Comparative Population Studies – Demographic Trends Around the Globe
Vol. 51 (2026): A1-A17 (Date of release: 29.07.2026)

Online Appendix

Triangle Simplex Plot for Representing Multiple Cause of Death Dynamics*

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Appendix A1

Tab. A1: The WHO 2016 international Medical Certificate of Cause of Death form

***Frame A:* Medical data: Part 1 and 2**				
1 Report disease or condition directly leading to death on line a Report chain of events in due to order (if applicable) State the underlying cause on the lowest used line			Cause of death	Time interval from onset to death
		a		
		b	Due to:	
		c	Due to:	
		d	Due to:	
2 Other significant conditions contributing to death (time intervals can be included in brackets after the condition)				

Source: https://www.who.int/standards/classifications/classification-of-diseases/cause-of-death

In Part 1, the physician documents the sequence of morbid events that led to death. The earlier a condition began, the lower it should be recorded. The initiating conditions, referred to as the underlying cause of death, should be recorded on the lowest line. The immediate condition should occupy the highest line, while any intermediate conditions should be recorded in between.

In Part 2, the physician records contributory causes that are not directly related to the underlying cause. These should include other significant conditions that contributed to the patient's death.

* This Online Appendix contains additional information regarding the article: https://www.comparativepopulationstudies.de/index.php/CPoS/article/view/768/463.

Appendix A2

Death certification rules and processes in selected countries

In this part, we describe the systems for collecting information on causes of death in the USA, Czechia, and Denmark, focusing on three key questions:

(i) How is COD information collected?
(ii) How is COD data processed?
(iii) What major updates to the COD data processing system have occurred since 2000?

The USA

Physicians, medical examiners (or coroners), and funeral home directors report deaths to the Vital Records Office, which manages the Electronic Death Registration System – a platform for electronically creating, updating, and certifying death certificates (*NCHS* 2022). The coding process is centralised at the national level, as all states use the same software for death certification (*Danilova et al.* 2021). The Vital Records Office then shares the data with the National Center for Health Statistics (NCHS), which manages the National Vital Statistics System and, among other functions, provides the Mortality Public-Use Data File.

The automated coding of COD started as early as 1968 in the USA. Once the data is collected on NCHS, it uses several programs to process them. First, SuperMICAR and MICAR are used to encode COD data and convert it into ICD codes. Then, the ACME program is applied to automate the selection of the UCD. ACME is a system of decision tables that establish relationships between causes of death according to WHO rules, which are then used to identify the UCD. Finally, TRANSAX is used to prepare the data output and to translate the entity-axis codes into record-axis codes. This step cleans MCD data by removing redundant or incorrectly assigned diagnoses. While translation of codes produces data with fewer errors, it also eliminates information about the original placement of each cause of death record on the death certificate (*NVSS*, 2025; *Danilova et al.* 2021).

Since 2000, states began adopting a new form of the death certificate; however, this did not directly affect the section for recording causes of death. Around the same time, the process of centralising and automating the collection of COD data began. By 2015, two states had still not fully transitioned to the new system, either continuing to use the old death certificate form or processing data independently using official software (*Murphy et al.* 2015; *Danilova et al.* 2021).

The individual death records are publicly available online on: https://www.cdc.gov/nchs/data_access/vitalstatsonline.htm#Mortality_Multiple

Czechia

The physician conducts an examination of the deceased and fills out the death certificate form, which serves as the basis for entering data into the Death Certificate

Register. This data is processed by several institutions, namely the civil registry, the Czech Statistical Office (ČSÚ), and the Institute of Health Information and Statistics (UZIS). Due to GDPR regulations, only UZIS processes COD data. The data is then transferred to ČSÚ, which prepares aggregated tables and provides individual death records to contracted institutions upon request (*UZIS* 2025; *Daňková* 2016).

The data in the Death Certificate Register is then subject to an automated process for selecting the UCD, using the Iris software. This software consists of a set of decision tables that, based on determining relationships between the recorded causes, selects the most likely UCD (*Poppová* 2011).

