Multi-Population Approaches to Forecasting All-Cause Mortality Using Cause-Specific Mortality Data

Pintao Lyu[1,2,3] Bertrand Melenberg[1,3] Anja De Waegenaere[1,3]

[1] Tilburg University
[2] Nationale-Nederlanden
[3] Netspar

(1) Why causes of death models

(2) Problems and Our Contribution

(3) Assumptions

(4) Models

(5) Performance

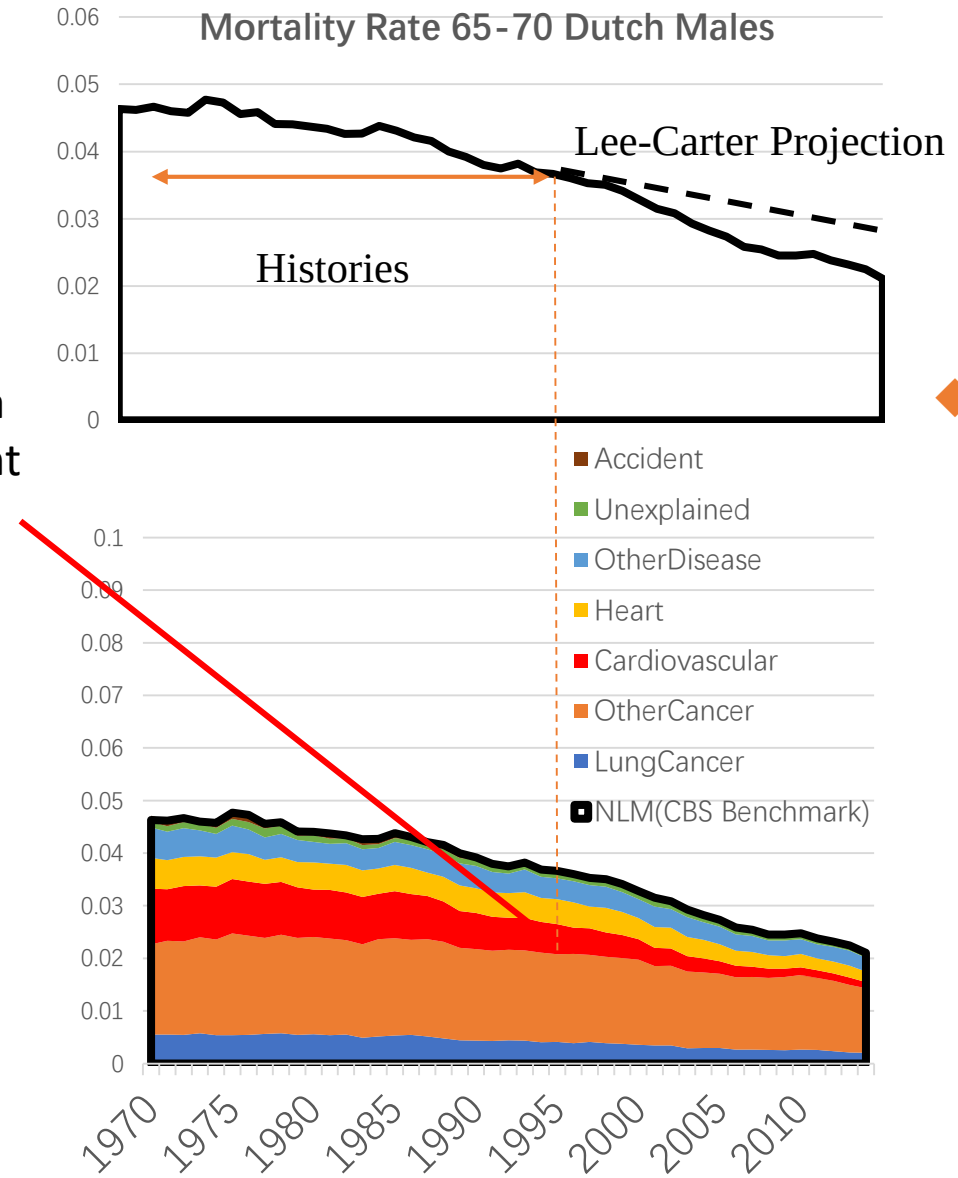
(6) Mortality Implications

(7) Next steps: Peterson Bounds

(8) Main Takeaways

Why Causes of Death(CoD) Model?

All-cause model fails to capture a substantial mortality improvement in cardiovascular mortality(CVD)



- Causes of death models can monitor the mortality improvement in different diseases and account for potential medical advances for a certain diseases.

Problems of Causes of Death Mortality Studies

Inferior cause-specific mortality data (Tabeau et.al 1999)

- Inconsistent International Code of Diseases(ICD)
- Few countries have long histories of cause specific mortality data

Pessimism of aggregation (Wilmoth 1995)

- If we aggregate the projections of each cause of death, the all-cause mortality projection is dominated by those causes that are decreasing most slowly or that are increasing.

Complex dependence structure (Carriere 1994)

- Causes of death that are exposed to same risk factors, are correlated with each other, e.g. Cancer and CVD due to smoking
- Such dependence structure is non-identifiable from the observed data (Tsiatis 1975), i.e. additional assumptions are needed

Our Contribution to Causes of Death Mortality Studies

- Use Access-Version WHO Database For NL, BE, FR from 1979-2013
  Official coded by WHO, male and female

◆CoDLi-Lee Model and nestedCoD Li-Lee Model

➢ Cope with pessimism and dependence problem by

(1) modelling the convergence between similar countries

(2) modelling the convergence between cancer and CVD

➢ CoDLi-Lee features (1), nestedCoDLi-Lee features (1) and (2)

- More tractable: Li-Lee framework, similar in-sample, better out-of-sample performance

