limitation in our work. However, given the very restricted variety of appropriate variables at the district level in Germany, the selection of this proxy was a pragmatic approach to test a weighting approach based on a linear regression.

We are aware that the stability of the GIMD could have also been tested by applying systematic changes to the weighting of the GIMD domains without using a framework of different weighting approaches. The correlation between some deprivation domains (e. g., income or employment) is relatively high and thus any weighting scheme would likely give highly correlated results with mortality. A recent study from the UK showed that 94% of the variance in the English IMD could be explained by the income and employment domains alone, even though they had weights of 22.5% each in the overall index. The authors stated that even if the weights for the other domains had been zero, there would have been very little impact on the overall index [46]. Nevertheless, the aim of our study was to provide a conceptual framework of weighting approaches (normative and empirical) for an index of multiple deprivation and to combine the results of the literature search with a sensitivity analysis based on the GIMD.

Conclusion

The variation in the domain weights of the GIMD did not have a large measurable impact on the relationship between area deprivation and mortality. The correlation between the GIMD and both total mortality and premature mortality proved to be very stable, regardless of the application of the different weighting approaches and the resulting different sets of domain weights. The GIMD versions produced relatively stable results with regard to the central distribution measures of the overall scores (Table 3).

The theory-based weighting of Maier et al. can be interpreted ex post as more conservative than the empirical weighting approaches, as the weighting of the income and employment domains is relatively strong at 50% in contrast to the empirical methods. Nevertheless, a theory-based selection of domains seems to be more meaningful than an empirically based selection because the results of the empirical methods are restricted, as discussed above. The stability with respect to the scores and the relationship to mortality support this advice. A modelling of the GIMD with a confirmatory factor analysis could be considered as a promising empirical approach with the prospect of temporal comparability in future studies.

Competing interests

No competing interests to declare.

Data sharing statement

Extra data regarding the GIMD is available by emailing Werner Maier (werner.maier@helmholtz-muenchen.de).

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Contributorship statement

FS and WM designed the study. FS performed the analysis and wrote the initial version of the manuscript. CK gave statistical advice, provided the greedy maximization algorithm and gave support preparing the manuscript. WM provided the German Index of Multiple Deprivation (GIMD), supervised the study and gave support preparing the manuscript. JF advised on deprivation indices and gave support preparing the manuscript. All authors read and approved the final manuscript.

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SUPPLEMENT

Supplement 1: Weighting of the domains and use of indicators from the 'German Index of Multiple Deprivation' (GIMD).

Domains	Domain weight (%)	Indicators (reference)
Income deprivation	25	- Total earnings (Number of Taxpayers)
Employment deprivation	25	- Total number of unemployed (Population, 15 to 65 years)
Educational deprivation	15	- Persons without vocational training (Employees subject to social security contributions at the place of residence)
Municipal revenue deprivation	15	- Tax revenue of municipalities (Total population)
Social capital deprivation	10	- Migration balance* (Total population) - Electoral participation in % (Federal parliament)
Environment deprivation	5	- Commercial, industrial and traffic areas ** (Total area)
Security deprivation	5	- Number of road accidents(Total population) - Number of crimes(Total population)

* People moving into a municipality or a district minus people leaving a municipality or a district.

** Indicator for soil sealing.

Supplement 2: Calculation of the standardized mortality rates (SMR):

1. SMR 'total mortality' per district = total deaths per district / expected total deaths per district

2. Expected total deaths per district = total population size per district * total mortality rate per 100,000 per district / 100,000

3. Total mortality rate per 100,000 per district = total deaths per district/total population size per district*100,000

4. SMR 'premature mortaltiy' per district = premature (before 65 years) deaths per district / expected premature (before 65 years) deaths per district

5. Expected premature deaths per district = premature population size per district * premature mortality rate per 100,000 per district / 100,000

6. Premature mortality rate per 100,000 per district = premature deaths per district/premature population size per district*100,000

Supplement 3: Working steps of the greedy weighting algorithm.