Since 2000, several major changes have been implemented in the system for collecting data on COD. In 2007, ACME tables were introduced, replacing the previous manual coding of COD data. In 2011, the Iris software for UCD selection was introduced. In 2013, the death certificate form was updated, which impacted the section for recording causes of death by adding an additional line to record the chain of morbid events leading to death (*UZIS* 2025; *Daňková* 2016).

Individual death records can be obtained by submitting an official request to the Czech Statistical Office at the following email address: objednavky@csu.gov.cz.

Denmark

When a person in Denmark dies, a doctor conducts a post-mortem examination. The doctor then fills out a death certificate and reports the death by submitting the certificate electronically to the National Board of Health (*Sundhedsdata-styrelsen* 2026).

The data is then transferred electronically to the National Death Registry. The data is processed centrally on a national level *(Helweg-Larsen* 2011).

In 2002, the automation of COD classification was introduced, and Denmark began using ACME decision tables. Later, in 2007, another innovation was implemented: full responsibility for COD certification was given to the physician performing the post-mortem examination, replacing the death coders who had previously conducted the central validation of the data received from the physicians. From this point onwards, death certificates have been submitted electronically to the National Board of Health. Since 2012, Danish authorities have been using the Iris system as a coding aid (*Helweg-Larsen* 2011; *Iris* 2022).

The rules for accessing individual death records are detailed at the following address: https://www.dst.dk/en/TilSalg/data-til-forskning/mikrodataordninger.

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Appendix A3

Bishop et al. (2023b) Multiple Cause of Death List

Infectious diseases	
Intestinal infections	A00–A09
Tuberculosis	A15–A19, B90
Septicaemia	A40–A41
Viral hepatitis	B15–B19, B942
HIV disease	B20–B24
Residual – infections	A20–A39, A42–A99, B00–B09, B25–B34, B35–B49, B50–B89, B91–B93, B940–B941, B948–B949, B95–B99
Neoplasms	
Oral cancers	C00–C14
Oesophagus cancer	C15
Stomach cancer	C16
Colorectal cancer	C18–C21, C260
Liver cancer	C22
Gallbladder cancer	C23–C24
Pancreatic cancer	C25
Larynx cancer	C32
Lung cancer	C33–C34
Malignant melanoma of skin	C43
Non-melanoma of skin	C44
Mesothelioma	C45
Breast cancer	C50
Cervical cancer	C53
Uterus cancer	C54–C55
Ovarian cancer	C56
Prostate cancer	C61
Kidney cancer	C64
Bladder cancer	C67
Brain cancer	C71
Thyroid cancer	C73
Cancer unknown primary	C76, C80, C97
Cancer secondary site	C77–C79
Hodgkin lymphoma	C81
Non-Hodgkin lymphomas	C82–C86
Other blood cancers	C88, C90–C96, D45–D46, D471, D473–D475
Residual – benign/in situ/uncertain neoplasms	D00–D44, D470, D472, D477–D479, D48

Residual – malignant neoplasms	C17, C261, C268, C269, C30–C31, C37–C39, C40–C41, C46–C49, C51–C52, C57–C58, C60, C62–C63, C65–C66, C68–C70, C72, C74–C75
Blood diseases	
Anaemias	D50–D64
Residual – blood diseases	D65–D89
Endocrine disorders	
Disorders of thyroid gland	E00–E07
Diabetes mellitus	E10–E14
Malnutrition	E40–E46
Obesity	E66
Amyloidosis	E85
Dehydration disorders	E86–E87
Metabolic disorders	E70–E84, E88–E90
Residual – endocrine	E15–E16, E20–E243, E248–E35, E50–E65, E67–E68
Mental and behavioural disorders	
Alcohol-induced diseases	E244, F10, G312, G621, G721, I426, K292, K70, K852, K860
Substance use disorders	F11–F19
Schizophrenia	F20–F29
Mood disorders	F30–F39
Residual – mental/behavioural	F04–F09, F40–F99
Nervous system diseases	
Inflammatory diseases – CNS	G00–G09
Systemic atrophies – CNS	G10–G14
Parkinson disease	G20
Dementia and Alzheimer disease	F00–F03, G30, G310, G318
Multiple sclerosis	G35
Epilepsy	G40, G41
Cerebral palsy	G80
Residual – nervous system	G21–G26, G311, G319, G32, G36–G37, G43–G44, G47, G50–G620, G622–G64, G70–G720, G722–G73, G81–G83, G90–G99 (G45–G46 – to TIA, G310, G318 to Dementia)
Hearing and vision diseases	H00–H95
Cardiovascular diseases	
Chronic rheumatic heart diseases	I05–I09
Hypertension	I10
Hypertensive diseases	I11–I15
Ischaemic heart disease	I20–I25