◆Non-parametric Peterson Bounds expressed in crude mortality rate

Access Version WHO Data

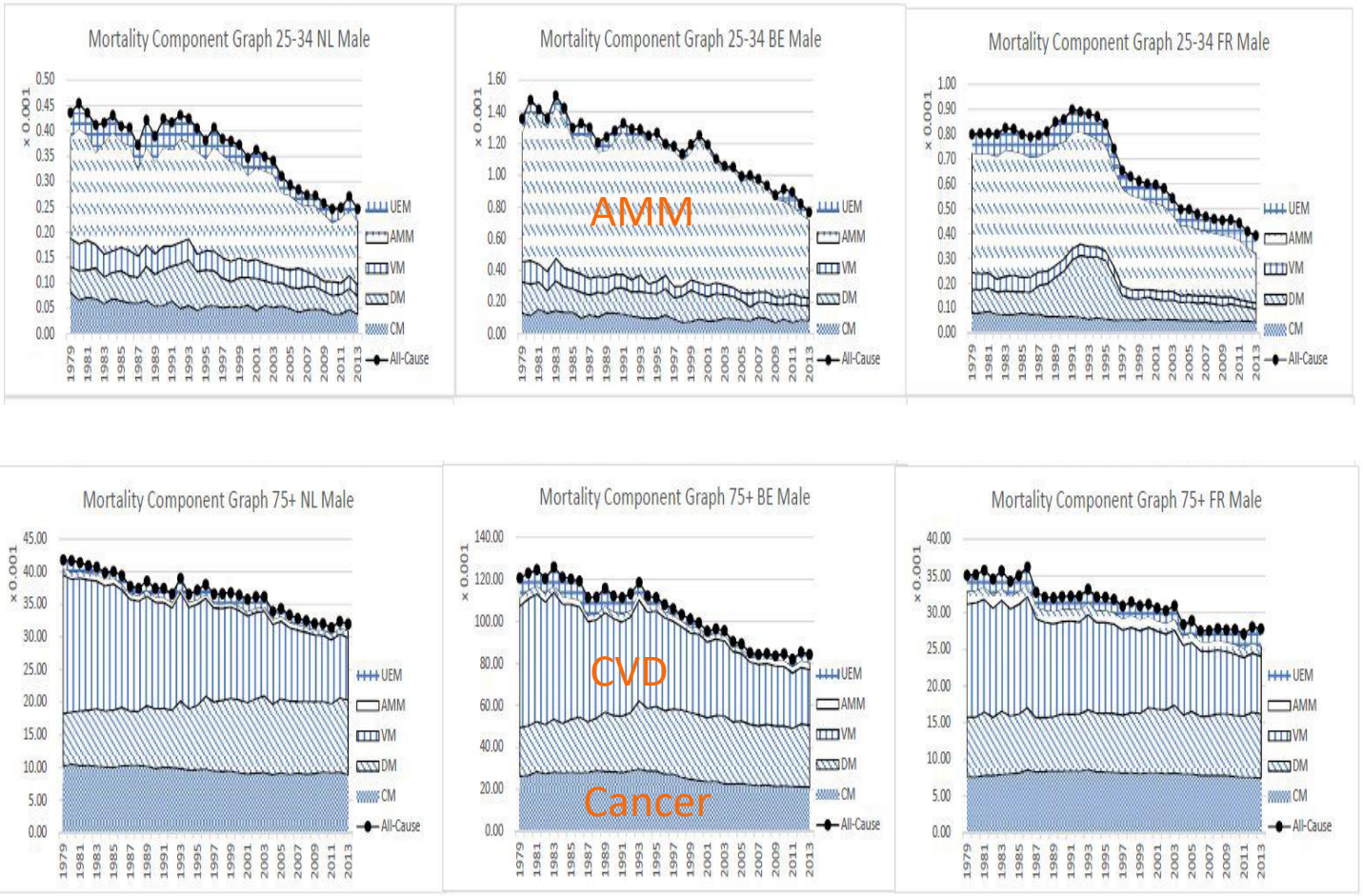
For NL, BE, FR, from 1979-2013, age group 25-35,35-55,55-75,75+

- Featured for user friendly UI and easy-to-export age-period table manner mortality data by age, year, cause, sex and country http://www.who.int/healthinfo/mortality_data/en/

Group the causes of death in 5 main categories

Abbreviation	1979-2013 Male
CM	Cancer
VM	Vascular Diseases(CVD)
DM	Other Diseases
AMM	Accidents and Murders
UEM	Unexplained

Access Version WHO Data: Mortality Component Graph (MCG)



- Accidents and Murders are more important CoDs in the young
- Cancer and CVD are more important CoDs in the senior
- CVD mortality improves fast in all three countries
- Cancer mortality improves slower than CVD

Assumptions

Assumption 1: Cause-specific International Coherence

- Among a coherent group of similar countries, e.g., NL, BE, and FR, we assume the cause-specific mortality in these countries will converge to the same common trend in the long run, while maintaining their individual trends in the short run.

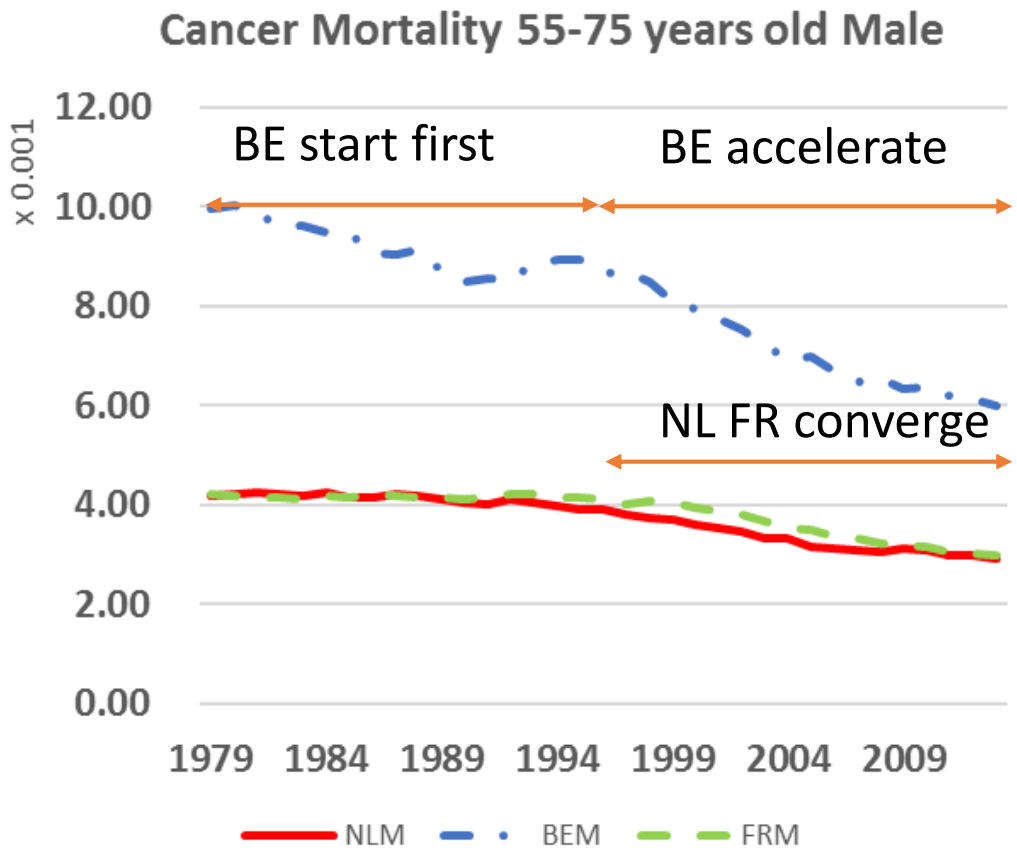
- Related literature: among developed countries, cancer (Jemal et al. 2010), cardiovascular (Vallin and Mesl´e 2004), and infectious disease, etc. (Omran 1998).

