D3.1 : Report on the EU index of multiple deprivation methodology

Quantifying social inequalities using a multiple deprivation index

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Table of abbreviations

BEST-COST	Burden of disease based methods for estimating the socio-economic cost of environmental stressors
DALY	Disability-Adjusted Life Years
EDI	European Deprivation Index
EEA	European Economic Area
EPICES	Evaluation de la précarité et des inégalités de santé dans les Centres d'examens de santé
EU	European Union
EU-SILC	EU Statistics on Income and Living Conditions
FA	Factor Analysis
GBD	Global Burden of Disease
IRIS	Ilots Regroupés pour l'Information Statistique
LAU	Local Administrative Units
MDI	Multiple Deprivation Index
NUTS	Nomenclature of territorial units for statistics
OECD	Organisation for Economic Co-operation and Development
PCA	Principal Component Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SA	Sensitivity Analysis
SD	Standard Deviation
SDH (or SDoH)	Social determinants of health
UA	Uncertainty Analysis
UK	United Kingdom
USA	United States of America
WHO	World Health Organisation

2 Executive Summary

The overall objective of BEST-COST is to improve the methodology for assessing the socioeconomic cost of environmental stressors. Environmental stressors disproportionately affect socially disadvantaged groups, and, therefore, contribute to socioeconomic inequalities in the burden of disease. Despite the increased attention to inequalities in health and the environment, there is currently no systematic monitoring of environmental health inequalities. To overcome this, BEST-COST Work Package 3 aimed to develop and implement an innovative and coherent methodological framework for assessing socioeconomic inequalities in the health impact of environmental stressors with a focus on air pollution and traffic-related noise. To achieve this objective, we propose the methodological framework for the development of a multiple deprivation index (MDI) based on a scoping review of previous European MDIs to quantify material and social deprivation in five European case study countries (Belgium, Estonia, France, Norway and Portugal). This report describes all the steps involved in establishing the framework for this MDI, including the scoping review to the final selection of indicators and construction of the MDI.

3 Introduction

The overall objective of BEST-COST is to **improve the methodology for the assessment of the socioeconomic cost of environmental stressors** to i) enhance regular usage of economic and health modelling in policy impact assessments and policy evaluation by the European Union (EU) and national public authorities, and ii) promote harmonised and consensual population health, quality of life and economic metrics for integrative socioeconomic assessments of environmental pollution in Europe and health impact and cost-benefit assessments of related policies. The BEST-COST project comprises a total of nine work packages involving 17 organisations from 10 European countries (Belgium, Switzerland, Germany, Denmark, Estonia, Finland, France, The Netherlands, Norway, Portugal) and the USA.

3.1 Health inequities and risk factors

According to the WHO[1], **health inequities** are defined as "the unfair and avoidable differences in health status seen within and between countries. In countries at all levels of income, health and illness follow a social gradient: the lower the socioeconomic position, the worse the health". Social determinants of health (SDH or SDoH) are "the conditions in which people are born, grow, work, live, and age, and the wider set of forces and systems shaping the conditions of daily life"[1]. SDH include domains such as income, education, unemployment, housing, basic amenities and any other non-medical factor that influence health outcomes.

As with SDH, health risks relate to non-medical determinants of health. **Risk factors** are defined by the OECD as "any attribute, characteristic or exposure of an individual that increases the likelihood of developing a disease or incurring an injury. Some examples of important behavioural and metabolic risk factors include tobacco, high alcohol consumption, high blood pressure, high fasting plasma glucose, a high body mass index and a diet low in fruits and vegtables"[2].

Many diseases and deaths can also be attributed to **environmental risk factors, including** air pollution, noise, land-use patterns, the working environment and climate change. According to the 2021 Global Burden of Disease (GBD) study estimates[3,4] particulate matter air pollution was the leading contributor to the global disease burden in 2021 (see figure 1), as measured by age-adjusted disability-adjusted life years (DALYs), which accounts for both fatal and non-fatal causes, and seventh contributor to the European region, including the leading risk factor for DALYs among all environmental and occupational risks. Particulate matter air pollution was estimated to contribute to 8.0% of total DALYs and 7.83 million deaths worldwide in 2019[4].

Individuals can further be exposed to environmental noise from traffic, street works or noise at work, which may be an additional significant source of disease burden not yet included in the GBD study. Moreover, exposure differences to environmental stressors such as chemicals, heat waves or radiations in our daily lives may impact health across the population.

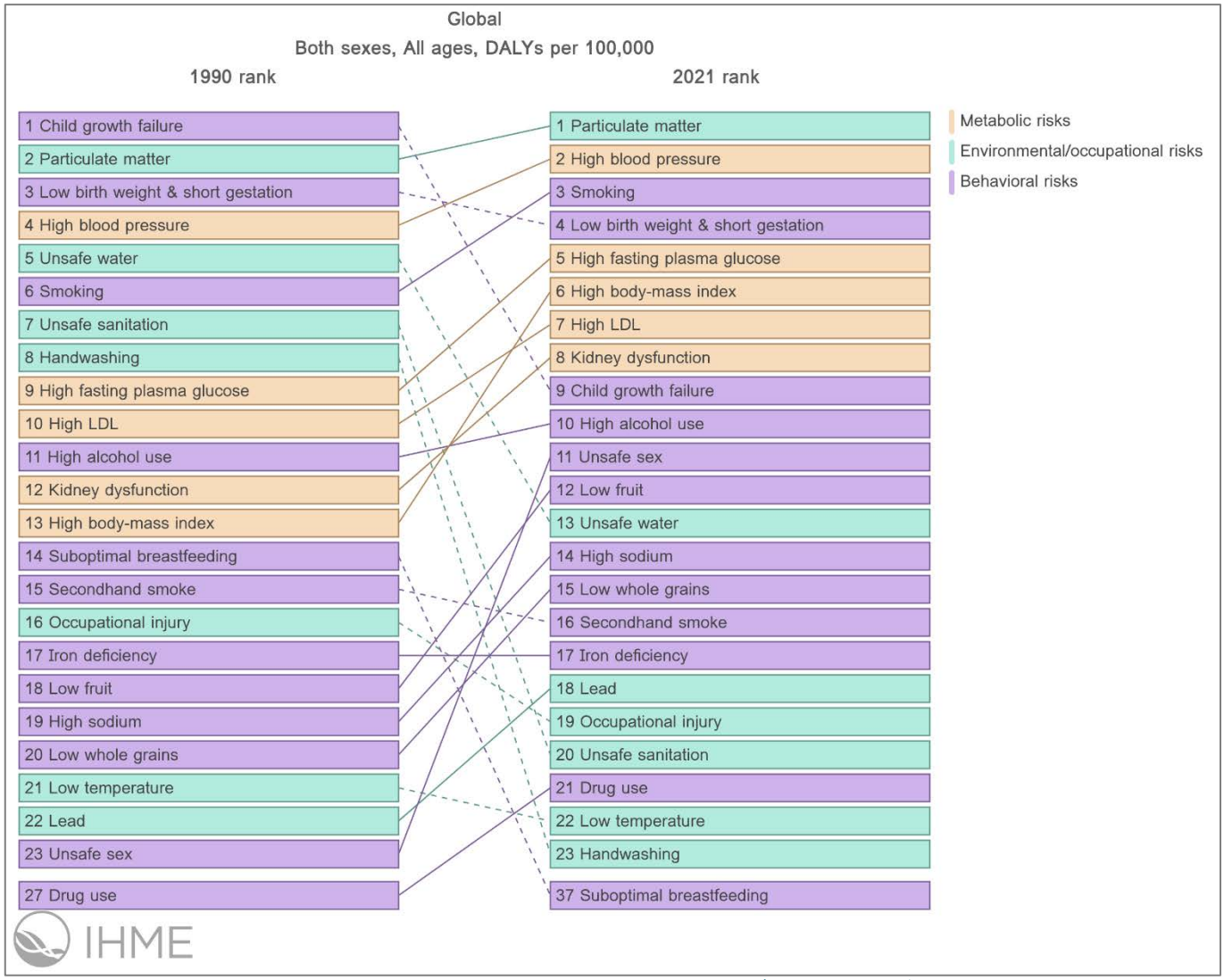

Figure 1: Leading level 3 risk factors by attributable DALYs per 100,000 (1990 and 2021) [4].