Pulmonary heart diseases	I26–I28
Non-rheumatic valve disorders	I34–I36
Atrial fibrillation	I48
Heart failure (specified)	I500, I501
Other heart diseases	I30–I33, I37–I39, I40–I41, I420–I425, I427–I43, I44–I45, I47, I49, I51, I52
Cerebrovascular disease	I60–I69
Artery diseases	I70–I79
Phlebitis and thrombophlebitis	I80
Transient cerebral ischaemic attack	G45–G46
Residual – cardiovascular	I00–I02, I81–I89, I950–I958, I96–I98
Respiratory diseases	
Influenza	J09–J11
Pneumonia	J12–J18
Other ALRI	J20–J22
COPD	J40–J44
Asthma	J45–J46
Bronchiectasis	J47
Pneumonitis	J69
Other interstitial respiratory diseases	J80–J84
Other diseases of pleura	J90–J94
Residual – respiratory	J00–J06, J30–J39, J60–J68, J70, J 85–J86, J95, J961–J968, J97–J99
Digestive diseases	
Diseases of oesophagus, stomach and duodenum	K20–K291, K293–K31
Other diseases of intestines	K55–K64
Diseases of peritoneum	K65–K67
Cirrhosis of liver	K74
Other diseases of liver	K71–K73, K75–K77
Disorders of gallbladder, biliary tract and pancreas	K80–K851, K853–K859, K861–K87
Residual – digestive	K00–K14, K35–K38, K40–K46, K50–K52, K90–K93
Skin diseases	
Infections of skin	L00–L08
Residual – skin diseases	L10–L99
Musculoskeletal conditions	
Infectious arthropathies	M00–M03
Rheumatoid arthritis	M05–M06
Osteoarthritis	M15–M19
Systemic connective tissue disorders	M30–M36
Osteopathies and chondropathies	M80–M94

Residual – musculoskeletal	M07–M14, M20–M25, M40–M79, M95–M99
Genitourinary diseases	
Glomerular diseases	N00–N08
Renal tubulo-interstitial diseases	N10–N16
Renal failure	N17–N19
Urolithiasis	N20–N23
Hyperplasia of prostate	N40
Residual – genitourinary	N25–N29, N30–N39, N41–N51, N60–N99
Maternal conditions	O00–O99
Perinatal conditions (including SIDS)	P00–P284, P286–P96, R95
Congenital conditions	Q00–Q99
Ill-defined causes	I46, I509, I959, I99, J960, J969, P285, R00–R99 (excluding R95)
Injuries	S00–T99
Traumatic brain injury	S020, S021, S027–S029, S06, T902, T90
Spinal cord injury	S140, S141, S147, S240, S241, S247, S340, S341, S347, T060, T061, T093, T903, T913
Internal and crush injuries	S07, S17, S18, S224, S225, S25–S28, S297, S35–S37, S380, S381, S396, S397, S47, S57, S67, S77, S87, S97, T04, T065, T147, T914, T915
Poisoning – other substances	T36–T39, T407–T409, T41–T50, T52–T65, T940, T941, T96, T97
Poisoning – alcohol	T51
Poisoning – opioid	T400–T406
Hip fracture	S72, T931
Tibia and ankle fracture	S82
Humerus fracture	S422, S423, S424, S427
Other fractures	S022– S026, S028, S12, S220– S223, S228, S229, S32, S420–S421, S428–S429, S497, S52, S597, S620–S628, S697, S820, S92, T02, T08, T10, T12, T142, T911, T912, T921, T922, T932
Drowning/submersion injuries	T751
Dislocations	S030–S033, S131–S133, S231–S232, S331–S333, S430–S433, S530, S531, S630– S632, S730, S830, S831, S930, S931, S933, T03, T092, T112, T132, T143