- Empirical arguments: the quick cross-border exchanges of medical advances in a certain disease are easier to be identified

Assumptions

Assumption 1: Cause-specific International Coherence

- Observation:



Assumptions

Assumption 2: Cancer-Cardiovascular(CVD) Convergence

- Cancer mortality and cardiovascular(CVD) mortality will converge to the same common trend in the long run, while maintain their individual trends in the short run. It is one possible form of Cancer-CVD dependence structure.

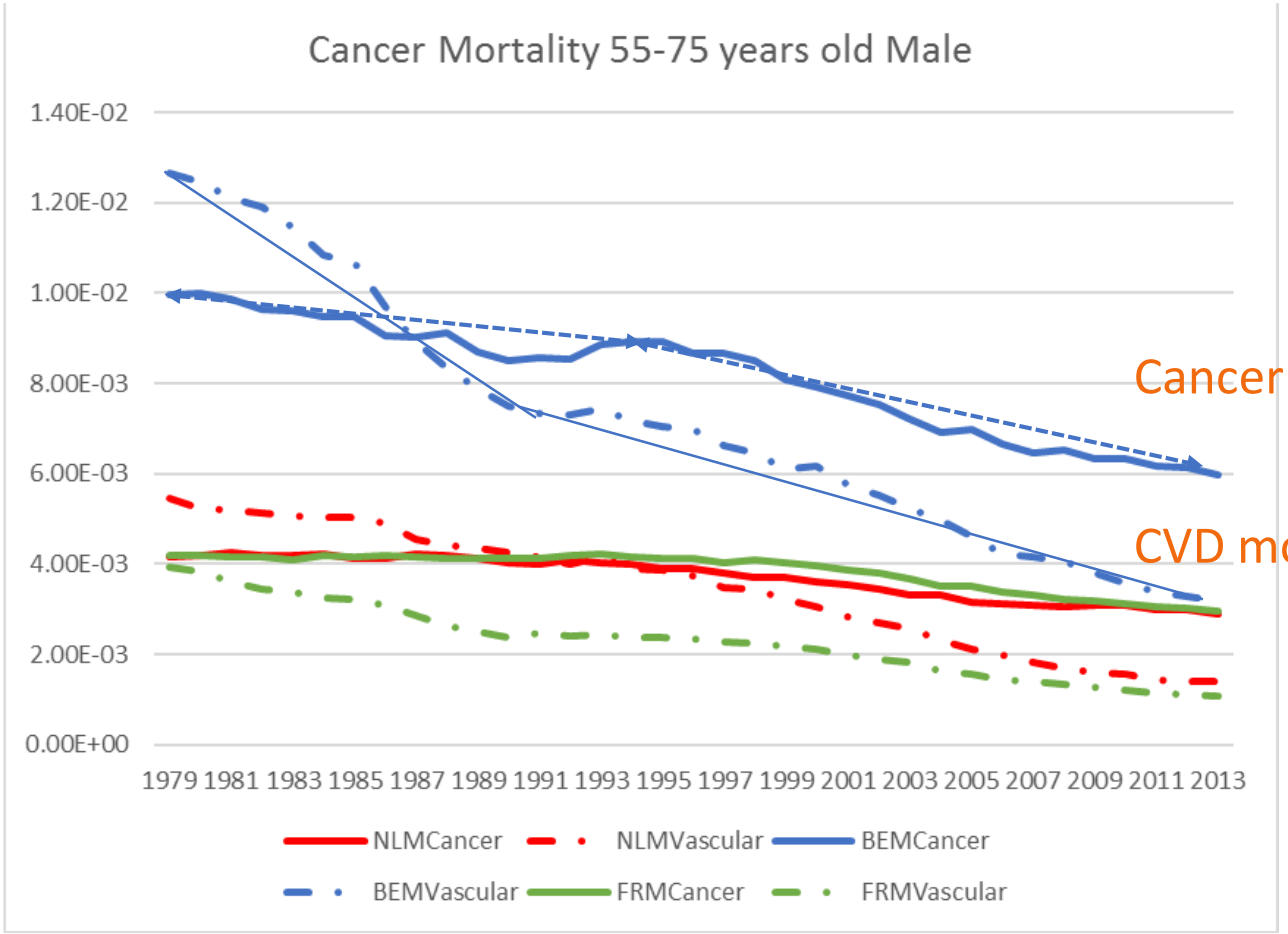
- Related literature: gap between cancer and CVD closed since 1970s (Feinleib 1984). Net(true) cancer mortality improvement is comparable to the one of CVD (Honore et.al, 2006)

- Empirical arguments: cancer and CVD could share some similar medical treatments, e.g., nano-capsule

Assumptions

◆Assumption 2: Cancer-Cardiovascular(CVD) Convergence

➢ Observation in Data:



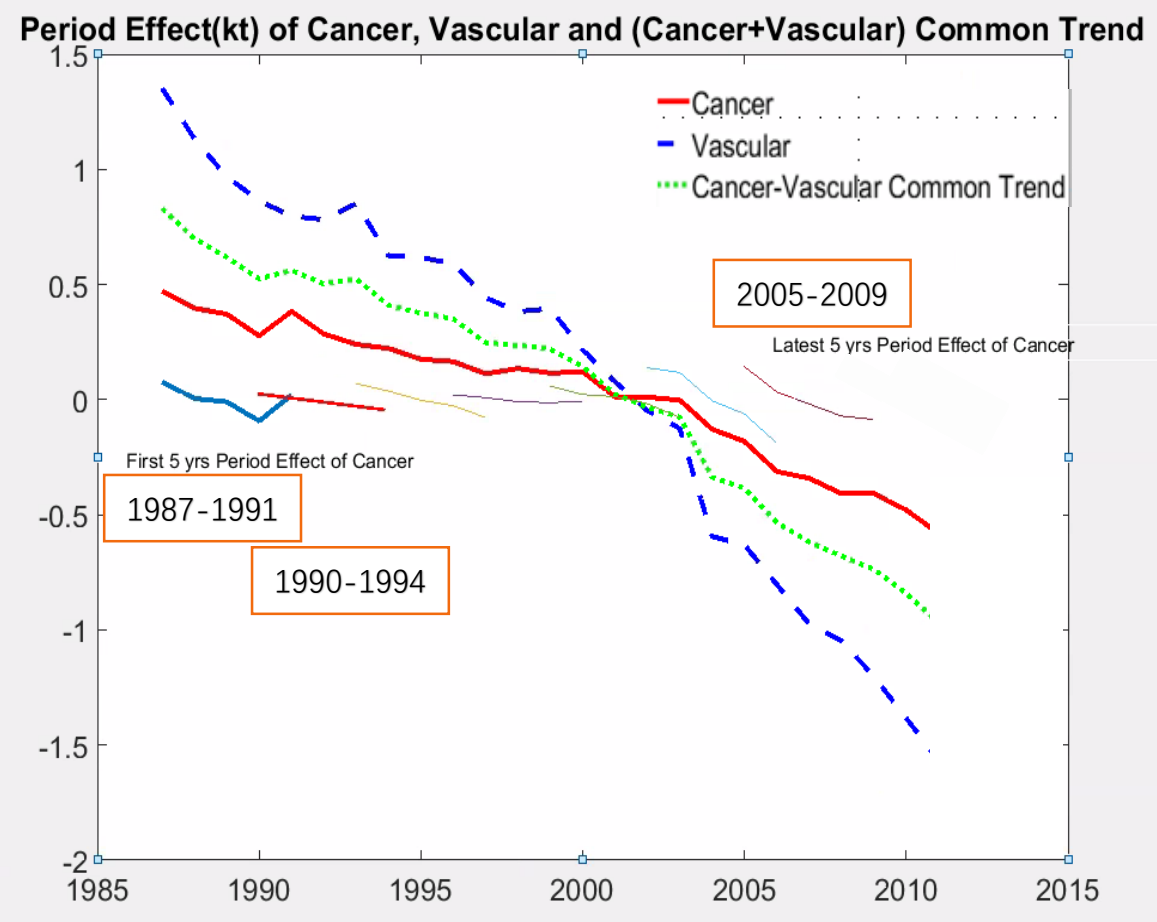
Cancer mortality decreases faster

CVD mortality decreases slower

Assumptions

Assumption 2: Cancer-Cardiovascular(CVD) Convergence

Observation in period effect(kt):

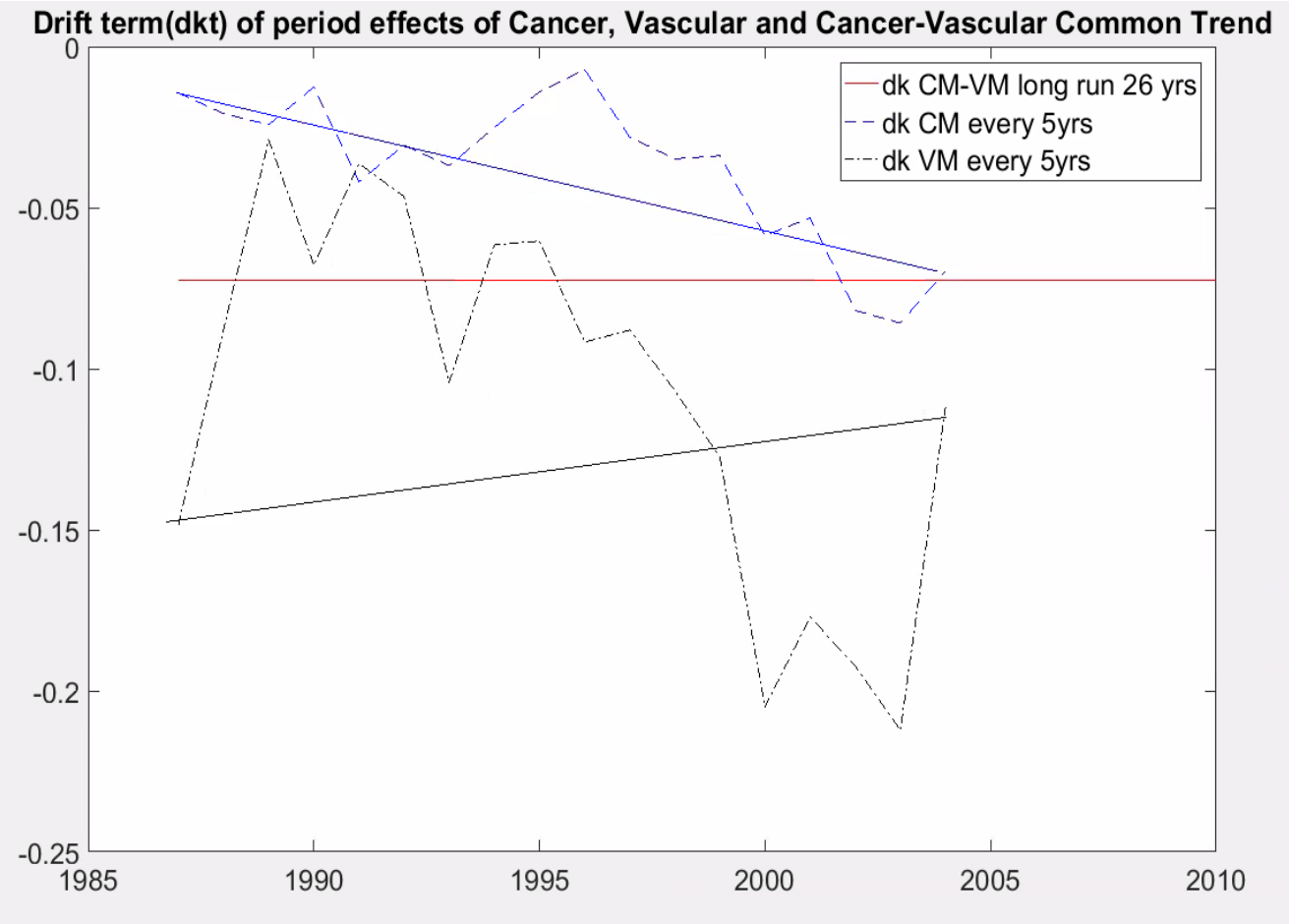


- We apply Lee-Carter model to obtain the kt of total mortality of cancer, vascular, and (cancer + vascular) in three countries.
- kt of cancer is decreasing faster and becoming parallel to the common trend
- Long-run kt use all mortality histories, short-run kt use every 5 years to capture latest development

Assumptions

Assumption 2: Cancer-Cardiovascular(CVD) Convergence

Observation in the drift term of period effect(kt):



- $k_t^{CM-VM} = d_0^{CM-VM} + k_{t-1}^{CM-VM} + u_t^{CM-VM}$ 26 years histories
- $k_t^{CM} = d_0^{CM} + k_{t-1}^{CM} + u_t^{CM}$, every 5 years
- Drift terms of kt (improvement) of cancer and vascular are converging to the long-run drift term of (cancer+vascular)
- Although the drift term of kt of vascular is quite volatile, it fluctuates around the long-term drift term

Models

Definitions

- Cause-specific mortality

$$m_{x,t}^{s,v} = \frac{D_{x,t}^{s,v}}{E_{x,t}^{v}}$$

$$v \in \{NL, BE, FR\}, s \in \{CM, DM, VM, AMM, UEM\}$$

- All-cause mortality

$$m_{x,t}^{v} = \frac{\sum_s D_{x,t}^{s,v}}{E_{x,t}^{v}}$$

$D_{x,t}^{s,v}$ is the number of deaths of cause s in country v for the age group x at time t. $E_{x,t}^{v}$ is the number of all-cause exposure in country v for the age group x at time t