3.2 Social and environmental inequalities

Research suggests that levels of exposure to environmental health hazards may vary among different socioeconomic groups, contributing to health inequalities[5]. It has been demonstrated that in Europe, vulnerable populations such as children, the elderly, people with a lower socio-economic status and those in poor health are more likely to experience adverse health outcomes from environmental exposures[6,7]. It is, therefore, important to quantify social determinants of health inequalities in order to identify population groups that should be specifically targeted by health policies. Measuring **deprivation,** defined as 'a state of observable and demonstrable disadvantage relative to the local community or the wider society to which an individual, family or group belongs,' is an effective way to assess social inequalities[8].

In line with the attention drawn to social inequalities in health, increased attention has been drawn to **environmental inequalities** – i.e., differences in the levels of environmental exposure between groups

of people according to their socioeconomic position. Quite often, this is referred to environmental justice[9]. As is the case with social inequalities in health, environmental inequalities are widespread and persistent, as was recently inventoried by the World Health Organization Regional Office for Europe[10].

Despite the increased attention to social inequalities in health and the environment, there is no systematic monitoring of environmental health inequalities, i.e social inequalities in the health impact of environmental stressors. To overcome this, the BEST-COST project aimed to develop and implement an innovative framework for assessing social inequalities in the health impact of environmental stressors using a novel multiple deprivation index (MDI).

3.3 Index of multiple deprivation

When studying social health or environmental inequalities, developing a measure of the socioeconomic position of groups within a population is a prerequisite. Socioeconomic position refers to “the position of persons in society, based on a combination of occupational, economic, and educational criteria, usually expressed in ordered categories”[11]. Its measurement usually includes multiple socioeconomic (e.g. occupation, income, wealth and education) and material dimensions (e.g. presence of residential heating, homes with basic amenities, clothes). All these domains capture distinct aspects of the socioeconomic spectrum, and are correlated to each other,without being interchangeable. While many studies focus on one indicator of socioeconomic position as a proxy measure, it is increasingly recognized that different indicators may lead to subtle differences in terms of their effects, patterns and gradients. Therefore, the focus of the current report is based on the recommendation of an MDI for measuring socioeconomic impact rather than using a single indicator as a proxy. The challenge is, therefore, to **construct a multidimensional deprivation indicator,** that represents socioeconomic position adequately, while also limiting the number of indicators.

Townsend[8] discusses the evolution of the concept of area-based MDIs, introduced in the UK in the 1970s, to support the selective allocation of resources to areas in greater need. Townsend[12] defined **deprivation as *“a state of observable and demonstrable disadvantage relative to the local community or the wider society or nation to which an individual, family or group belongs”***, denoting a phenomenon more complex than poverty, associated with an accumulation of disadvantages. Based on 1981 census data, he combined four indicators (unemployment, household overcrowding, non-home ownership and non-car ownership) to create this index at the area level (also referred to as the ecological level), offering a different perspective than that gained by income alone and highlighting the social aspects of deprivation that are relevant for health care planning and resources allocation. MDIs are, therefore, measured at the area level, reflecting overall area-level deprivation rather than individual-level socioeconomic position. Area-level deprivation reflects the socioeconomic disadvantage experienced by residents within a specific geographic area, such as a neighbourhood or district. It assesses the overall level of disadvantage within that area based on various indicators, offering a comprehensive view of socioeconomic conditions.

Since the development of the first MDI by Townsend, several other countries have developed their own MDI with a defined geographical resolution. A widely used MDI in the European context is the European

Deprivation Index, which was initially developed for application in France, but can be applied in 25 additional European countries[13].

The European Deprivation Index initially provided a deprivation score available for all the smallest geographical statistical units of the entire French mainland (Ilots Regroupés pour l'Information Statistique [IRIS]). This index was constructed from a European survey (EU-SILC) specifically designed to study deprivation and is composed of ten ecological variables identified best to reflect the individual experience of deprivation in France[13]. However, although the European Deprivation Index has been developed using the same data source and methodology, each country uses specific indicators and weights to create the composite score. This country-specific approach, although acknowledging regional and cultural variations in deprivation, poses challenges for cross-country comparability due to differences in how the underlying measurements are weighted. Some indicators may also seem inappropriate in certain geographical contexts (for example, car ownership might be considered a necessity in rural areas but less so in urban settings).

3.4 Objectives

In this report, we present the objectives and results from task 3.1 of work package 3 (Figure 1), which consists of developing a coherent methodological framework for integrating the dimension of social inequalities in the burden of environmental stressors **at a small geographical level**. The BEST-COST project targets the smallest geographical unit possible to be able to capture local variations of deprivation. Local Administrative Units (LAU)[14] is a common measure used as small geographical level since they comprise the municipalities and communes of the European Union. With this aim in mind, a step-by-step approach was developed:

1. A scoping review is conducted to summarize the methodological approaches used in the currently existing MDIs developed in Europe;
2. A summary of data collected through the scoping review is conducted to make informative decisions on the development of a standardised MDI;
3. Benefits and shortcomings of methodological decisions are considered (e.g. the application of indicator weights, the temporal and geographical validity of specific indicators, the availability of data at small geographical areas, etc...);
4. To provide final recommendations, including the advantages and disadvantages, for the construction and computation of the composite score of the European MDI to be used and recommended by BEST-COST;
5. To calculate the MDI for five European case study countries selected within BEST-COST: Belgium, Estonia, France, Norway and Portugal.

3.5 Special requirements of the BEST-COST project

An MDI tailored for the BEST-COST project must **prioritise feasibility**, ensuring that the necessary data for its construction are obtainable from all five case study countries at a minimum, with the aspiration for data availability across the entire European region. These data should be accessible at a small-area level, defined as granular enough to capture localised variations in deprivation, environmental stressors, and disease burden. Furthermore, the MDI should embrace a multidimensional concept of deprivation, encompassing both material and social dimensions. However, the index should deliberately exclude domains associated with exposure to environmental stressors and outcomes, such as health, to ensure the MDI does not confound estimates from environmental burden assessments. Notably, the MDI design should aim for simplicity and ease of implementation to facilitate practical usage across diverse settings.