Soft tissue injuries	S034–S035, S134–S136, S16, S230, S233–S235, S290, S335–S337, S390, S434–S437, S46, S532–S534, S56, S633–S637, S66, S731, S76, S832–S837, S86, S932, S934–S936, S96, T064, T095, T115, T135, T146
Burns	T20–T32, T95
Medical-related injuries (consequences)	T80–T88, T983
Residual – injuries	S00, S01, S04, S05, S08–S11, S130, S142–S146, S15, S19, S20, S21, S242–S246, S298, S299, S30, S31, S330, S334, S342–S346, S348, S382, S383, S398, S399, S40, S41, S44, S45, S48, S498, S499, S50, S51, S54, S55, S58, S598, S599, S60, S61, S64, S65, S68, S698, S699, S70, S71, S74, S75, S78, S799, S80, S81, S84, S85, S88–S91, S94, S95, S98, S99, T00, T01, T05, T062, T063, T068, T07, T090, T091, T094, T096, T098, T099, T110, T111, T113, T114, T116, T118, T119, T130, T131, T133, T134, T136, T138, T139, T140, T141, T144, T145, T148, T149, T15–T19, T33–T35, T66–T75, T900, T901, T904, T908, T909, T910, T918–T920, T924, T928–T930,T933, T934, T936, T938, T939, T980, T981, T982 T980–T982
External causes	V00–Y98
RTI – motorcyclists	V203 –V209, V213–V219, V223–V229, V233–V239, V243–V249, V253–V259, V263–V269, V273–V279, V283–V289, V294–V299
RTI – motor vehicle occupants	V304–V309, V314–V319, V324–V329, V334–V339, V344–V349, V354–V359, V364–V369, V374–V379, V384–V389, V394–V399, V404–V409, V414–V419, V424–V429, V434–V439, V444–V449, V454–V459, V464–V469, V474–V479, V484–V489, V494– V499,

	V504–V509, V514–V519, V524–V529, V534–V539, V544–V549, V554–V559, V564–V569, V574–V579, V584–V589, V594–V599, V604–V609, V614–V619, V624–V629, V634–V639, V644–V649, V654–V659, V664–V669, V674–V679, V684–V689, V694–V699, V704–V709, V714–V719, V724–V729, V734–V739, V744–V749, V754– V759, V764–V769, V774–V779, V784–V789, V794–V799, V870–V879, V892, Y850
RTI – pedal cyclists	V103–V109, V113–V119, V123–V129, V133–V139, V143–V149, V153–V159, V163– V169, V173–V179, V183–V189, V194–V199
RTI – pedestrians	V011, V019, V021, V029, V031, V039, V041, V049, V051, V059, V061, V069, V092, V093, V099
Accidental poisoning – alcohol	X45
Accidental poisoning – drugs	X42–X44
Falls	W00–W19
Drowning	V90, V92, W65–W74
Accidental threats to breathing	W75–W84
Suicide	X60–X84, Y870
Homicide and violence	X85–Y09, Y871
Medical-related injuries (external)	Y40–Y84, Y88
Residual – external causes	V010, V020, V030, V040, V050, V060, V090, V091, V100–V102, V110–V112, V120–V122, V130–V132, V140–V142, V150–V152, V160–V162, V170–V172, V180–V182, V190–V193, V200–V202, V210–V212, V220–V222, V230–V232, V240– V242, V250– V252, V260–V262, V270–V272, V280–V282, V290–V293, V300–V303, V310–V313, V320–V323,

