Quantifying excess mortality by cause of death against a pre-pandemic and socio-economic factor-dependent baseline

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University of Amsterdam

RCLR Research Centre for Longevity Risk

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CBS microdata

Modelling cause-specific, pre-pandemic mortality with socio-economic factors
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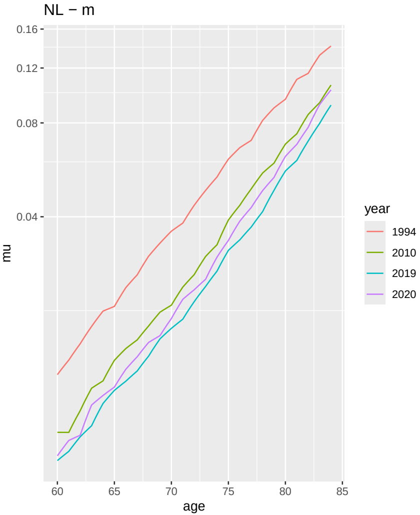

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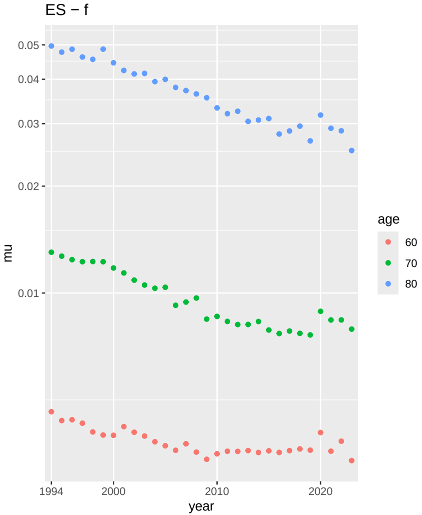

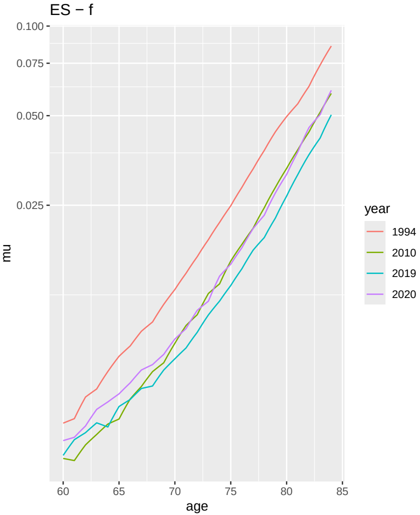

Introduction

- European countries lost about 10 years of mortality improvement.
- But in many countries, including the UK and the US, mortality slowdowns started earlier than 2020
- The challenge for setting mortality assumption for internal models is to project mortality
- ... and for that we need to deal with the effect of the pandemic
- In the Netherlands, CBS reported:
  - Excess mortality for the third consecutive year in 2022

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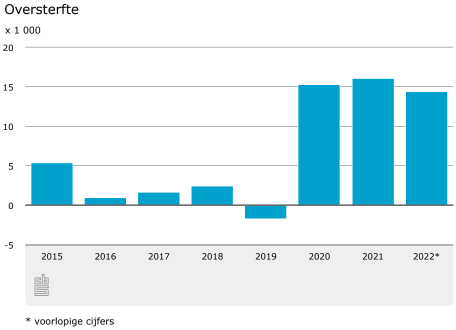