All-Cause Benchmark Models

- Lee-Carter model (LC) applies for all-cause mortality for each country separately see (Lee-Carter 1992 JASA)

$$\ln(m_{x,t}^{v}) = a_x^v + B_x^v K_t^v + \varepsilon_{x,t}^v$$

$$K_t^v = B_0^v + K_{t-1}^v + e_t^v$$

- Li-Lee model (Li-Lee) applies for all-cause mortality for three countries see (Li and Lee 2005, Demography)

$$\ln(m_{x,t}^{v}) = a_x^v + B_x K_t + b_x^v k_t^v + \varepsilon_{x,t}^v$$

$$K_t = B_0 + K_{t-1} + e_t$$

$$k_t^v = \beta_0^v + \beta_1^v k_{t-1}^v + \mathrm{u_t^v}$$

Models

CoDLi-Lee model and nestedCoDLi-Lee model

- **CoDLi-Lee:** (1)applying Li-Lee model to each cause specific mortality across three countries (2) obtaining all-cause mortality projections by aggregating up cause specific mortality projections. Only take into account the convergence between similar countries

$$\ln(m_{x,t}^{s,v}) = a_x^{s,v} + B_x^s K_t^s + b_x^{s,v} k_t^{s,v} + \varepsilon_{x,t}^{s,v}$$

$$K_t^s = B_0^s + K_{t-1}^s + e_t^s$$

$$k_t^{s,v} = \beta_0^{s,v} + \beta_1^{s,v} k_{t-1}^{s,v} + u_{t-1}^{s,v}$$

$$m_{x,t}^v = \sum_s m_{x,t}^{s,v}$$

- **nestedCoDLi-Lee**. (1)Modeling cancer and CVD via Li-Lee jointly. (2) applying CoDLi-Lee standard models to other causes(DM,AMM,UEM). Take into account both the convergence between similar countries and the convergence between cancer and CVD

$$m_{x,t}^{CM\&VM} = \frac{\sum_v (D_{x,t}^{CM,v} + D_{x,t}^{VM,v})}{\sum_v E_{x,t}^v} \quad v \in (NL, BE, FR)$$

$$\ln(m_{x,t}^{CM\&VM}) = \alpha_x^{CM\&VM} + B_x^{CM\&VM} K_t^{CM\&VM} + \varepsilon_{x,t}^{CM\&VM}$$

$$\ln(m_{x,t}^{CM,v}) = a_x^{CM,v} + B_x^{CM\&VM} K_t^{CM\&VM} + b_x^{CM,v} k_t^{CM,v} + \varepsilon_{x,t}^{CM,v}$$

$$K_t^{CM\&VM} = B_0^{CM\&VM} + K_{t-1}^{CM\&VM} + e_t^{e_t^s}$$

$$k_t^{CM,v} = \beta_0^{CM,v} + \beta_1^{CM,v} k_{t-1}^{CM,v} + u_{t-1}^{CM,v}$$

$$m_{x,t}^v = \sum_{s'} m_{x,t}^{s',v} + m_{x,t}^{CM,v} + m_{x,t}^{VM,v}$$

$$s' \in \{CM, AMM, UEM\}$$

- LHS equations are Similar for VM
- Apply CoDLi-Lee standard models to DM,AMM,UEM

Model Summary

	Cause of Death Info	International Convergence(Assumption 1)	Cancer-CVD Convergence(Assumption 2)
Lee-Carter	NO	NO	NO
Li-Lee	NO	YES	NO
CoDLi-Lee	YES	YES	NO
NestedCoDLi-Lee	YES	YES	YES

- Lee-Carter model and Li-Lee model are all-cause mortality models. The Li-Lee model accounts for all-cause mortality international coherence, similar as Assumption 1.

- CoDLi-Lee model and nestedCoDLi-Lee model are causes of death mortality models. The CoDLi-Lee model accounts for Assumption 1. The nestedCoDLi-Lee model accounts for Assumption 1&2

First Part: Cause-specific performance

Cause-specific In-sample Fit

Country	Explanation Ratios											
	Cancer			Vascular			Other Disease		Accident & Murders		Unexplained	
	CoDLC	CoDLi-Lee	nestedCoDLi-Lee	CoDLC	CoDLi-Lee	nestedCoDLi-Lee	CoDLC	CoDLi-Lee	CoDLC	CoDLi-Lee	CoDLC	CoDLi-Lee
Netherlands	0.92	0.87	0.86	0.94	0.96	0.94	0.55	0.63	0.72	0.59	0.60	0.64
Belgium	0.79	0.80	0.88	0.92	0.95	0.91	0.66	0.56	0.58	0.63	0.94	0.93
France	0.88	0.93	0.81	0.95	0.97	0.95	0.96	0.96	0.97	0.97	0.65	0.84

Explanation ratios of the different models 1979-2013 male population

Explanation ratios, see Li and Lee(2005)

- Models perform more or less the same. All models work poorly in the cause with a relative volatile historical pattern, but work well for the causes with a relative smooth historical pattern