V330–V333, V340–V343,
V350–V353, V360–V363,
V370–V373, V380–V383,
V390–V393, V400–V403,
V410–V413, V420–V423,
V430–V433, V440–V443,
V450–V453, V460–V463,
V470–V473, V480–V483,
V490–V493, V500–V503,
V510–V513, V520–V523,
V530–V533, V540–V543,
V550–V553, V560–V563,
V570–V573, V580–V583,
V590–V593, V600–V603,
V610–V613, V620–V623,
V630–V633, V640– V643,
V650–V653, V660–V663,
V670–V673, V680–V683,
V690–V693, V700–V703,
V710–V713, V720–V723,
V730–V733, V740–V743,
V750–V753, V760–V763,
V770–V773, V780–V783,
V790–V793, V80–V86, V88, V890,
V891, V893, V899 , , V91, V93– V99,
W20–W64, W85–W99, X00–X39,
X40–X41, X46–X49, X50–X59,
Y10–Y34, Y35–Y36, Y859, Y86,
Y872, Y89, Y90–Y98

Appendix A4

R Code for producing the figures

1. Load Input data for Lexis plot and simplex plots to R

   Load to the environment a data frame with your data and call it s3. The data frame must contain the following columns and the names and order of columns must be exactly the same:

Column name	Column description
`rok`	Calendar year
`age _ num`	Age at death
`Ar`	Cause of death name
`Dx.UCD`	Proportion of deaths by year and age, classified as deaths with a cause as UCD
`Dx.CC`	Proportion of deaths by year and age, classified as deaths with a cause as CC in Part 2
`Dx.MCD`	Proportion of deaths by year and age, classified as deaths with a cause as non-UCD in Part 1
`Total`	Total number of deaths by year and age, with a cause regardless of the position of its record

2. Load Input data for age-standardised death rates to R

   Load to the environment a data frame with your data and call it `hmu.stan.all`. The data frame must contain following columns and the names and order of columns must be exactly the same:

Column name	Column description
`rok`	Calendar year
`Ar`	Cause of death name
`CDRsUCD`	Age-standardised death rate by UCD
`CDRsMCD`	Age-standardised death rate by CC

Note: values in variable `Ar` must be the same in data frame `s3` and `hmu.stan.all`.

3. Create a vector named `pric` that contains the names of the causes of death for which you wish to generate plots.

   If you would like to generate the visualisations for all diseases, you can use the following command: `pric=unique(s3$Ar)`

4. Set a directory where you would like your plots to be exported as `.png files`.
   You can use the command `setwd("path")`