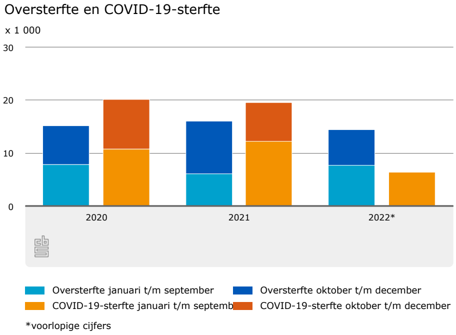

www.cbs.nl/en-gb/news/2023/04/excess-mortality-for-the-third-consecutive-year-in

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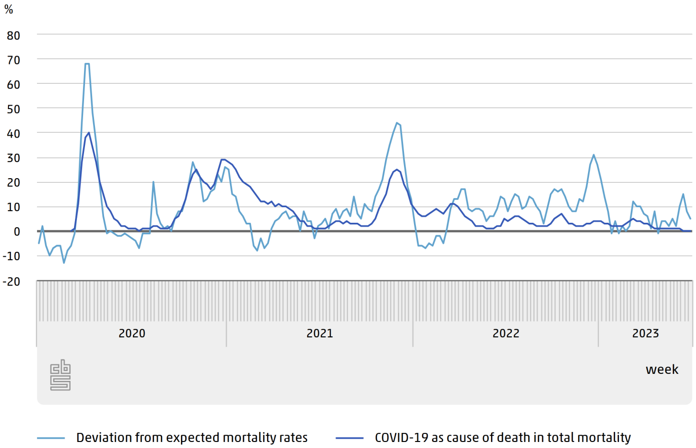
Deviation from expected mortality, and share of COVID-19 mortality



www.cbs.nl/en-gb/news/2023/50/covid-19-mortality-continues-to-decline-in-2023

Introduction

CBS:

- In 2023, excess mortality stood at 12.7 thousand (8 percent).
- In 2022, the figure was 14.7 thousand (9 percent).
- based on the COVID-19 mortality monitor
- CBS launched this monitor at the start of the pandemic, but stopped calculating possible excess mortality on a weekly basis at the end of 2023

www.cbs.nl/en-gb/news/2024/06/fewer-deaths-in-2023

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Introduction

- For calculating excess mortality and for taking the pandemic effect into account for mortality projections, **we need to construct a reliable baseline = expected mortality during 2020 - 2023**
- This is the aim of an RCLR research project funded by ZonMw

About RCLR: the Research Centre for Longevity Risk is a joint initiative of NN Group and the University of Amsterdam, with additional funding from the Dutch government's Public-Private Partnership (PPP) programme.

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Research objectives and approach

Overall objective: to quantify and to analyze excess mortality against a pre-pandemic baseline for expected cause-specific mortality in 2020 and 2021, taking socio-economic factors into account.

A phased approach, with intermediate research objectives:

1. to establish a cause-specific, pre-pandemic baseline mortality level, taking socio-economic factors into account

2.a. to quantify cause-specific excess mortality during the COVID waves in 2020 and 2021

2.b. to analyze to what extent excess mortality can be attributed to socio-economic risk factors and information on COVID-19 testing and vaccination.

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CBS microdata

Overview of datasets used

Dutch registry data

Made available via CBS microdata service

125 jaar Centraal Bureau voor de Statistiek

We combine data sources on:

- (per spell) start and end date of residence spells in the Netherlands
- (per event) cause, date and location of death + (during pandemic) vaccination uptake and COVID-19 tests
- (static) date of birth, gender, migration background, education
- (annual) property value, medical expenses, income and socio-economic status.

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CBS microdata

Construction of annual, pre-pandemic data

Merge the microdata to individual spells:

- time $t \in \mathcal{T} = \{2016, ..., 2019\}$
- CoDs $c \in \mathcal{C} = \{1, ..., C = 20\}$
- individuals $j \in \mathcal{J}_t = \{1, ..., J_t\}$
- individual-specific spells $i \in \mathcal{I}_{t,j} = \{1, ..., I_{t,j}\}$ with constant socio-economic factors

For each (t, j, i) combination we have:

- exposure-to-risk $\tau_{t,j,i}$
- death indicator $\delta_{t,j,i}$ and cause-specific death indicator $\delta^c_{t,j,i}$
- combination of constant risk factors.

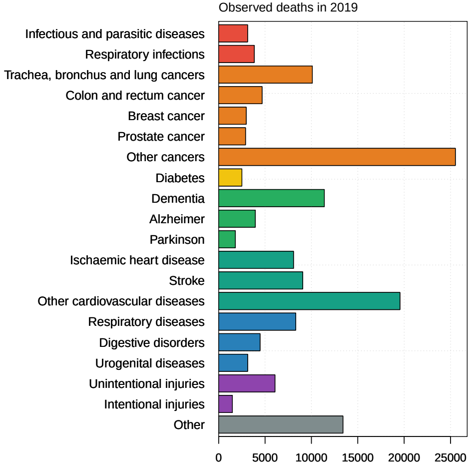
CBS microdata

Construction of annual, pre-pandemic data, CoDs under investigation

Mapping based on WHO, 2020:

1. Communicable diseases
2. Non-communicable diseases
3. Injuries

Final selection of 20 pre-COVID causes based on materiality.