First Part: Cause-specific performance

◆ Cause-specific Out-of-Sample Performance

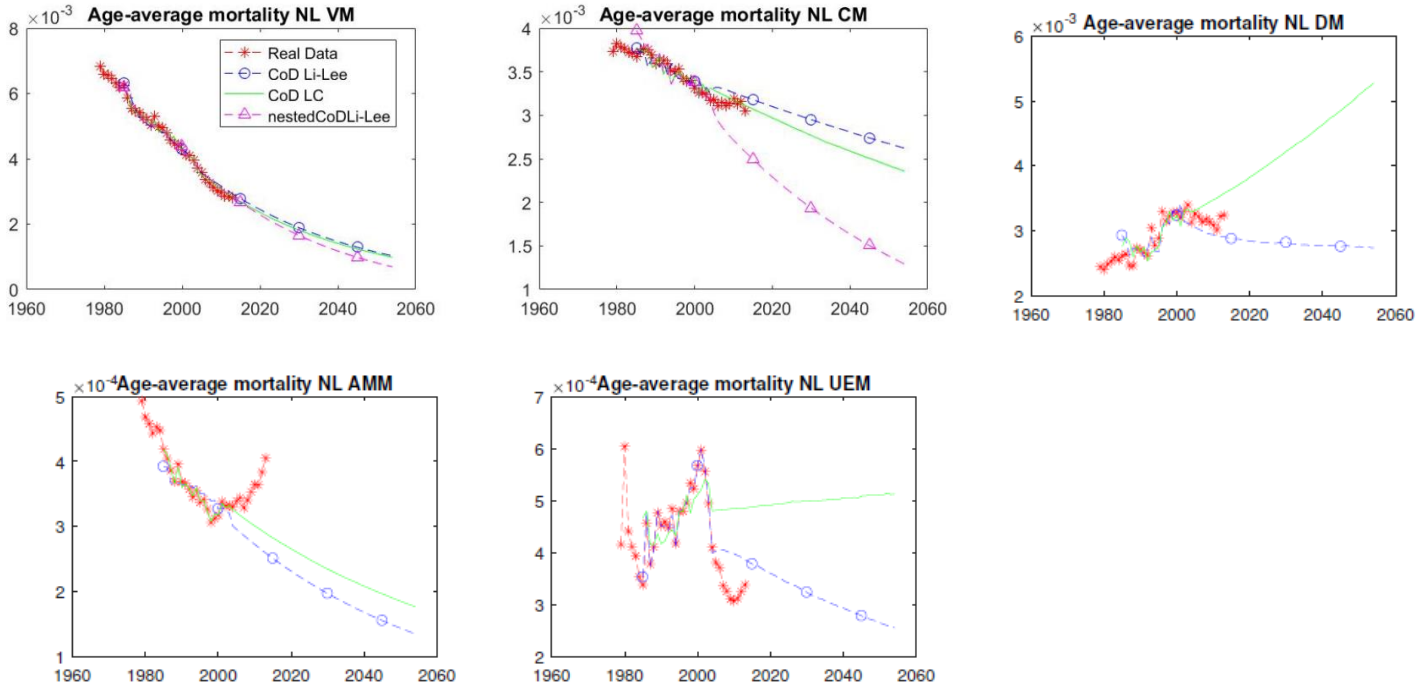


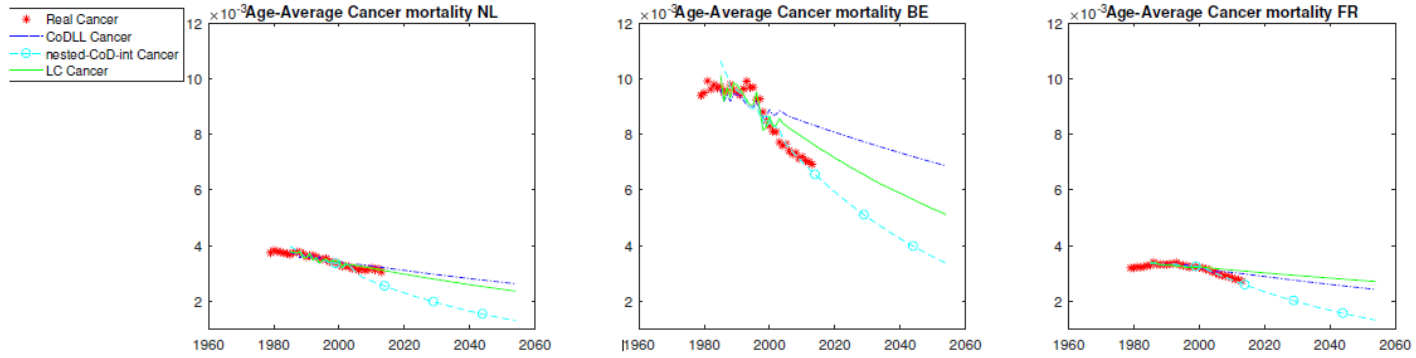
Figure 2: Age-Average Cause-specific Mortality of Dutch Male

- CoDLi-Lee model that accounts for the international coherence, perform much better than CoDLC model(directly apply LC to cause-specific mortality), because CoDLi-Lee model could filter out the country-specific turbulence in some causes, like Other Diseases that contains influenza-like-diseases.

First Part: Cause-specific performance

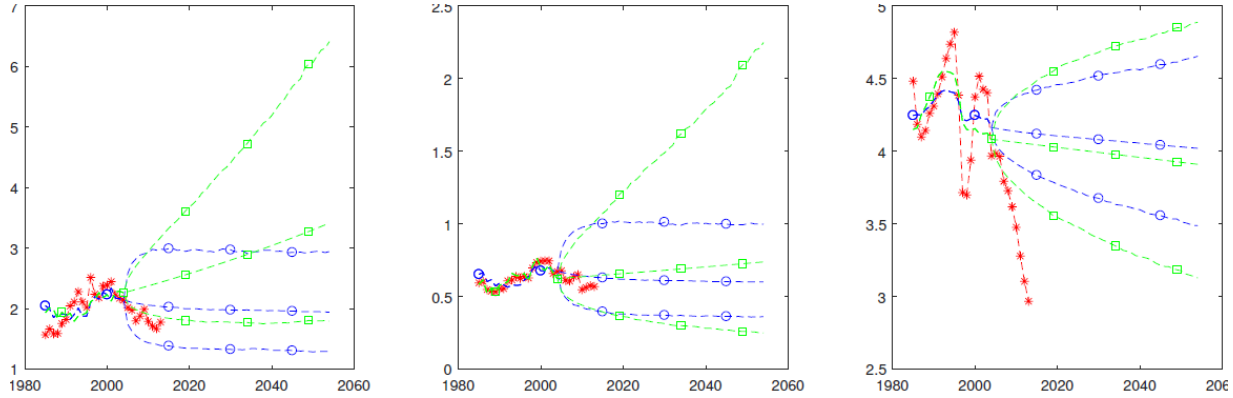
◆ Out-of-Sample Performance

➢ Cancer of All Three Countries



- Cancer-CVD convergence: nestedCoDLi-Lee(circle marker) captures the realizations of cancer mortality better

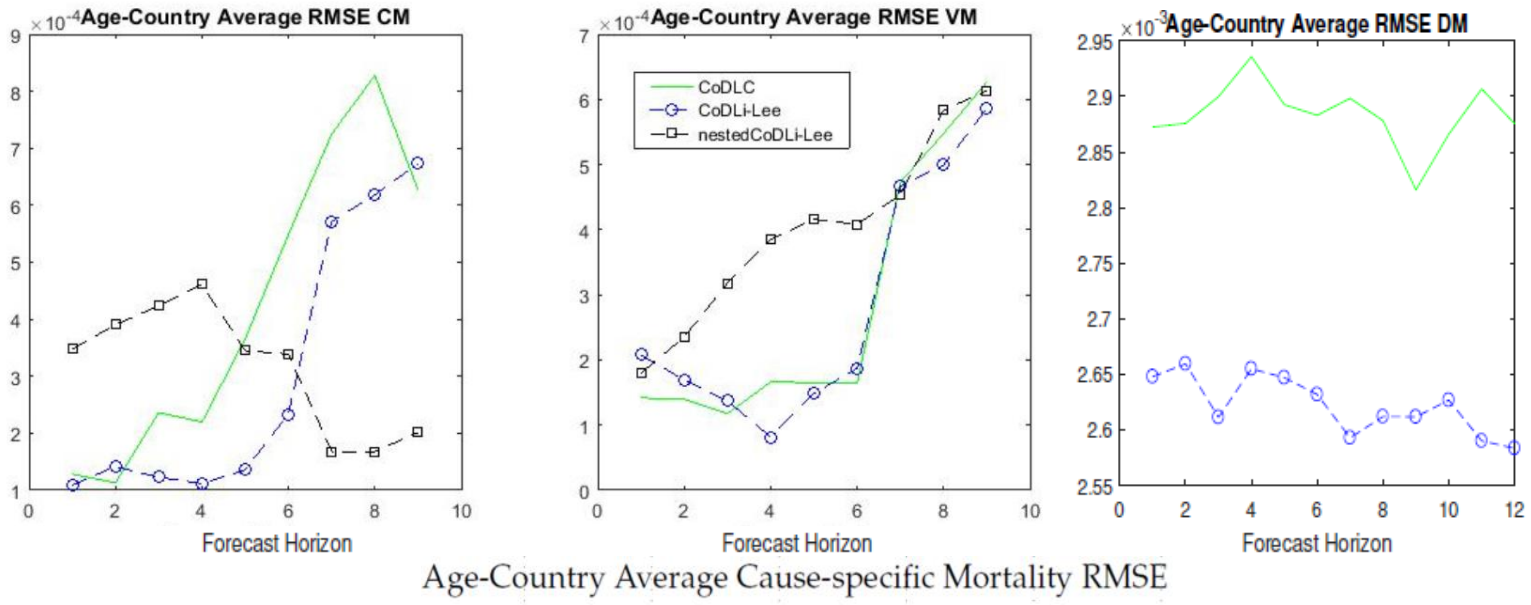
➢ Other Diseases of All Three Countries



- International Convergence: CoDLi-Lee(circle marker) is more robust to the jumps (some outbreaks of influenza) mortality within one country