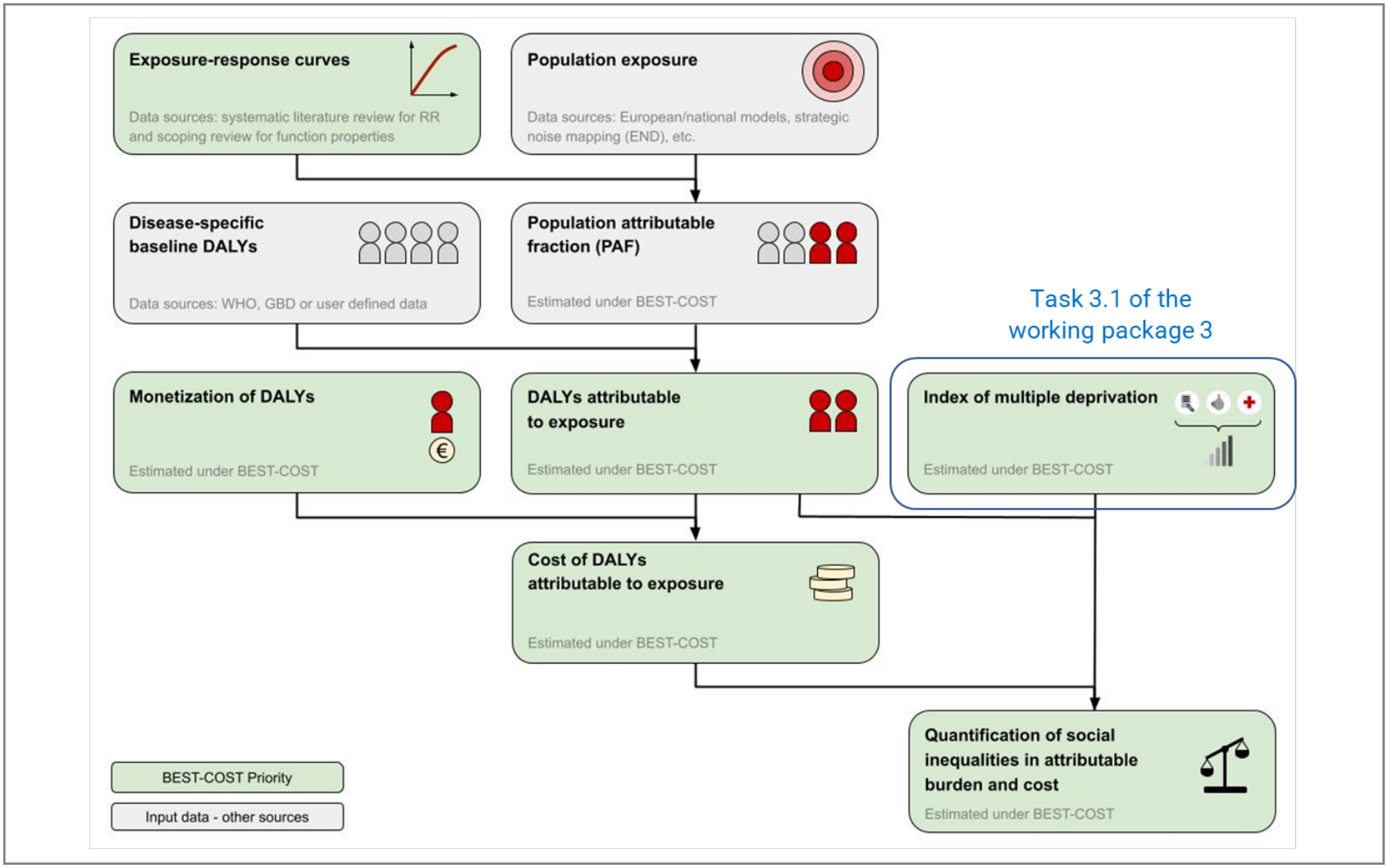

Figure 1: Tasks and objectives of the BEST-COST project. Importance of the multiple deprivation index within the project

4 Scoping review

The first task of this project was to identify and examine MDIs that have been developed and used in Europe. The aim was to summarise both current MDIs used within the European region as well as the various methods employed in the creation of these indices, to guide the development of a European index for the BEST-COST project. In addition, we were interested in determining the smallest geographical resolution possible for the application of the MDIs in the five European case study countries.

4.1 Database search

The used search strategy is presented in Annex 1. It includes 1) elements referring to deprivation index (only in title and major index terms) and 2) European countries. Three databases were searched: Medline, Embase and Web of Science. A total of 860 studies were included. See Table 1.

Table 1: Results of the database search

Database searched	Platform	Years of coverage	Records	Records after duplicates removed
Medline ALL	Ovid	1946-Present	586	578
Embase	Embase.com	1971-Present	535	101
Web of Science Core Collection*	Web of Knowledge	1975-Present	480	181
Total			1601	860

*Science Citation Index Expanded (1975-present) ; Social Sciences Citation Index (1975-present) ; Arts & Humanities Citation Index (1975-present) ; Conference Proceedings Citation Index- Science (1990-present) ; Conference Proceedings Citation Index- Social Science & Humanities (1990-present) ; Emerging Sources Citation Index (2005-present)

4.2 Inclusion and exclusion criteria

The selected studies were then imported into the Rayyan[15] platform for a second selection based on the abstract, according to the following inclusion and exclusion criteria:

Inclusion criteria:

1. Included a multiple deprivation index
2. European Study: Studies conducted within Europe
3. European Language (as used by European countries as the National language)
4. The index included a socioeconomic dimension, such as the inclusion of at least one indicator of educational attainment, occupational status, wealth, income, crime, unemployment, risk of poverty, social isolation, etc...
5. The study investigated included an association between health and deprivation
6. Study period from 2013 to 2023 (previous 10 years)

Exclusion criteria:

1. No Deprivation Index: Studies that lack an index of social deprivation or socioeconomic status.

2. Single Measurement: Studies relying on a single observable measurement of deprivation/socioeconomic status (such as education, income, or occupation), rather than an aggregated measurement (i.e., a proxy of socioeconomic position).
3. Non-European Study: Studies conducted outside of Europe.
4. Non-European Language: Studies not written in a European language.
5. Studies with a deprivation index that does not include a social dimension (e.g., an MDI that does not include one of income, education, crime, unemployment, etc…)
6. Studies with a deprivation index that includes a health dimension (e.g., an MDI that includes a dimension of disability or mortality).

Figure 3 shows the results of the screening. After abstract and full-text screening, a total of 195 studies were included.

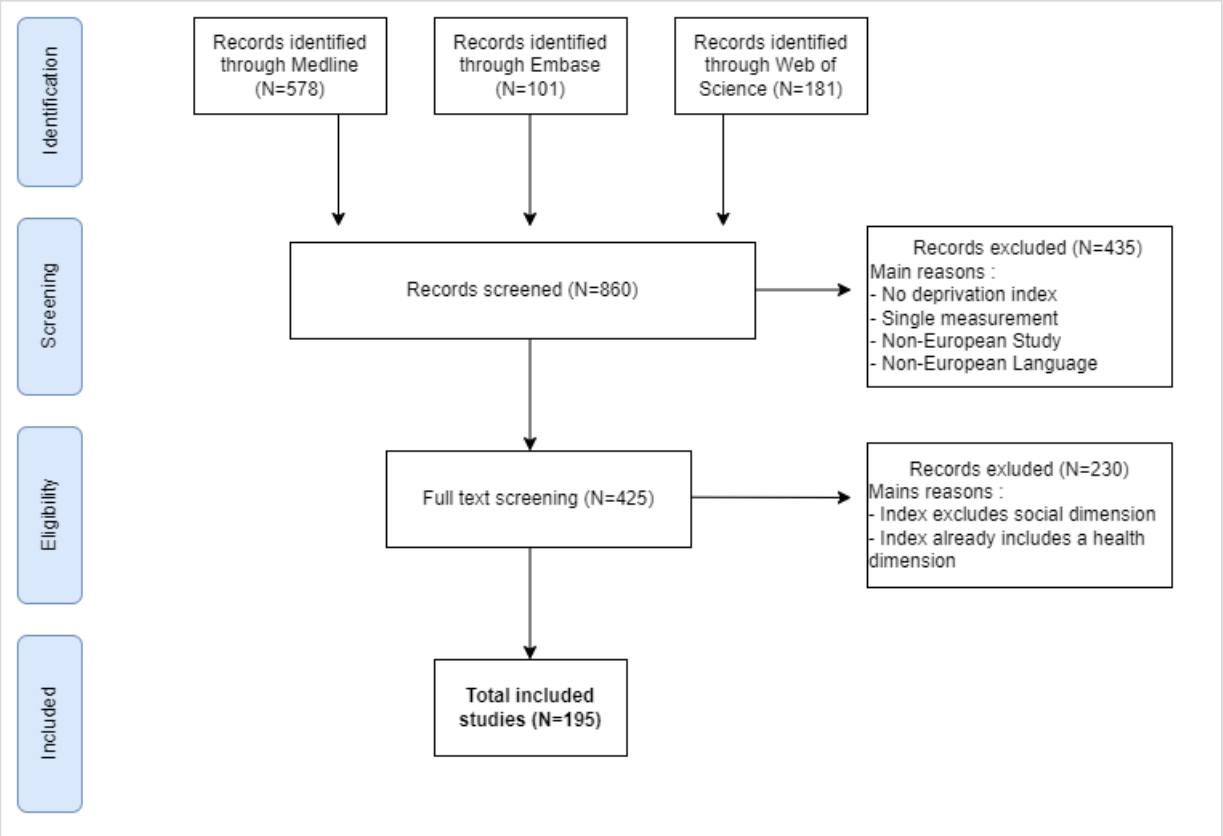

Figure 2: PRISMA flow chart

4.3 Data extraction

The data extraction proceeded in two steps:

1. The general study characteristics of each published study was extracted – see 4.3.1
2. Information on the methods (variables, data source, weighting, geographical scale,..) was extracted per index rather than per study as the focus of the review was to develop a methodological framework based on existent MDIs. This means that a second extraction sheet was developed containing the information on the composition of the index by index rather than

by study – see 4.3.2. The main focus of the extraction was therefore, based on the methods of the MDI rather than the results of the analysis for each individual study.