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Construction of weekly, pandemic data

Merge the microdata to weekly, individual spells:

- time $t \in \{2020,\ 2021\}$, the pandemic period
- ISO-8601 week definition
- additional CoD: COVID-19.

Extend available socio-economic factors, per week, with:

- time elapsed since last positive COVID infection test (in days and weeks)
- time elapsed since last COVID vaccination (in days and weeks)
- indicators for infection or vaccination in the given week.

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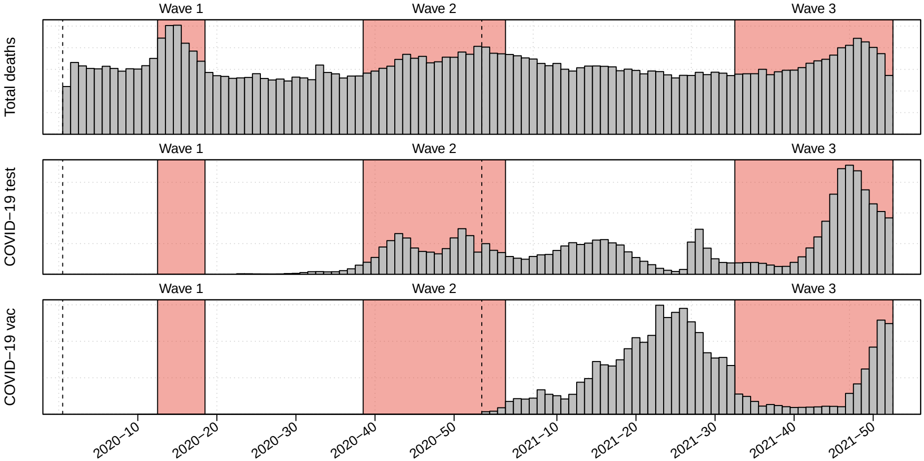
Observed deaths and COVID-19 information



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Pre-pandemic mortality levels

Rationale: importance of the baseline mortality level when studying excess mortality during the pandemic.

Use statistical learning to calibrate

on the data from $\{2016, \ldots, 2019\}$

- $\mu_{t,j,i}$: the all cause force of mortality
- $\mu^{c}_{t,j,i}$: the cause c specific force of mortality,

applicable to individual j, in year t, with socio-economic factors specific to spell i,

including a time trend, an age and gender effect and the effect of selected socio-economic factors.

Pre-pandemic mortality levels

Quasi-Poisson regression with GAMs, all cause

From the (t, j, i) records of individual-specific spells we construct

$$\mathcal{L}(\boldsymbol{\theta}|\boldsymbol{\delta}, \boldsymbol{\tau}) = \prod_{t \in \mathcal{T}} \prod_{j \in \mathcal{J}_t} \prod_{i \in \mathcal{I}_{t,j}} \exp\left[-\tau_{t,j,i} \cdot \mu_{t,j,i}(\boldsymbol{\theta})\right] \cdot \left(\mu_{t,j,i}(\boldsymbol{\theta})\right)^{\delta_{t,j,i}},$$

the survival likelihood, where the force of mortality depends on parameter vector $\boldsymbol{\theta}$.

This likelihood function is proportional a Poisson likelihood, see Brouhns et al., 2002. We switch to quasi-Poisson to allow for overdispersion.

We use Generalized Additive Models (GAMs) to calibrate an additive predictor (with smooth functions of covariates) for $\log \mu_{t,j,i}$, see van Berkum et al., 2020.

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Pre-pandemic mortality levels

Quasi-Poisson regression with GAMs, cause-specific

Analogously, for cause-specific mortality we construct

$$\mathcal{L}(\boldsymbol{\theta}^c|\boldsymbol{\delta}^c, \boldsymbol{\tau}) = \prod_{t\in\mathcal{T}} \prod_{j\in\mathcal{J}_t} \prod_{i\in\mathcal{I}_{t,j}} \exp\left[-\tau_{t,j,i} \cdot \mu^c_{t,j,i}(\boldsymbol{\theta}^c)\right] \cdot \left(\mu^c_{t,j,i}(\boldsymbol{\theta}^c)\right)^{\delta^c_{t,j,i}},$$

the cause-specific survival likelihood, where the force of mortality depends on parameter vector $\boldsymbol{\theta}^c$.

Again, we use GAMs with quasi-Poisson, log link and smooth functions of continuous covariates.