First Part: Cause-specific performance

Out-of-Sample



Age-Country Average Cause-specific Mortality RMSE

Data period: 1979-2000 + forecast horizon(1 to 13) e.g., it means if forecast horizon is equal to 1, we use data 1979-2012 to forecast 1 period ahead and compare the forecast with the realization of 2013

- nestedCoDLi-Lee model performs much better in long run in cancer !
- CoDLi-Lee model performs much better in all horizon in Other Disease that has a volatile mortality pattern

Second Part: All-cause performance

In-sample Fit

Explanation Ratios	LC model	standard Li-Lee model (common factor)	standard Li-Lee model (augmented)	codLi-Lee model	nested codLi-Lee model
Netherlands	0.898	0.887	0.933	0.912	0.914
Belgium	0.899	0.838	0.918	0.894	0.866
France	0.946	0.920	0.986	0.989	0.977

Explanation ratios of the different models 1979-2013 male population

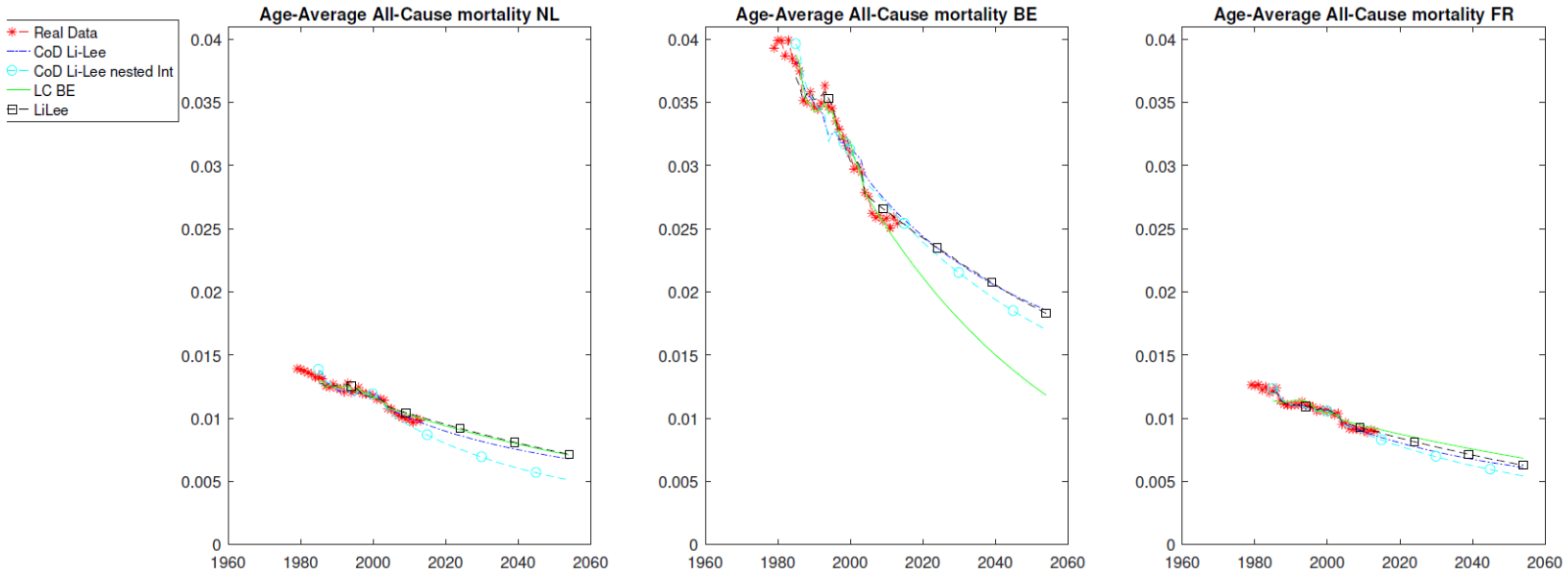
Explanation ratios, see Li and Lee(2005)

- Models perform more or less the same, although CoDLi-Lee models (both standard and nested) are subject to slightly higher noise when aggregating the cause specific mortality to for all-cause mortality.

Second Part: All-cause performance

◆Out-of-sample

➢ All-cause mortality projections



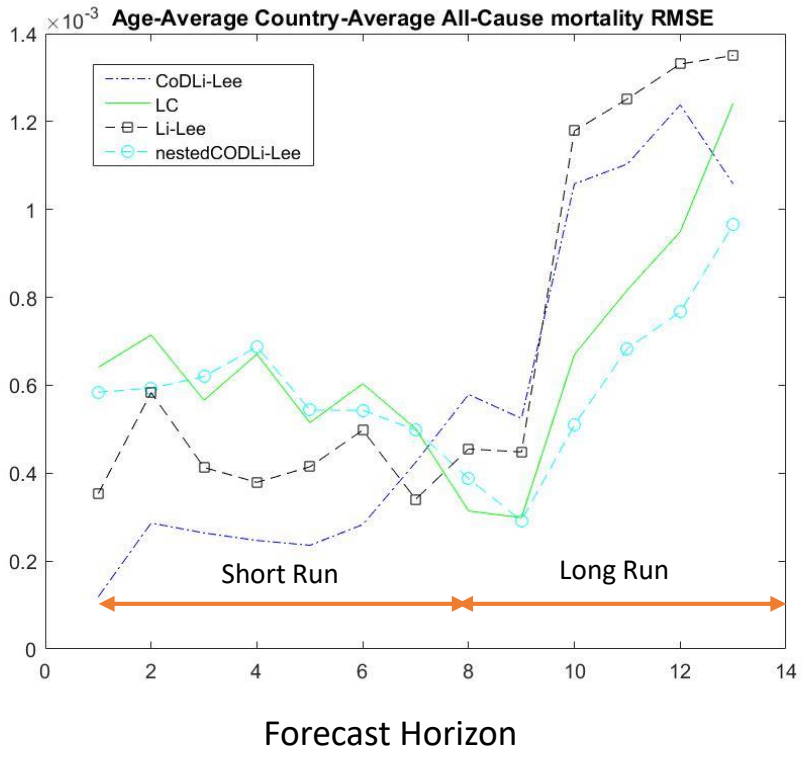
- nestedCoDLi-Lee is not always pessimistic, comparing to all-cause multi-population Li-Lee model