- The vector P containing the greedy solution of the non-normalized weighted sum in each step is initialized with zero elements.
- All column weights and the total number of weights are also initialized to zero. In each iteration, first, the total number of weights is incremented.
- Then, all sums of P with a column of X are normalized by the total number of weights and evaluated separately on the evaluation metric (correlation).
- The column corresponding to the highest value is assigned one weight factor and added to P. This procedure is repeated 100 times.
- The algorithm returns a vector of length N, with the number of columns of X, containing weights for each column, summing to 1.

Supplement 4: Results of the linear regression: Outcome: deprivation proxy, Covariables: domains of the GIMD10.

Deprivation of living space = Income + Employment + Education + Municipal income + Social capital + Environment + Security

Coefficients (Robust Standard Errors in Parenthesis)	
Income	0.014
	(0.051)
Employment	0.067*
	(0.029)
Education	-0.048*
	(0.023)
Municipal income	-0.094***
	(0.025)
Social capital	0.035**
	(0.014)
Environment	0.045***
	(0.011)
Security	-0.006
	(0.008)

Model

R-squared = 0.34
adj. R-squared = 0.33
F = 30.01
p < 0.001
Log-likelihood = -1050.76
Deviance = 3959.74
AIC = 2117.52
BIC = 2149.69
N = 412

*** p < 0.001; ** p < 0.01; * p < 0.05; n.s. not significant

Source: R-Output, regression results conducted with R-package 'stargazer'

(Hlavac M. stargazer: Well-Formatted Regression and Summary Statistics Tables. R package version 5.2. 2015.)

→ All domains have a significant effect on the proxy, except security and Income

→ Overall model explains the variance of living space deprivation significantly, $R^2 = 0.34$

Test of the assumptions of the linear regression model:

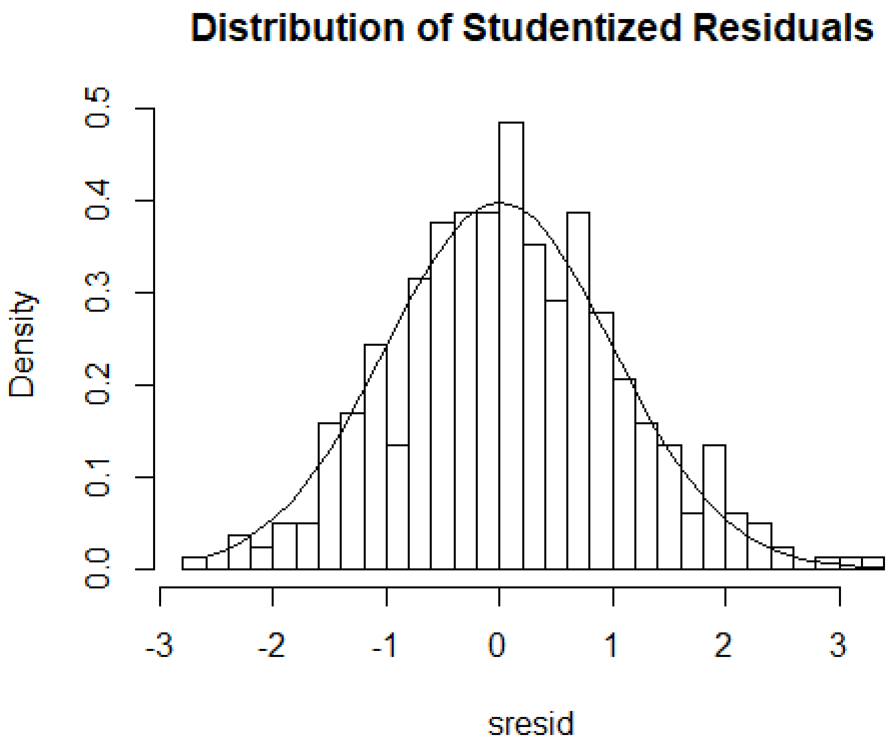
1. Normality of the residuals

Shapiro-Wilk normality test of the residuals of the model:

W = 0.99668, p-value = 0.5588

→ Distribution of residuals of the model differ not significantly from normal distribution

Figure 1: Histogram of the distribution of the residuals:



2.