The background information of all articles was first filled out, and then the second extraction sheet was filled out by indicator (i.e., the individual components that together comprise the MDI) using different research articles reporting the computational methods. The other articles that used the same MDI were reviewed in order to verify that the extracted data coincided, and to identify whether this MDI was used to describe a health phenomenon.

4.3.1 General information sheet

It included:

- **PMID or DOI:** A unique identifier number assigned to a specific reference/article in the PubMed website.
- **First author:** Name of the first author cited in the paper.
- **Year:** The year the study was published.
- **Title:** The full title of the selected article.
- **Journal:** The name of the journal that published the selected article.
- **Country(s)/region included:** The country or region to which the selected article refers.
- **Reference population:** Population for which the analysis was carried out in the selected article. For example, the paper might focus on a specific population, like children, elderly, women.
- **Name of the index (acronym):** Name used for the deprivation index – if available also report the acronym
- **Outcome:** Report which outcomes were considered in the analysis together with the MDI. These might include but not be limited to prevalence, incidence, mortality, disability-adjusted life years (DALY).

4.3.2 Index information sheet

It included:

- **Name of the index (acronym):** Name used for the deprivation index – if available also report the acronym
- **Indicators:** the indicators of deprivation that compose the MDI. These might include, but not limited to, income, education, housing, etc...
- **Data source of the specific indicator:** These might include, but not limited to, survey data, cohort studies, census data, etc...
- **Reference year:** The year for which the indicator was reported.
- **Geographical scale:** The geographical area that was used for each indicator, for example municipality, regional level, etc...
- **Average size of the geographical scale:** This can be either in terms of the population size or the geographical extension or both.
- **Use of weights in the index formula:** If weights were used when combining the different indicators in one index.
- **Method for computation of weights:** Information on the methods used to combine the different indicators into one index. For example, multivariate regression, principal component analysis (PCA), factor analysis (FA), expert assessment, etc...

- **Description of the statistical analysis:** A short description of the statistical analysis done to compute the final index.
- **Uncertainty assessment:** Whether an uncertainty analysis of any kind was performed (i.e. parameter uncertainty, scenario uncertainty, etc...).

5 MDI exploration

5.1 General information of the indices

In total, we identified 22 indices of multiple deprivation. Some general information of these indices is summarised in Table 2. In the last 10 years the most cited index was the European Deprivation index developed in recent years and adapted to a number of different European countries (e.g. France, Italy, Slovenia, England, Portugal). Most of the indices were updated in 2011, namely the previous year of the European census at which time socioeconomic data was publicly available. The MDIs that were extracted were primarily developed for or used in a variety of European regions, including numerous instances in France, Italy, the UK, and Ireland, with additional applications in Portugal, Spain, Slovenia, Cyprus, Russia, Germany, Hungary, Romania, and the broader EU.

Table 2: General information of extracted indices

Name of the index (acronym)	Number of citations extracted	Latest year of update*
European Deprivation Index (EDI)	39	2012
Carstairs score	30	2011
EPICES score	23	2017
French Deprivation Index (FDEP)	13	2017
Townsend Deprivation Index (TDI)	10	2010
Neighborhood Deprivation Index	8	2009
Italian Deprivation Index (DI)	5	2011
Socio-Economic and Health-related Deprivation Index (SEHDI)	5	2011
Pobal HP Deprivation Index	4	2013
German Index of Socioeconomic Deprivation (GISD)	4	2019
Bavarian Index of Multiple Deprivation (BIMD)	3	2015
Irish National Deprivation Index	3	2006
Composed Socioeconomic Index	2	2015
Rural Deprivation Index	2	2016
Area Based Deprivation Index (ABDI)	2	2011
Rural Carstairs score (English IMD)	1	2011
Russian derivation index	1	2010
Child Material and Social deprivation	1	2014
SoDep Index	1	2017
Frailty index of cumulative deficit (FI-CD)	1	2020
Danish Deprivation Index (DANDEX)	1	2013
Socio-Economic Vulnerability Index (SEVI)	1	2011

*Reference year of the latest data used for the index

5.2 Methodological choices

Within this scoping review, we were interested in comparing the methodological choices carried across the MDIs to make an informative choice on the development of the BEST-COST MDI. The most used data source in the development of the index was census data (half of the indices). Alternatively, administrative data or registry data were also frequently used (around 20% of the indices). Almost all indices were applied at a small geographical level, which varied depending on the study and the country. The Russian deprivation index was the only index that was based completely on data at the individual level. The most often used geographical scales were based on census sections and municipalities. Half of the included studies (55%) used weights when combining the indicators into a single composite score, meaning that certain indicators were assigned different values that reflect their relative importance in the index. Forty-five percent opted for equally weighted indicators. The most common method used to compute indicator weights was principal component analysis by computing the principal component score for each indicator (58%). In MDI weighting, PCA is a statistical data-driven method that identifies underlying principal components from a list of indicators based on the coefficient matrix, which indicates the contribution of each original indicator to the principal components. In this way, the components can be used to assign weights to different indicators in an MDI. Other methods that were reported for developing weights included the use of the beta coefficients derived from regression models, or factor scores derived from factor analysis. FA, while similar to PCA, additionally explains the common variance among the indicators using a model-based approach, which can then be used to assign weights to different indicators in an MDI.

Table 3: Methodological choices of the included multiple deprivation indices

Name of the index (acronym)	Latest year*	Data source of the specific indicator	Geographical scale	Use of weights in the index formula	Method for computation of weights	Nb indicators in index
Area Based Deprivation Index (ABDI)	2011	Census	Census section, neighbourhoods, districts	No	NA	16
Bavarian Index of Multiple Deprivation (BIMD)	2015	Administrative data (Regional statistics)	District	Yes	Principal component analysis	7
Carstairs score	2011	Census	Postal code	No	NA	4
Child Material and Social deprivation	2014	Survey data (EU-SILC)	Statistical unit	No	NA	17
Composed socioeconomic index	2015	Registry (Catalan Health Service)	Basic health area (ABS)	Yes	Principal component analysis	3
Danish Deprivation Index (DANDEX)	2013	Administrative data (Statistics Denmark)	Parish level	Yes	Principal component analysis	9
EPICES score	2017	Survey	Different high-level areas	Yes	Principal component analysis	11
EuropeanD –eprivation Index (EDI)	2012	Survey data (EU-SILC); census data	Census tract and lower super output areas (Portugal and England); municipal level for other countries	Yes	Multivariate logistic regression; weights are constructed individually for each country	16
Frailty index of cumulative deficit (FI-CD)	2020	Examinations	Metropolitan area of Lille	No	NA	39
French Deprivation Index (FDEP)	2017	Census	IRIS level	Yes	Principal component analysis	4
German Index of Socioeconomic Deprivation (GISD)	2019	Administrative data (INKAR database)	Municipality	Yes	Principal component analysis	9
Irish National Deprivation Index	2006	Census	Electoral Divisions	Yes	Principal component analysis	4
Italian Deprivation Index (DI)	2011	Census	Municipality	No	NA	5

Name of the index (acronym)	Latest year*	Data source of the specific indicator	Geographical scale	Use of weights in the index formula	Method for computation of weights	Nb indicators in index
Neighbourhood Deprivation Index	2009	Census	Metropolitan area of Lille Metropolitan area of Lyon	No	NA	22
Pobal HP Deprivation Index	2013	Registry (depending on the country)	Different small areas	Yes	Confirmatory factor analysis	5
Rural Carstairs score (English IMD)	2011	Census	Rural–Urban Area Classifications for 2011	Yes	Factor analysis	4
Rural Deprivation Index	2016	Administrative data	Lower Layer Super Output Areas (LSOAs)	Yes	Principal component analysis	4
Russian deprivation index	2010	Census	Individual level	Yes	Principal component analysis	9
Socio-Economic and Health-related Deprivation Index (SEHDI)	2011	Census	Municipality, region	No	NA	8
Socio-Economic Vulnerability Index (SEVI)	2011	Census	Local Administrative Units (LAU)	No	NA	23
SoDep Index	2017	Survey	Country	No	NA	6