Pre-pandemic mortality levels

Lee-Carter structure

Recall the Lee-Carter structure:

$$\log \mu_{t,x} = \alpha_x + \beta_x \cdot \kappa_t.$$

We calibrate a smooth variant of the Lee-Carter model:

$$\log \mu_j = f_{g_j}(x_j) + h_{g_j}(x_j) \cdot (\bar{t} - t_j),$$

where only the gender g, the time t and age x of an individual j is used as covariate information. Hereby,

- $f_g(x)$ and $h_g(x)$ are gender specific smoothers of age x
- $\bar{t}$ is the average of t for $t \in \mathcal{T}$.

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Pre-pandemic mortality levels

Lee-Carter baseline structure plus socio-economic factors

To assess pandemic excess mortality we want to account for pre-pandemic existing differences in mortality among socio-economic groups.

Hereto, we examine model specifications built-up as follows:

$$
\begin{aligned}
\log \mu_i &= f_{g_i}(x_i) + h_{g_i}(x_i) \cdot (\bar{t} - t_i) \\
&+ s_{\text{ME}}(\log \text{ME}_i) \cdot \mathbb{I}(\text{ME}_i > 0) + \beta_{\text{ME\_0}} \cdot \mathbb{I}(\text{ME}_i = 0) \\
&+ s_{\text{Wealth}}(\text{Wealth}_i) \cdot \mathbb{I}(\text{Wealth}_i \text{ not missing}) \\
&+ \sum \beta_\ell \cdot \mathbb{I}(\text{PersIncSrc}_i = \ell) + \sum \beta_\ell \cdot \mathbb{I}(\text{HomeOwn}_i = \ell) \\
&+ \sum \beta_\ell \cdot \mathbb{I}(\text{Geo}_i = \ell),
\end{aligned}
$$

where i denotes a spell for individual j in year t during which the covariates do not change.

Pre-pandemic mortality levels

Lee-Carter baseline plus socio-economic factors

A closer look at the building blocks in the specification of μ_i:

$$\begin{aligned}
\log \mu_i &= f_{g_i}(x_i) + h_{g_i}(x_i) \cdot (\bar{t} - t_i) \\
&+ s_{\text{ME}}(\log \text{ME}_i) \cdot \mathbb{I}(\text{ME}_i > 0) + \beta_{\text{ME_0}} \cdot \mathbb{I}(\text{ME}_i = 0) \\
&+ s_{\text{Wealth}}(\text{Wealth}_{,i}) \cdot \mathbb{I}(\text{Wealth}_i \text{ not missing}) \\
&+ \sum \beta_\ell \cdot \mathbb{I}(\text{PersIncSrc}_i = \ell) + \sum \beta_\ell \cdot \mathbb{I}(\text{HomeOwn}_i = \ell) \\
&+ \sum \beta_\ell \cdot \mathbb{I}(\text{Geo}_i = \ell).
\end{aligned}$$

Based on pre-screening with single factor specifications (BIC + data availability): focus on: medical expenses + wealth (property value or income quantiles), source of personal income and home ownership + migration background.

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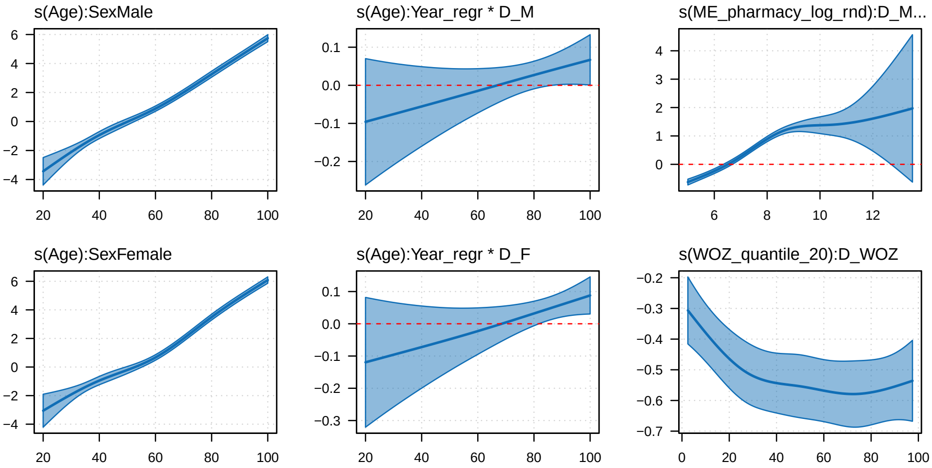
Example of model selection results