→ Distribution of residuals of the model differ not significantly from normal distribution

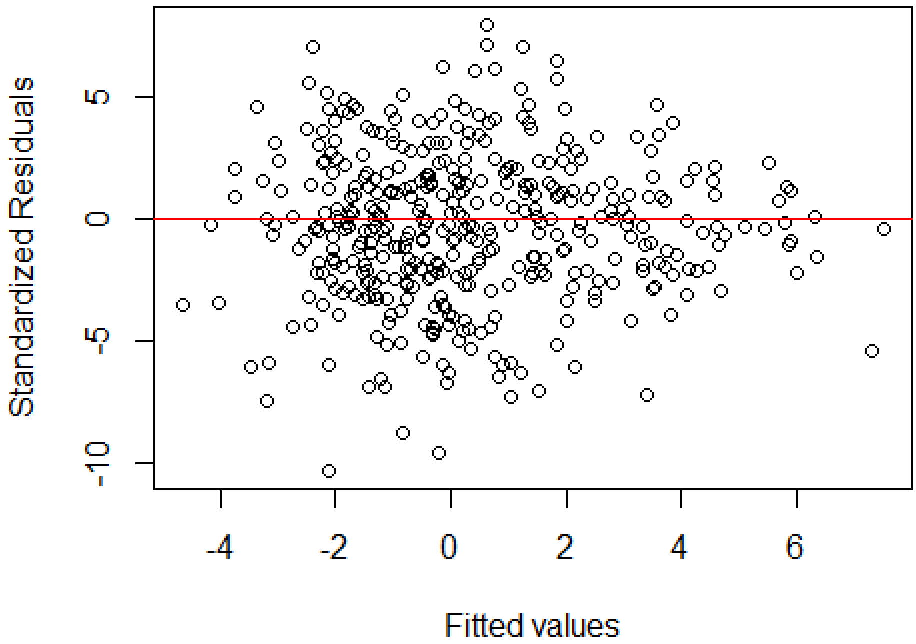
2.Homoscedasticy

Non-constant Variance Score Test

Chi-square = 5.910324 Df = 1 p = 0.0150524

→ assumption of constant variance violated

Figure 2: Plot of the standardized residuals vs. fitted values



→ Visually no violation of the homoscedasticy assumption

→ Due to the results of the Non-constant Variance Score Test, we conducted robust standard errors for the model

3. Multicollinearity

Variance inflation factors of the independent variables:

Income: 10.01, Employment: 8.79, Education: 2.49, Municipal Income: 5.75, Social Capital: 7.86, Environment: 3.96, Security: 2.88