*Reference year of the latest data used for the index

6 Framework for index development

Developing an MDI typically involves several key steps:

The **first step involves selecting relevant indicators**, encompassing usually both social and material factors. Examples include educational attainment, income, employment status, risk of poverty, occupation (reflecting socioeconomic position), house ownership, car ownership, overcrowding within households, type of housing (representing material deprivation), and access to amenities (indicating neighborhood deprivation). While a literature review can guide indicator selection, the inclusion of specific indicators often hinges on data availability within a region or country. Therefore, it's advisable to assess data availability at this stage. To reduce the number of indicators, statistical techniques such as principal component analysis (PCA) or factor analysis (FA) can be utilised, although conducting a pilot study for data collection would also be necessary.

The **second step is to decide if weights will be assigned to each** indicator to reflect their relative importance in defining a deprivation score **or if equal weighting** of indicators will be used instead. Weights can be determined through methods such as expert opinion, PCA or FA. Although PCA and FA use data driven approaches (requiring relevant data), they entail some subjective choices on behalf of the researchers. If weights are used, they can either be created at the country level, reflecting the relative importance of the indicator to that country, or the European level (universal weights), with a discussion of the limitations and benefits discussed below.

The **third step is to create a composite score from the several indicators**. PCA and FA inherently standardise the variables during the analysis process. If equal weighting or expert opinion have been employed, then standardisation techniques like z-scores may be applied to individual domain scores to ensure comparability. We may also decide to convert the composite score into percentile ranking.

6.1 Extraction and selection of the indicators

To select relevant indicators for the construction of the BEST-COST MDI, the project team extracted all the indicators included in each MDI. A total of 156 different indicators were extracted from the 22 MDIs identified. They have been classified into 14 domains, as presented in Table 4.

Table 4: indicators domains, examples and number of indicators in the category

Domain	Examples of indicators	Nb indicators
Basic amenities	Access to heating, having a car	33
Employment	% of people unemployed	22
Family structure	Single-parent household	19
Education	% of population with high school degree	16
Housing	% of population renting from social housing	16
Occupation	% manual workers	11
Demographics	% foreign nationality	10
Overcrowding	% of household with ≥6 people	8

Income	% of people under a low income threshold	6
Social capital	% of people in social class 1 to 6 census	5
Health	Access to a healthy diet	3
Environment	Air quality	2
Financial	% of people with financial difficulties	2
Security	% of population with a criminal record	2
Social insurance	Consultation with a social worker	1
TOTAL		156

The indicators were then selected and evaluated three times by three different persons separately according to the following three criteria:

- **Redundancy:** is the indicator already covered? Keep if the description is different. For example, in the domain of housing different indicators were available covering a similar concept, i.e. percentage of people living in rented homes vs percentage of non-home ownership.
- **Cultural validity:** is the indicator appropriate, relevant, and meaningful within the cultural context of the European population?
- **Temporal validity:** does the indicator remain relevant and meaningful for Europe in 2024 and beyond?

A moderator was chosen to settle any disagreements between the three parties. A final decision was taken with the four persons to include the indicator if all criteria were met.

In the end, 13 indicators were selected for evaluation as part of the data mapping process (Table 5). These were considered as culturally and temporally valid. Redundancy was also assessed but for some categories, such as "basic amenities" and “education” several variables are included. The aim is to have only one indicator per domain, depending on the data available and supplied by the partners. On the other hand, categories such as "health" and "environment" were excluded, as these variables will form part of the exposure-outcome pairs of the study.

Table 5: Selected indicators for the development of the MDI, prior to data mapping

Domain	Indicator	Operational description
Basic amenities	No access to heating	% with no access to a system of central or electric heating
Basic amenities	No hot water supply	% of households without hot water supply
Basic amenities	No central sewerage system	% of households with toilets emptying into a cesspit
Basic amenities	No access to internet	% of household without access to internet
Crime	Criminal record	% of inhabitants with criminal record
Education	School graduates	% of high school graduates in the population ≥20 y of age
Education	University grade	% with post-secondary diploma in the population ≥30 years of age
Employment	Unemployed individuals	% of unemployed individuals aged 16-60 y in the active population
Family structure	Single-parent households	% single-parent households

Income	Low income	% of people below a low-income threshold in the total population
Overcrowding	Household with >=6 persons	% of household with six or more persons
Demographics	Change in population	% change in population over the previous five years
Housing	Social housing	% persons in households renting from social landlord, as a proportion of all people in households

6.2 Data mapping

Sub-national, national and European data sources were screened for data regarding the indicators described in Table 5. The focus of this study were the five case study countries, i.e. Belgium, France, Estonia, Norway and Portugal. In addition to the case study countries, data sources available at European level were also screened. A key element of the data extraction was the smallest geographical level at which the data were available. Tables 6a and 6b summarize the smallest geographical level for which the indicators are available in the case study countries and all European countries. The tables also highlight which indicators were not available.

At a broader geographical scale (i.e., NUTS level-2 regions), several of the above indicators are available via Eurostat (Europe column in table 6b). This dataset is publicly available, regularly updated, and harmonised, and available for most EU and the European Economic Area (EEA) countries. Eurostat also develops several socioeconomic indicators that could be combined to fulfill the requirements of the current project, such as persons who are at risk of poverty or severely materially deprived or living in households with very low work intensity[16]. Persons at risk-of-poverty are persons with an equivalised disposable income below the risk-of-poverty threshold, which is set at 60% of the national median equivalised disposable income (after social transfers). Material deprivation covers indicators relating to economic strain and durables. Severely materially deprived persons have living conditions severely constrained by a lack of resources, they experience at least 4 out of 9 following deprivations items: cannot afford to i) pay rent or utility bills, ii) keep home adequately warm, iii) face unexpected expenses, iv) eat meat, fish or a protein equivalent every second day, v) take a week holiday away from home, vi) own a car, vii) own a washing machine, viii) own a colour TV, or ix) own a telephone. People living in households with very low work intensity are those aged 0-59 years old living in households where the adults (aged 18-59 years) work less than 20% of their total work potential during the past year. At the same level of geographical coverage, several other indicators are also available via Eurostat, such as education, family structure, income, and demographics. However, it should be noted that not all data are available for each country and for each year.

The major limitation of these data are the coarse nature of the geographical scale. Given that the main focus of BEST-COST and, specifically WP3, is to prioritise a small geographical level, we have therefore decided to construct an indicator based on the scoping review, selecting a list of potential indicators available for the five case study countries, focusing on small geographical scales, defined for these purposes at the municipality level (i.e., LAU 2) at least. Indicators that fulfilled these criteria included the six following indicators:

- percentage of households without central heating,
- percentage of high school graduates in the population,
- percentage of population with post-secondary diploma,
- percentage of unemployed individuals in the active population (aged 18-65 years),
- percentage of a single-parent households, and
- percentage change of population size over the previous 5 years.

This list of indicators would cover five domains (basic amenities, education, employment, family structure, and demographics).