Alternatives considered: seven for Model 2 and nine for Model 3

Model for Diabetes	logL	EDF	BIC	ΔlogL	ΔEDF	ΔBIC
Model 1 (base)	-88.411	14,3	177.086			
Model 2 (pharmacy)	-83.840	19,5	168.041	4.571	5,2	-9.046
Model 2 (hospital)	-87.046	19,1	174.446	1.365	4,8	-2.641
...	...	...	...	...	...	...
Model 2 (chronic)	-85.682	18,9	171.715	2.729	4,7	-5.371
Model 2 (total expenses)	-84.954	20,3	170.283	3.457	6,0	-6.804
Model 2 (pharmacy)	-83.840	19,5	168.041			
Model 3 (property value)	-82.468	23,8	165.376	1.372	4,3	-2.665
Model 3 (property value + income source)	-82.088	27,4	164.684	1.752	7,9	-3.357
Model 3 (household income)	-82.403	23,5	165.241	1.437	4,0	-2.800
...	...	...	...	...	...	...
Model 3 (personal income by percentile and source)	-82.432	43,1	165.661	1.408	23,6	-2.380
Model 3 (property value + income source)	-82.088	27,4	164.684			
Model 4 (home ownership)	-81.720	32,5	164.040	368	5,1	-643
Model 4 (home ownership)	-81.720	32,5	164.040			
Model 5 (migration background)	-81.645	41,5	164.058	74	9,0	18

Example of calibrated risk factors

Other cardiovascular diseases



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From expected annual to weekly mortality

What we have at this point:

- the expected number of deaths (total or per cause) over an exposure period $\tau \in [0, 1]$ for individual j with characteristics i

  $$\tau \cdot \hat{\mu}_{tji} \text{ or } \tau \cdot \hat{\mu}^{c}_{tji} \text{ with } t \in \{2020, 2021\},$$

  where only the baseline Lee-Carter structure (t, x and g) or the LC structure + selected socio-economic factors can be included

However, this approach ignores the seasonality observed in weekly, empirical data on death counts (cfr. supra)!

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From expected annual to weekly mortality

Strategy to incorporate seasonal effect

Inspired by van Berkum et al., 2025 and Koninklijk Actuarieel Genootschap, 2022 we calibrate:

- week effects $\phi_{w,x,g}$ (all cause) and $\phi^{c}_{w,x,g}$ (cause specific) using cyclical cubic splines
- for males and females separately
- for all ages, but also for specific age groups $20-54$, $55-64$, $65-74$, $75-84$ and $85+$ separately
- on the prepandemic period 2016-2019, thus: no calibrated seasonal effect for COVID-19 CoD!

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Quantifying excess mortality in 2020 and 2021

As such, we obtain the expected number of deaths for every week w in $t = \{2020, 2021\}$, assuming pre-pandemic conditions:

$$\begin{array}{ll} \text{all cause} & \hat{d}_{t,w,j,i} = \tau_{t,w} \cdot \hat{\mu}_{tji} \cdot \hat{\phi}_{w,x,g} \\ \text{cause specific} & \hat{d}^{c}_{t,w,j,i} := \tau_{t,w} \cdot \hat{\mu}^{c}_{tji} \cdot \hat{\phi}^{c}_{w,x,g} \end{array}$$

We compare expected and observed weekly death counts in order to quantify excess mortality.

We quantify excess all-cause mortality on an annual basis (and similarly for individual causes) as:

- absolute excess mortality : $\sum_{w \in t,j,i} \{d^{\text{obs}}_{t,w,j,i} - \hat{d}_{t,w,j,i}\}$
- relative excess mortality : $\sum_{w \in t,j,i} d^{\text{obs}}_{t,w,j,i} / \sum_{w \in t,j,i} \hat{d}_{t,w,j,i} - 1$.

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Analyzing excess mortality in 2020 and 2021

Strategy

To dig deeper in the differences between expected and observed deaths during the pandemic, we explore

$$D_{t,w,j,i} \sim \text{POI}(\quad . \quad)$$

with a specification for the mean that is built up from

$$\underbrace{\tau_{t,w} \cdot \hat{\mu}_{tji} \cdot \hat{\phi}_{w,x}}_{\text{pre-pandemic}} \cdot \underbrace{\exp(\quad . \quad)}_{\text{socio-econ info}} \cdot \underbrace{\exp(\quad . \quad)}_{\text{infection + vacc info}},$$

where

- further adjustments based on socio-economic factors and information on COVID-19 infections and vaccinations.