5. Install packages
   You can use the following command to install the packages:
   `install.packages("package.name")`

6. Run the code below:

```
library(ggplot2)
library(dplyr)
library(tidyr)
library(gridExtra)
library(Ternary)
library(gridExtra)
library(grid)
for (i in 1:length(pric)){
  s4=subset(s3, Ar==pric[i] & age _ num>40 & age _ num<100)
  head(s4)

  #Data to data matrix
  data <- as.matrix(s4[4:6], ncol = 3)

  #Function to generate colors
  get _ color <- function(A, B, C, resolution = 10) {
   # Define the binning resolution (fewer bins = lower resolution)
    bin _ size <- 1 / resolution

    # Round A, B, C to the nearest bin
    A _ bin <- round(A / bin _ size) * bin _ size
    B _ bin <- round(B / bin _ size) * bin _ size
    C _ bin <- 1 - A _ bin - B _ bin  # Ensure sum = 1

    # Ensure values stay in valid ternary range
    if (C _ bin < 0) {
      C _ bin <- 0
      B _ bin <- 1 - A _ bin
    }

    # Generate an RGB color based on binned A, B, C
    rgb(A _ bin, B _ bin, C _ bin, maxColorValue = 1)
  }

  # Generate colors for each point
    colors <- apply(data, 1, function(row) get _ color(row[1],
row[2], row[3]))
  colors=as.data.frame(colors)

  #Connect color and data and age and year
  dc=as.data.frame(cbind(data, colors,s4$rok, s4$age _ num))
  dc[,1]=as.numeric(dc[,1])
  dc[,2]=as.numeric(dc[,2])
  dc[,3]=as.numeric(dc[,3])
```

```
  #Convert to data frame
  dcf=as.data.frame(dc)
  head(dcf)
  colnames(dcf)=c("UCD", "CC", "MCD", "barva", "rok", "age _ num")
  head(dcf)
  dcf$rok=as.numeric(dcf$rok)
  dcf$age _ num=as.numeric(dcf$age _ num)

  #Create a legend for colors
  get _ color <- function(A, B, C) {
    # Example: Use RGB based on composition
    rgb(A, B, C) # Each component directly maps to RGB
  }
 png("ternary _ large.png", width=880, height=880)  # Square and
larger
  par(mar = c(0, 0, 0, 0))  # Remove margins
  TernaryPlot(alab = "UCD", blab = "CC in Part 2", clab = "Non-
UCD in Part 1",
              main = NA, axis.cex=4, lab.cex=4)
  values <- TernaryPointValues(get _ color, resolution=10)
   try(ColourTernary(values, spectrum = NULL, legend=TRUE),
silent=TRUE)
  barva = as.vector(as.matrix(colors))
   TernaryPoints(data, bg=barva, col="black", pch=21, cex=6,
lwd=2)
  dev.off()

  # Read this large, borderless image
 ternary _ img <- rasterGrob(png::readPNG("ternary _ large.png"))

  p2 <- ggplot(dcf, aes(rok, as.factor(age _ num), fill = barva)) +
    geom _ tile() +
    scale _ fill _ identity() +
    theme _ minimal() +
    theme(
      panel.grid = element _ blank(),
      axis.text.x = element _ text(size = 20, color = "black"),
      axis.text.y = element _ text(size = 20, color = "black"),
      axis.title.x = element _ blank(),
      axis.title.y = element _ blank(),
     plot.title = element _ text(size = 30, color = "black", hjust
= 0.5),  # Center the title
     plot.margin = unit(c(0, 0, 0, 0), "cm"),  # No extra margins
```

```
     text = element _ text(color = "black")  # Set the text color
to black throughout
    ) +
    coord _ fixed(ratio = 2.2) +
    labs(title = "")

  #Line plots with standardized death rates
  hmu.stan=subset(hmu.stan.all, Ar==pric[i])
  p1 = ggplot(data = hmu.stan, aes(x = rok, y = CDRsUCD)) +
    geom _ line(aes(y = CDRsUCD), color = "red", size = 1.5) +
    theme _ minimal() +
    labs(x = "",
         y = "") +  # No primary y-axis label needed
   geom _ point(shape = 21, fill = "white", color = "black", size
= 3, stroke = 1) +  # Points for CDRsUCD
    ylim(0, max(hmu.stan$CDRsUCD)) +  # Primary y-axis limit
   theme(axis.text.x = element _ text(size = 20, color = "black"),
         axis.text.y = element _ text(size = 20, color = "black"),
          plot.margin = unit(c(1, 0, -0.5, 0), "cm")) +  # Adjust
margins if needed

    # Add the secondary line for CDRsMCD, transformed for the
secondary axis
   geom _ line(aes(y = CDRsMCD / max(hmu.stan$CDRsMCD) * max(hmu.
stan$CDRsUCD)), color = "blue", size = 1.5) +  # Rescale CDRsMCD
for the secondary axis

    # Add points for the secondary axis (scaled)
   geom _ point(aes(y = CDRsMCD / max(hmu.stan$CDRsMCD) * max(hmu.
stan$CDRsUCD)), shape = 21, fill = "white", color = "black", size
= 3, stroke = 1) +

    scale _ y _ continuous(
      name = "",  # No name for primary y-axis
     sec.axis = sec _ axis(~ . * max(hmu.stan$CDRsMCD) / max(hmu.
stan$CDRsUCD), name = "")  # No name for secondary axis
    ) +

    # Adding UCD label positioned above the plot area
    annotate("text", x = 2000, y = max(hmu.stan$CDRsUCD) * 1.1,
# Adjust y to be above the highest point
             label = "UCD", color = "red", size = 6, fontface
= "bold",
             vjust = 0.5, hjust = 1, angle = 0) +  # Rotate if
needed (set angle = 0 for horizontal)
```

```
    # Adding MCD label positioned above the plot area
      annotate("text", x = 2020, y = max(hmu.stan$CDRsMCD /
max(hmu.stan$CDRsMCD) * max(hmu.stan$CDRsUCD)) * 1.1,
             label = "CC", color = "blue", size = 6, fontface =
"bold",
             vjust = 0.5, hjust = 0, angle = 0)

  # Save combined plot as square
  png(paste0("simplex _ ", pric[i], " _ ","CZE",".png"), width=1200,
height=400)
    grid.arrange(ggplotGrob(p1), ggplotGrob(p2), ternary _ img,
ncol = 3,
                 widths = unit(c(1, 1, 0.8), "null"),
                 heights = unit(1, "null"))
  dev.off()
}
```