Table 6a: Summary of data mapping for Belgium, Estonia and France for the selected indicators

		Belgium		Estonia		France	
Domain	Indicator	Description of the indicator	Geographical area	Description of the indicator	Geographical area	Description of the indicator	Geographical area
Basic amenities	Heating	Percentage of households without central heating	Province (NUTS 2)	Percentage of households without central heating	County (LAU 1)	Number of main residences with collective central heating + number of main residences with individual central heating	IRIS
	Hot water supply	Not available		Percentage of households without heat water supply	County (LAU 1)	Not available	
	Sewerage system	Not available		Percentage of households with toilets emptying into a cesspit	County (LAU 1)	Not available	
	Access to internet	Percentage of household without access to internet	Province (NUTS 2)	Percentage of household without access to internet	County (LAU 1)	Not available	
Crime	Criminal record	Number of criminal acts	Municipality (LAU 2)	Registered crimes in counties per 10 000 inhabitants	Group of counties (NUTS 3)	Not available	

		Belgium		Estonia		France	
Domain	Indicator	Description of the indicator	Geographical area	Description of the indicator	Geographical area	Description of the indicator	Geographical area
Education (stratified by age)	School graduates	Percentage of high school graduates in the population	Statistical sector	Percentage of high school graduates in the population	Municipality (LAU 2)	Number of unschooled people aged 15 or over with a Baccalaureate, professional certificate or equivalent	IRIS
	University graduates	Percentage of population with post-secondary diploma	Statistical sector	Percentage of population with post-secondary diploma	Municipality (LAU 2)	Number of unschooled people aged 15 or over with different levels of education	IRIS
Employment	Unemployment individuals	Percentage of unemployed individuals in the active population (aged 18-65)	Statistical sector	Percentage of unemployed individuals in the active population (aged 16–60)	Municipality (LAU 2)	Number of unemployed aged 15 to 64	IRIS
Family structure	Single-parent household	Percentage of a single-parent households	Statistical sector	Percentage of a single-parent households	Municipality (LAU 2)	Number of single-parent families	IRIS
Income	Low income	Percentage of people at monetary poverty risk	Province (NUTS 2)	Not available		Poverty rate (%)	IRIS
Overcrowding	Household with six or more persons	Percentage of households with six or more persons	Statistical sector	Percentage of households with six or more persons	Country (NUTS 2)	Percentage of overcrowded main residences	Canton (LAU 1)

		Belgium		Estonia		France	
Domain	Indicator	Description of the indicator	Geographical area	Description of the indicator	Geographical area	Description of the indicator	Geographical area
Demographics	Change in population	Percentage change of population size over the previous 5 years	Municipality (LAU 2)	Percentage change of population over the previous 5 years	Municipality (LAU 2)	Percentage of population change over the period 2014-2020	Municipality (LAU 2)
Housing	Households on social renting	Percentage of social housing	Region (NUTS 1)	Not available		Number of social housing	Canton (LAU 1)

Table 6b: Summary of data mapping for Norway, Portugal and the ensemble of European countries for the selected indicators

		Norway		Portugal		Europe	
Domain	Indicator	Description of the indicator	Geographical area	Description of the indicator	Geographical area	Description of the indicator	Geographical area
Basic amenities	Heating	Not available		Private households in conventional dwellings of usual residence by place of residence and type of heating most often used	Parish (LAU 2)	Percentage of households without central heating	NUTS 2
	Hot water supply	Not available		Not available		Not available	
	Sewerage system	Not available		Private households in housing units of usual residence by geographic localization and sewerage disposal system	Parish (LAU 2)	Percentage of households with toilets emptying into a cesspit	Country
	Access to internet	Percentage of household without access to internet	County (NUTS 3)	Percentage of household with internet access	Country	Percentage of household without access to internet	Province (NUTS 2)
Crime	Criminal record	Percentage of inhabitants with criminal record	Municipality (LAU 2)	Not available		Percentage of inhabitants with criminal record	Country
Education	School graduates	Percentage of high school graduates in the population	Municipality (LAU 2)	Percentage of high school graduates in the population	Parish (LAU 2)	Percentage of high school graduates in the population	NUTS 2
	University graduates	Percentage of population with post-secondary diploma	Municipality (LAU 2)	Proportion of resident population with higher education completed	Parish (LAU 2)	Percentage of population with post-secondary diploma	NUTS 2
Employment	Unemployment individuals	Percentage of unemployed individuals in the active population (aged 16-60)	Municipality (LAU 2)	Unemployment rate in the population aged 16-89	Parish (LAU 2)	Percentage of unemployed individuals in the active population (aged 16–60)	NUTS 2

		Norway		Portugal		Europe	
Domain	Indicator	Description of the indicator	Geographical area	Description of the indicator	Geographical area	Description of the indicator	Geographical area
Family structure	Single-parent household	Not available		Proportion of mono-parental family nuclei	Parish (LAU 2)	Percentage of a single-parent households	NUTS 3
Income	Low income	Percentage of people below a low income threshold in the total population	Municipality (LAU 2)	People at risk of poverty	Country	Percentage of people below a low income threshold in the total population	NUTS 2
Overcrowding	Household with six or more persons	Household with six or more persons	Municipality (LAU 2)	Dimension (private household)" only 5 or more persons	Parish (LAU 2)	Percentage of households with six or more persons	Country
Demographics	Change in population	Percentage change of population size over the previous 5 years	Municipality (LAU 2)	Resident population by Place of residence	Administrative regions (NUTS 2)	Percentage change of population over the previous 5 years	NUTS 2
Housing	Households on social renting	Not available		Existence of rental support and Time period of tenancy agreement	Parish (LAU 2)	Percentage of households renting from social landlords	Country

6.3 Weighting indicators

Weights in the context of MDIs refer to the assigned values that reflect the relative importance of different domains or indicators used to measure deprivation. Weights prioritise certain indicators over others based on their significance in affecting the defining of deprivation. By incorporating weights, MDIs attempt to ensure that domains with greater impact on deprivation contribute more to the overall index score.

There are various methods for determining weights for domains of an MDI, with degrees of subjectivity varying across approaches. Equal weighting assumes equal contribution from each indicator and domain, while subjective weighting relies on researchers' judgments. Objective weighting through literature review offers an empirical basis but may still involve subjectivity. Data-driven techniques like multivariate regression models, latent variable models (e.g., PCA, and FA) identify domain importance based on data structure but require interpretation and have become quite popular in developing multidimensional indices[17,18]. In the current scoping review, PCA was used by several MDI indices, including the Rural Deprivation Index[19]. Deriving weights for MDI indicators via data-driven methods is dependent on the underlying data, and, therefore, depends on factors like data quality, context, temporal dynamics, spatial variation, and coverage.

Weights can also either be tailored to specific regions to accommodate local differences (region-specific/relative weights) or standardised across regions (universal weights). Region-specific weights capture unique regional disparities, whereas universal weights facilitate straightforward comparisons but might oversimplify nuances between regions. For cross-country comparisons like those in BEST-COST, a European-level measure might be preferred. However, it's essential to recognize that certain domains may vary in significance across different contexts. For instance, car ownership may signify material deprivation in some areas but not in others, such as densely populated urban centres where amenities are easily accessible on foot, by bike or by public transport. Similarly, while primary school educational attainment could indicate deprivation in certain countries, it might not hold the same relevance in countries with longer compulsory education systems. An example of a cross-European MDI that is constructed based on relative weights includes the European Deprivation Index[20].

The Italian Deprivation Index used simple equal weighting with the authors arguing:

> *"Sometimes different weights are assigned for each simple indicator, based on factorial analysis or a priori arbitrariness. However, in general it is preferred not to weight, unless we have additional information on the relative importance of the variables."* [21]

Given the significant challenge of establishing valid and temporally consistent weights for an MDI within the BEST-COST study, there is an argument that utilizing equal weights may be more advantageous than employing differential weights. This argument arises from the concern that European wide differential weights constructed at a certain time could lack specificity in particular settings. Furthermore, the assignment of weights depends in whole or part on subjective decision making. Another concern regarding the use of different weights arises from the potential methodological difficulties inherent in the construction of composite indicators, that may be misleading and manipulated[22]. However, it should be

acknowledged that using equal weights has also received criticisms for being oversimpilistic[23]. Therefore, it may be useful that when data have been collected that uncertainty and sensitivity analyses are conducted to assess the robustness of our choice.

Like the issue with weights, if we chose to use a z-score to standardise our indicators, we will also need to consider if the z-scores are calculated based on the mean and standard deviation of each indicator within a country or across all countries in the European region. The choice between calculating z-scores at the country level versus the European level can impact the interpretation and comparability of deprivation estimates. Calculating z-scores at the country level may result in differences in the interpretation of deprivation levels between countries, as each country's distribution of indicators may vary. Comparisons across countries using country-level z-scores may be influenced by differences in the scales and distributions of indicators within each country. Calculating z-scores at the European level provides a standardised framework for comparing deprivation across countries, potentially leading to more consistent and comparable estimates.