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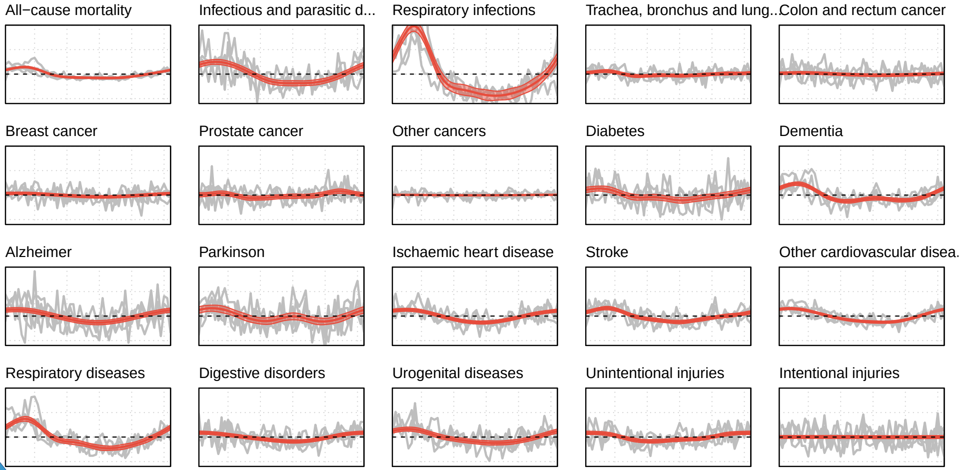
Quantifying excess mortality

Empirical and calibrated seasonal patterns



Quantifying excess mortality

Disclaimer on results

- The results for this phase are based on calibrations using 50% of the Dutch population because of computational challenges (even when using OSSC, the ODISSEI Secure Super Computer).

- The results on the following slides are preliminary; we have not yet been able to complete the analyses for all causes and for the separate COVID-waves.

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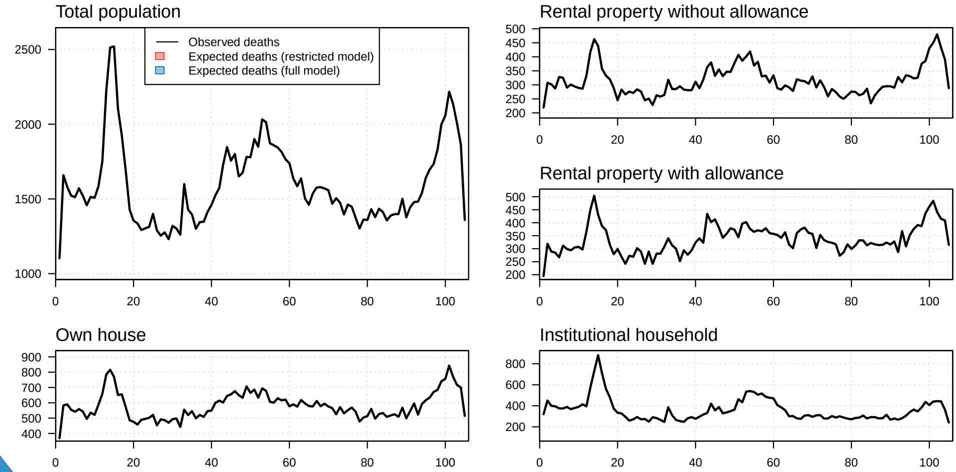
Quantifying excess mortality