→ Only Income has a value above the critical value of 10

→ Some minor multicollinearity regarding Income

4. Autocorrelation

Durbin Watson Test

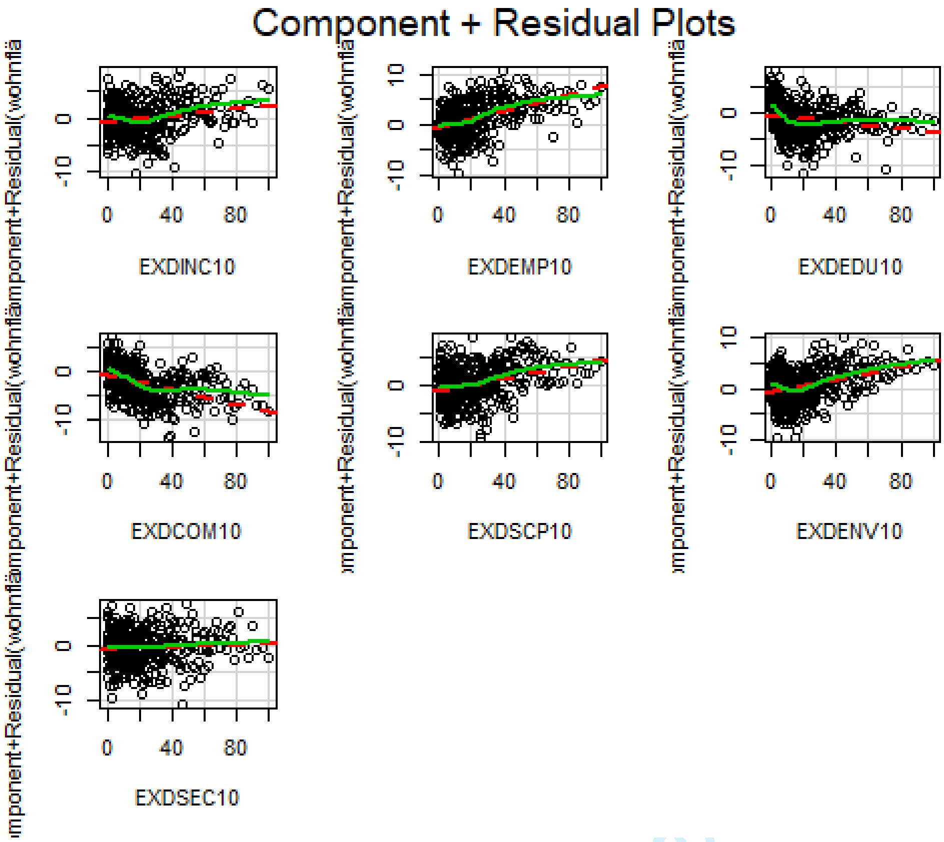
Autocorrelation	D-W Statistic	p-value
0.5036934	0.9876657	<0.001

Alternative hypothesis: rho != 0

→ Autocorrelation is present

5. Nonlinearity

Figure 3: Partial residuals plot



→Linearity assumption violated for domains of education(EXDEDU10), municipal income (EXDCOM10) and Environment (EXDENV10)

→ But domain weights should be obtained, so we use the untransformed variables

Supplement 5: Results of an exploratory factor analysis of the deprivation domains with the extraction of one factor, method = principal axis factor analysis.

Standardized loadings	Factor 1	Communality (u^2)	Specific variance ($1– u^2$)
Income	0.92	0.85	0.15
Employment	0.76	0.58	0.42
Education	–0.36	0.13	0.87
Municipal income	0.87	0.75	0.25
Social capital	0.80	0.64	0.36
Environment	-0.23	0.06	0.94
Security	-0.05	0.01	0.99

Model	Factor 1
Variance, explained by the factor (SS loadings)	3.01
Proportion of total variance	0.43

Model fit measures	
Root mean square of the residuals (RMSR)	0.17
Likelihood chi square	584.65 (p < 0.001)
Tucker–Lewis index of fact oring reliability	0.50
RMSEA index (confidence interval)	0.32 ([0.30; 0.34])
BIC	500.35

Source: Tables output from R and own presentation

Supplement 6: Test[1] of the differences in the Spearman correlation coefficients for the relationship of the GIMD[2] versions and both total and premature mortality