6.4 Creation of a composite score

The final selection of indicators to create our MDI included:

- percentage of households without central heating,
- percentage of high school graduates in the population, (also referred to as upper-secondary education and corresponds to the International Standard Classification of Education level 3)
- percentage of unemployed individuals in the active population (definition of “active population” is country-dependent),
- percentage of single-parent households, and
- percentage change of population size over the previous 5 years.

Figure 4 depicts the composition of the BEST-COST MDI, incorporating the domains and indicators above described in a single composite score. As previously argued, for the purposes of the current project, these are joined using equal weights.

It was decided to exclude one of the education indicators (percentage of the population with post-secondary diploma) to simplify the composite score calculation and data collection. Therefore, only one indicator per domain was included in the final proposed MDI. The two education indicators are also highly correlated and therefore, it is not expected that much information will be lost.

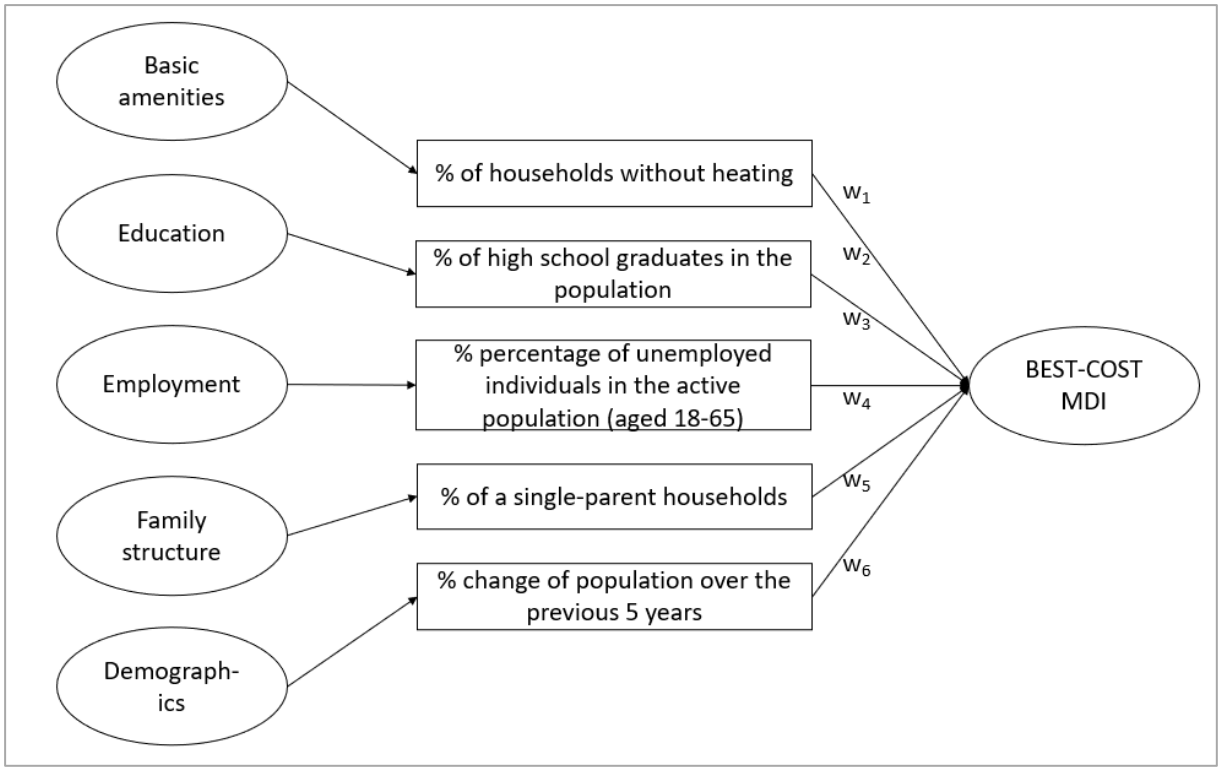

Figure 3: Domains and indicators that comprise the BEST-COST MDI.

All indicators are measured using the same scale (i.e., as a percentage of the population for a given geographical area). However, bias may arise from indicators with different distributions. For example, whereas only a small proportion of a given population may not have central heating (e.g., 4%), it is likely that the proportion with a high school diploma will be much larger (i.e., 40%). Such differences will give aeducation a much higher weight than material deprivation in our equation. Therefore, each indicator should be transformed to compare values of different distributions. A common method used for transforming variables is the z-score, which is the number of standard deviations (SD) a value is above or below the mean with a mean of 0 and a SD of 1. Z-scores are, therefore, scores that have been standardised to the theoretical normal curve. This is calculated using the following formula: $z= x - \mu / \sigma$, or in our case, by subtracting the indicator value (x) from the indicator mean (μ) and then dividing by the indicator SD (σ). See Figure 5 for a visual representation of a standard normal distribution.

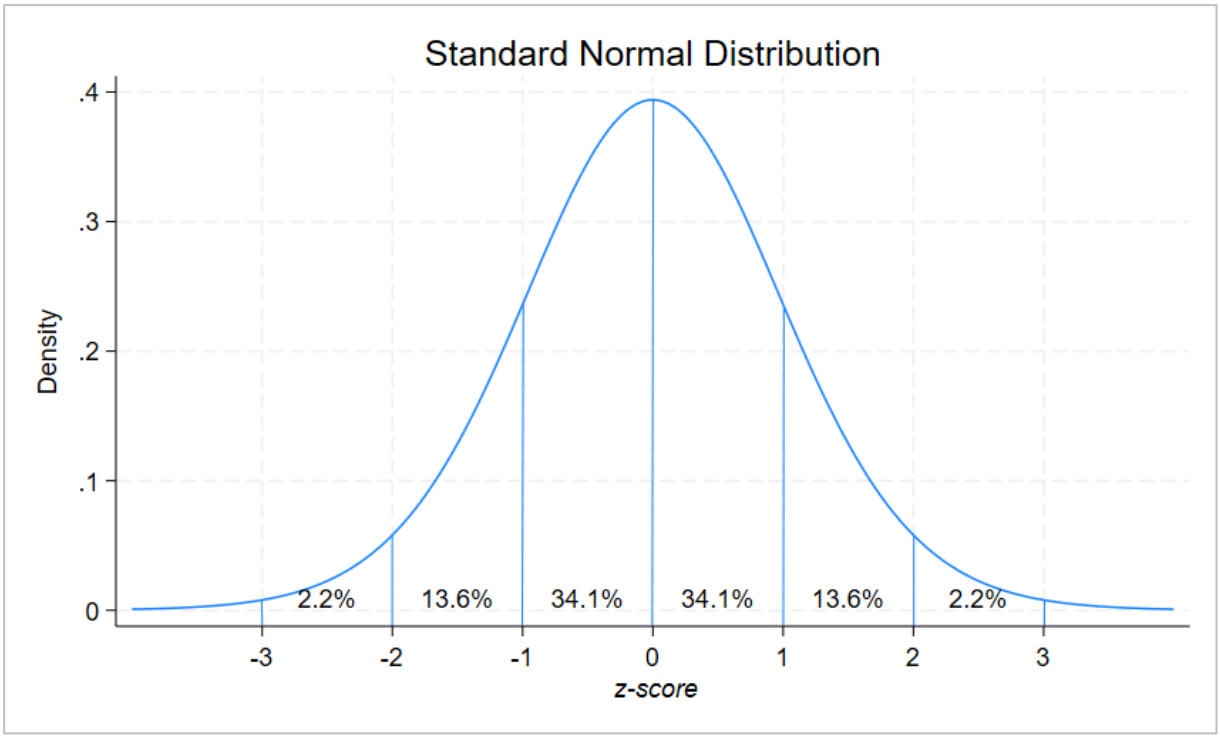

Figure 4: Visualization of a standard normal distribution with a mean of 0, and a SD of 1.0 (z-score) as well as corresponding percentages of values that fall within 1, 2 and 3 ±SDs of the mean.