Illustrating the importance of a good baseline



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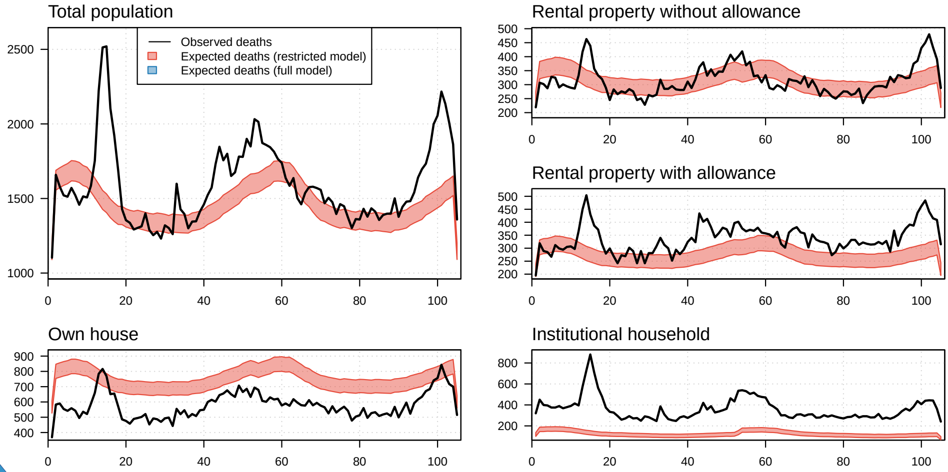
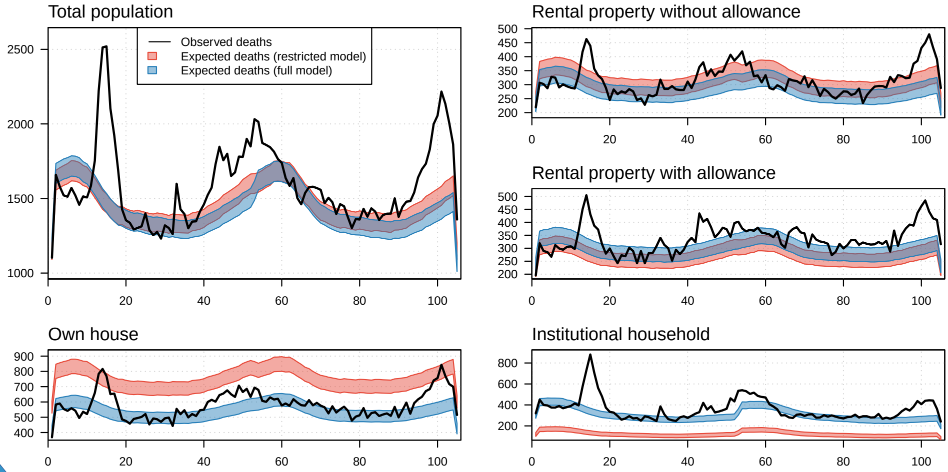
Illustrating the importance of a good baseline



Quantifying excess mortality

Illustrating the importance of a good baseline



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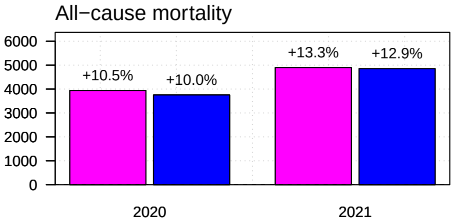
Quantifying excess mortality

Excess mortality by cause (absolute and relative)



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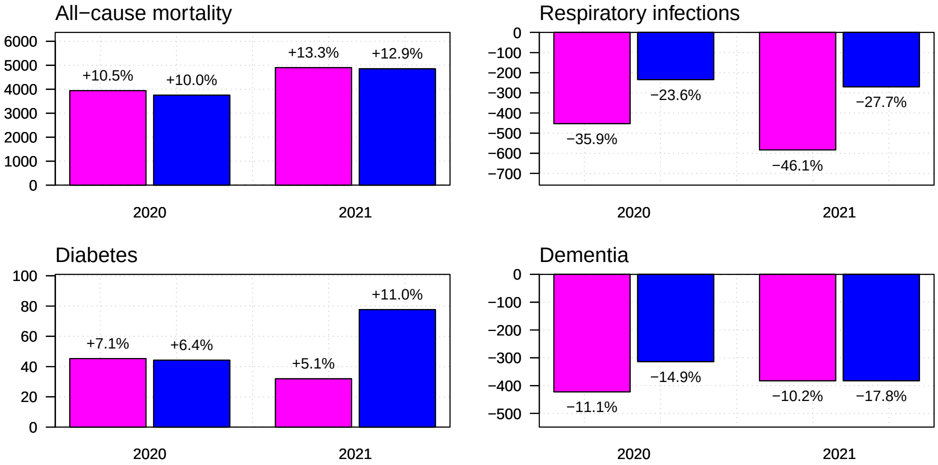

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Analyzing excess mortality

Diabetes regression results (baseline mortality based on restricted model)