Total mortality	Original weighting	Equal weighting	Linear regression	Maximization algorithm	Factor analysis
Original weighting	0	0.043** [0.015, 0.074]	0.014 n.s. [-0.006, 0.034]	–0.037*** [-0.060, -0.016]	–0.020** [-0.038, -0.005]
Equal weighting	–0.043** [-0.074, -0.015]	0	–0.029* [-0.059, -0.001]	–0.080*** [-0.122, -0.041]	–0.063*** [-0.105, -0.025]
Linear regression	–0.014 n.s. [-0.034, 0.006]	0.029* [0.001, 0.059]	0	–0.051*** [-0.080, -0.024]	-0.034** [-0.059, -0.011]
Maximization algorithm	0.037*** [0.016, 0.060]	0.080*** [0.041, 0.122]	0.051*** [0.024, 0.080]	0	0.016** [0.003, 0.031]
Factor analysis	0.020** [0.005, 0.038]	0.063*** [0.025 , 0.105]	0.034** [0.011, 0.059]	–0.016 ** [-0.031, -0.003]	0
Premature mortality					
Original weighting	0	0.068*** [0.044, 0.097]	0.028*** [0.012, 0.049]	–0.065*** [-0.093, - 0.043]	–0.005 n.s. [-0.021, 0.019]
Equal weighting	–0.068*** [-0.097, -0.044]	0	–0.040***	–0.133*** [-0.174, -0.098]	–0.073*** [0.110, -0.040]
Linear regression	–0.028*** [-0.049, -0.012]	–0.040***	0	–0.094 *** [-0.128, -0.066]	–0.034*** [-0.014, -0.057]
Maximization algorithm	0.065*** [0.043, 0.093]	0.133*** [0.098, 0.174]	0.094*** [0.066, 0.128]	0	0.060*** [0.037, 0.088]
Factor analysis	0.005 n.s. [-0.019, 0.021]	0.073*** [0.040, 0.110]	0.034*** [0.014, 0.057]	–0. 060*** [-0.088, -0.037]	0

*** p < 0.001; ** p < 0.01; * p < 0.05; n.s. not significant, 95% confidence intervals in square brackets

[1] Test of the significance of the differences with Williams's t-test for paired correlations

[2] **GIMD:** German Index of Multiple Deprivation

Original weighting: Spearman correlation between GIMD (weighting according to Maier et al. [8]) and both total and premature mortality;

Equal weighting: Spearman correlation between GIMD (domains equally weighted) and both total and premature mortality;

Linear regression: Spearman correlation between GIMD (weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables) and both total and premature mortality;

Maximization algorithm: Spearman correlation between GIMD (weighting of the domains for the maximum Spearman correlation between overall index and mortality) and both total and premature mortality;

Factor analysis: Spearman correlation between GIMD (weighting of the domains with loadings from principal axis factoring) and both total and premature mortality.

Supplement 7: Corrected Test[1] of the differences in the Spearman correlation coefficients for the relationship of the GIMD[2] versions and both total and premature mortality.

Total mortality (all age groups)	Original weighting	Equal weighting	Linear regression	Maximization algorithm	Factor analysis
Original weighting	0	0.043*	0.014n.s.	–0.037**	–0.020*
Equal weighting	–0.043*	0	–0.029*	–0.080***	–0.064**
Linear regression	–0.014n.s.	0.029*	0	–0.051 ***	–0.034*
Maximization algorithm	0.037**	0.080**	0.051**	0	0.016*
Factor analysis	0.020*	0.064**	0.034*	–0.016 *	0
Premature mortality (< 65 years)					
Original weighting	0	0.068***	0.028***	–0.065***	–0.005n.s.
Equal weighting	–0.068***	0	–0.040**	–0.133***	–0.073***
Linear regression	–0.028***	–0.040**	0	–0.094 ***	–0.034***
Maximization algorithm	0.065***	0.133***	0.094 ***	0	0.060***
Factor analysis	0.005n.s.	0.073***	0.034***	–0. 060***	0

*** p < 0.001; ** p < 0.01; * p < 0.05; n.s. not significant

[1] Test of the significance of the differences with Williams's t-test for paired correlations

[2] **GIMD:** German Index of Multiple Deprivation

Original weighting: Spearman correlation between GIMD (weighting according to Maier et al. [8]) and both total and premature mortality;

Equal weighting: Spearman correlation between GIMD (domains equally weighted) and both total and premature mortality;

Linear regression: Spearman correlation between GIMD (weighting of the domains with regression coefficients with a deprivation proxy as dependent and domains as independent variables) and both total and premature mortality;

Maximization algorithm: Spearman correlation between GIMD (weighting of the domains for the maximum Spearman correlation between overall index and mortality) and both total and premature mortality;

Factor analysis: Spearman correlation between GIMD (weighting of the domains with loadings from principal axis factoring) and both total and premature mortality.