In our example above, if a specific geographical region scored 40% for education, for example, with a sample mean of 50% and a SD of 20%, its Z-score would be -.50 [Z = (40 - 50)/20 = -10/20 = -.50]. In other words, they scored half a standard deviation below the mean for that indicator. For our other example, a location with a score of 4% for material deprivation with a sample mean of 5% and an indicator SD of 2%, the z-score would be, again -.50. Therefore, the difference would be the same in terms of the z-score. One potential issue, however, is that our data comprises of percentages, which may or may not be normally distributed. The z-score, based on the mean and SD assumes normally distributed indicators. However, with a large enough sample size, percentages tend to approximate a normal distribution because of the Central Limit Theorem. This theorem states that the sample mean's distribution becomes approximately normal, regardless of the population's distribution, when sample size is sufficiently large. Therefore, for indicators that do not conform to the assumption of normality (assessed by visual inspection of histograms and assessing skewness and kurtosis), the values should be first transformed by applying, for example, a natural logarithm or another common and appropriate method to force normality before we apply the z-score transformation.To then calculate the composite score from the several indicator z-scores is achieved using the following formula:

$$BEST\text{-}COST\ MDI\ CompositeScore = (Z_1 \times W_1) + (Z_2 \times W_2) + (Z_3 \times W_3) + (Z_4 \times W_4) + (Z_5 \times W_5) + (Z_6 \times W_6)$$

Where $Z_1\ Z_{2...}Z_6$ are the z-scores, and $W_1\ W_{2...}W_6$ are the weights assigned to each indicator. However, given the use of equal weights for the purposes of the BEST-COST project, each weight would be set to 1.0, or simply removed. Therefore, the composite score can be simplified to summing up all the indicators:

BEST-COST MDI CompositeScore=Z_1 +Z_2 +Z_3 +Z_4 +Z_5 +Z_6

By using the sum of the individual indicator scores, we make less assumption of the data than applying an average (e.g., mean or medium). However, it is important to note that missing indicator scores will potentially bias the composite score. Therefore, for countries with missing data for a specific indicator, it is suggested to use a valid imputation method, such as multiple imputation or regression imputation if the data is missing mostly at random.

From the summed composite score, it is possible to further create ranked deciles to create a more robust overall score. Therefore, in summary, for each small-scale district/region and year of interest, 1) the percentage for each indicator will be calculated, 2) each percentage will be then converted to a z-score as described above, 3) the z-scores will be summed to create a composite score, and 4) each area will be assigned to a decile rank based on this score and relative to the composite scores calculated for all other districts/regions.

6.5 Uncertainty and Sensitivity Analyses

Once data has been collected, it is recommended that the BEST-COST MDI is assessed for robustness by uncertainty analysis (UA) and sensitivity analysis (SA). UA examines how changes in input choices (e.g., using equal weights vs. non-equal weights) affect the final index outcome, while SA measures the variance attributed to these uncertainties[17]. In UA, input factors are randomly chosen in, for example, the use of Monte Carlo simulations to monitor index values, differences between units, and rank shifts. SA focuses on variance-based techniques, calculating sensitivity indices for each input and identifying interactions between factors. Total sensitivity indices, commonly computed using Sobol's method, offer insights into how input changesaffect composite index variance considering the joint effect of all input parameters rather than one parameter at a time. However, robustness analysis alone cannot validate an index's soundness; it aids in model fit and concept interpretation. The Organisation for Economic Co-operation and Development (OECD) emphasizes the importance of a sound theoretical framework, suggesting community peer review for assessment[24], while Burgass et al. advocate for systems modeling and transparent discussions among stakeholders to improve theoretical frameworks[25]. See Greco, S., Ishizaka, A., Tasiou, M. et al. for a summary of UA, SA, as well as other robustness analytical techniques[17].

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8 Appendix

Annexe 1: Scoping review search strategy

Embase

('deprivation index'/de OR 'social deprivation index'/de OR 'Townsend deprivation index'/mj/de OR 'socioeconomic deprivation'/mj/de OR (('social isolation'/mj/de OR 'social inequality'/mj/de) AND (indicator/de OR 'health status indicator'/de)) OR (((deprivat* OR socioecomic* OR socio-economic* OR soc*-ineq*) NEAR/12 (index* OR indices OR measure* OR indicator*)) OR ((socioecomic* OR socio-economic* OR social* OR econom*) NEAR/3 (deprivat*)) OR socio-index* OR social-index*):ti,kw) **AND** ('Europe'/exp OR 'Yugoslavia'/de OR 'Israel'/de OR 'European Union'/de OR 'European'/de OR 'EU citizen'/de OR Cyprus/de OR 'Turkey (republic)'/de OR (europ* OR austria* OR belgium OR belgian* OR Denmark OR danish OR france OR french* OR german* OR ireland OR irish* OR italy OR italian* OR luxemb* OR netherlands OR dutch OR norway OR sweden OR switzerland OR swiss OR united-kingdom OR albania OR armenia OR bosnia* OR herzegovin* OR bulgar* OR croatia* OR cyprus OR czechoslovakia* OR estonia* OR finland OR georgia OR greece OR hungar* OR iceland* OR israel* OR kosov* OR latvia* OR lithuan* OR macedoni* OR malta OR montenegr* OR poland OR polish OR portug* OR romani* OR rumani* OR serbi* OR slovak* OR sloven* OR spain* OR spanish OR turkey* OR mediterran* OR czech* OR england* OR UK OR scotland OR wales OR britain* OR holland* OR scandinav* OR nordic-countr* OR yugoslov* OR baltic* OR flander* OR wallon* OR benelux* OR greek* OR andorra* OR azerbaijan* OR belarus* OR byelarus* OR byelorus* OR russia* OR monaco* OR moldova* OR moldovia* OR san-marin* OR ukrain*):ab,ti,kw,jt) AND [2013-2030]/py NOT ([Conference Abstract]/lim OR [Conference Review]/lim)

Medline

(*Social Deprivation/ OR ((*Social Isolation/ OR *Socioeconomic Factors/) AND (Health Status Indicators/)) OR (((deprivat* OR socioecomic* OR socio-economic* OR soc*-ineq*) ADJ12 (index* OR indices OR measure* OR indicator*)) OR ((socioecomic* OR socio-economic* OR social* OR econom*) ADJ3 (deprivat*)) OR socio-index* OR social-index*).ti,kf.) **AND** (exp Europe/ OR exp Yugoslavia/ OR exp Israel/ OR exp European Union/ OR exp European People/ OR Turkey/ OR (europ* OR austria* OR belgium OR belgian* OR Denmark OR danish OR france OR french* OR german* OR ireland OR irish* OR italy OR italian* OR luxemb* OR netherlands OR dutch OR norway OR sweden OR switzerland OR swiss OR united-kingdom OR albania OR armenia OR bosnia* OR herzegovin* OR bulgar* OR croatia* OR cyprus OR czechoslovakia* OR estonia* OR finland OR georgia OR greece OR hungar* OR iceland* OR israel* OR kosov* OR latvia* OR lithuan* OR macedoni* OR malta OR montenegr* OR poland OR polish OR portug* OR romani* OR rumani* OR serbi* OR slovak* OR sloven* OR spain* OR spanish OR turkey* OR mediterran* OR czech* OR england* OR UK OR scotland OR wales OR britain* OR holland* OR scandinav* OR nordic-countr* OR yugoslov* OR baltic* OR flander* OR wallon* OR benelux* OR greek* OR andorra* OR azerbaijan* OR belarus* OR byelarus* OR byelorus* OR russia* OR monaco* OR moldova* OR moldovia* OR san-marin* OR ukrain*).ab,ti,kf,jw) AND 2013:2030.(sa_year). NOT (news OR congres* OR abstract* OR book* OR chapter* OR dissertation abstract*).pt.

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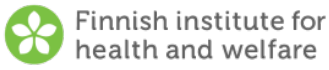
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