Model	logL	EDF	BIC	Delta_logL	Delta_EDF	Delta_BIC
Baseline mortality (restricted model)	-36.726	1,0	73.473,1			
Baseline + home ownership	-36.150	7,0	72.443,0	576,3	6,0	-1.030,1
Baseline + property value + income source	-36.057	12,4	72.367,6	669,3	11,4	-1.105,5
Baseline + household income + income source	-36.104	12,2	72.457,7	622,1	11,2	-1.015,4
Baseline + personal income + income source	-36.147	16,6	72.632,4	579,2	15,6	-840,7
Baseline + medical expenses (pharmacy)	-35.197	7,0	70.537,1	1.529,0	6,0	-2.936,0
Baseline + migration background	-36.626	11,0	73.476,7	100,3	10,0	3,6
Baseline + COVID-19 infection	-36.710	4,1	73.503,7	16,5	3,1	30,6
Baseline + COVID-19 vaccination	-36.642	6,9	73.424,9	84,3	5,9	-48,2
Baseline + COVID-19 infection + vaccination	-36.652	5,9	73.424,8	74,5	4,9	-48,3

Table: logL = log-likelihood, EDF = number of parameters, BIC: lower is better

- Medical expenses seem to be the key predictor in explaining excess mortality
- COVID information on infections and testing seems to be of little importance

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Analyzing excess mortality

Diabetes regression results (baseline mortality based on full model)

Model	logL	EDF	BIC	Delta_logL	Delta_EDF	Delta_BIC
Baseline mortality (full)	-34.567	1,0	69.153,8			
Baseline + home ownership	-34.556	7,0	69.255,7	10,3	6,0	101,9
Baseline + property value + income source	-34.553	8,0	69.268,8	13,9	7,0	115,1
Baseline + household income + income source	-34.530	10,5	69.275,3	36,4	9,5	121,5
Baseline + personal income + income source	-34.529	13,5	69.333,8	37,2	12,5	180,0
Baseline + medical expenses (pharmacy)	-34.549	5,0	69.200,6	17,8	4,0	46,9
Baseline + migration background	-34.525	11,0	69.274,8	41,5	10,0	121,0
Baseline + COVID-19 infection	-34.559	3,0	69.178,4	8,1	2,0	24,6
Baseline + COVID-19 vaccination	-34.501	5,6	69.118,0	65,2	4,6	-35,7
Baseline + COVID-19 infection + vaccination	-34.506	5,4	69.122,0	61,0	4,4	-31,8

Table: logL = log-likelihood, EDF = number of parameters, BIC: lower is better

- When using a more refined baseline model, all socio-economic risk factors are no longer relevant in explaining excess mortality

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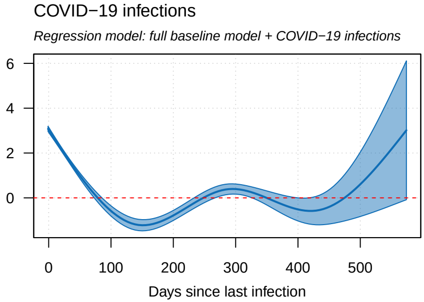
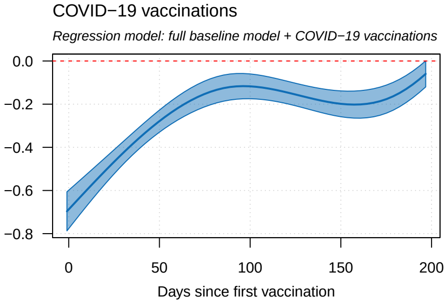
Analyzing excess mortality

All-cause mortality, estimated COVID-effects





- COVID-19 infections: increased risk of mortality immediately after infection, protection after some time but this protection wears off
- COVID-19 vaccinations: decreased risk of mortality immediately after vaccination, protection wears off over time

Key findings

- Mortality occurs most often at higher ages and risk factors that are available for older people are therefore likely to be more relevant
- Information on wealth / income and medical expenses are key in predicting the level of individuals' mortality
- Though on all-cause mortality there is substantial excess mortality in the period 2020-2021, for many individual causes observed mortality was lower than predicted (in line with previous CBS publications)
- When an appropriate baseline is used to define expected mortality, there seem to be limited differences in excess mortality between individuals with different socio-economic risk factors; COVID information is more relevant in explaining differences in excess mortality

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