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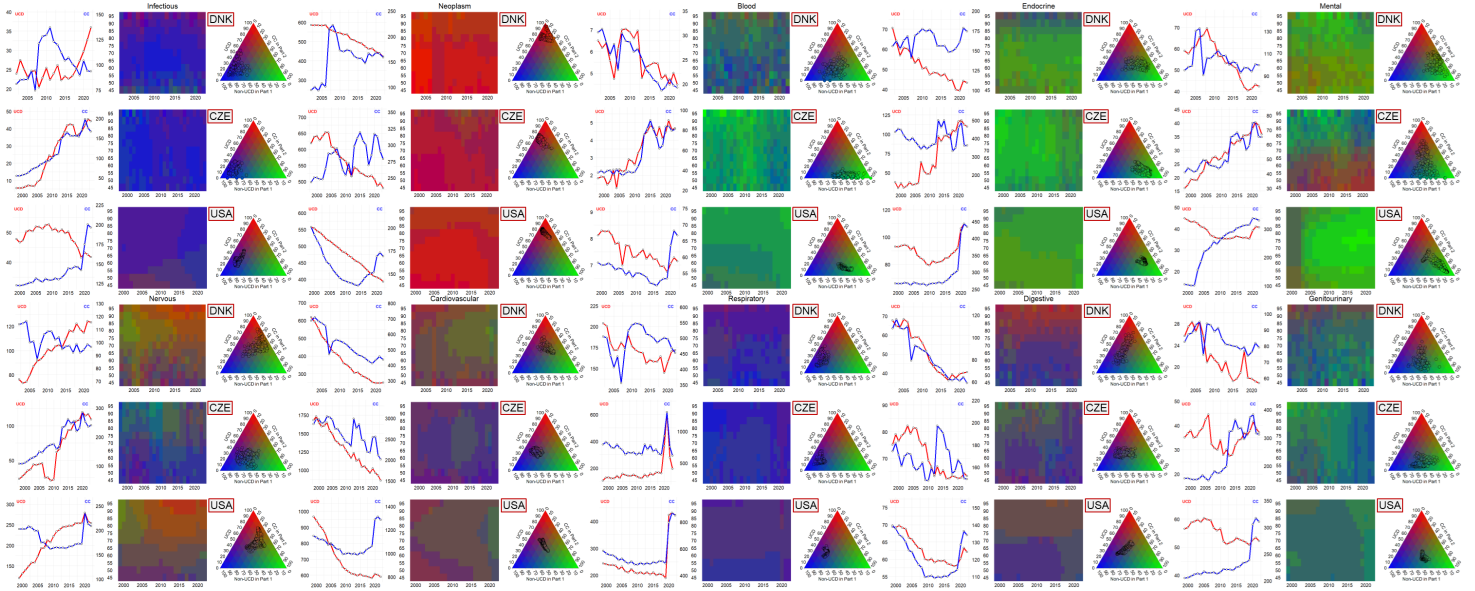
Appendix A5

Fig. 1: Age-standardised death rates, simplex plots and Lexis plots for major cause of death groups



Source: own design

Comparative Population Studies

www.comparativepopulationstudies.de

ISSN: 1869-8980 (Print) – 1869-8999 (Internet)

Published by
Federal Institute for Population Research (BiB)
65180 Wiesbaden / Germany

E-mail: cpos@bib.bund.de