Second Part: All-cause performance

◆Out-of-sample

➢ Root Mean Square Error(RMSE) of All-cause mortality projections

RMSE



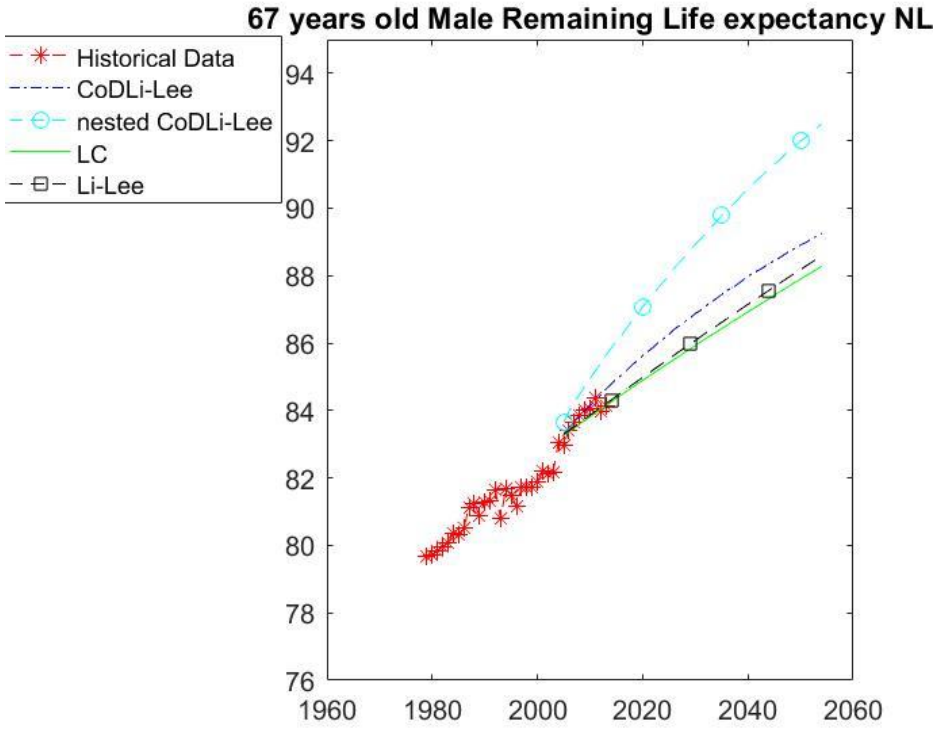
Data period: 1979-2000 + forecast horizon(1 to 13) e.g., it means if forecast horizon is equal to 1, we use data 1979-2012 to forecast 1 period ahead and compare the forecast with the realization of 2013

- In long run, nested CoDLi-Lee model outperforms the other models.

- Intuitions: Cancer and CVD will not converge immediately but will converge in long run, (1) in long run as fewer people die from CVD, less relative exposure can be shifted from CVD to Cancer. (2) more focus of media and more efforts of medical researches are shifted from CVD to cancer given enough time.

Mortality Implications

Period Life Expectancy Projections



- For NL, when taking into account cancer-vascular convergence and international coherence (nestedCoDLi-Lee), the remaining life expectancy of a 67-years-old male can gain 4 years more in 2050.

Mortality Implications

◆Old Age Pension Pricing Impacts for Netherlands

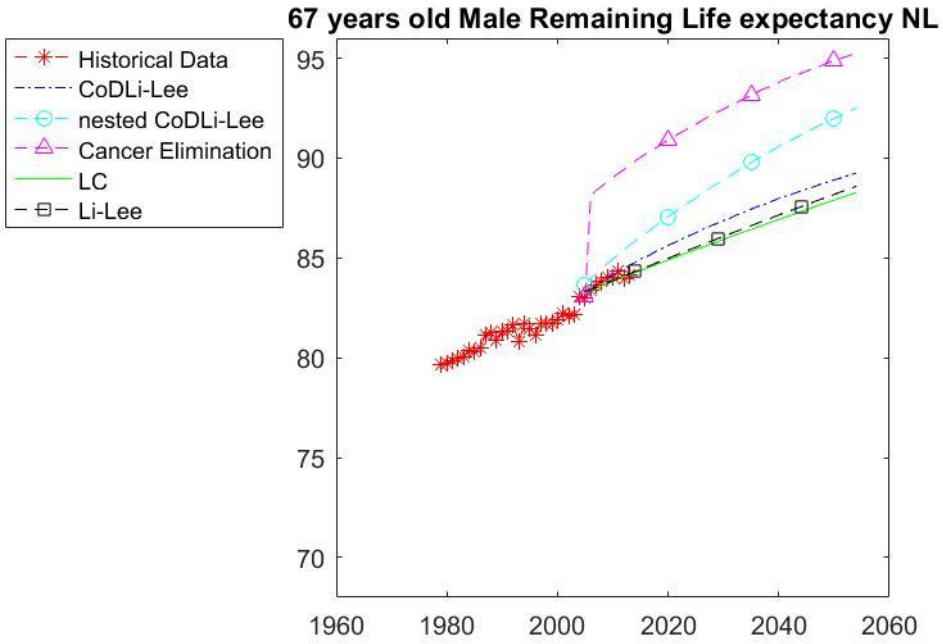
Old Age Pension Capital Reserve (Outlook 2015-2060) 1% Discount Rate				
Age	CBS(Lee-Carter)	Li-Lee	CoDLi-Lee	nestedCoDLi-Lee
45	€ 13,813.82	99.50%	101.44%	105.79%
65	€ 16,240.23	100.24%	102.77%	106.89%
75	€ 11,301.80	100.93%	104.59%	108.39%

% of CBS capital reserve
Statistics Netherlands(CBS)

- For NL, pension funds need to increase Old Age Pension Capital Reserve up to about 8% for the 75-years-old male pensioners, to prepare for potential cancer-vascular convergence and international coherence

Mortality Implications

The Cancer Elimination Scenario



Old Age Pension Capital Reserve(Outlook 2015-2060) 1% Discount Rate					
Age	CBS(Lee-Carter)	Li-Lee	CoDLi-Lee	nestedCoDLi-Lee	Cancer Elimination
45	€ 13,813.82	99.50%	101.44%	105.79%	116.99%
65	€ 16,240.23	100.24%	102.77%	106.89%	117.19%
75	€ 11,301.80	100.93%	104.59%	108.39%	120.42%

% of CBS capital reserve

- If cancer is eliminated in the future, 67-year-old-male will gain more than 10 years in 2050 and pension funds need to prepare 20% more capital reserve for 75 year old participant

Extension: Peterson Bounds

- Motivation: Assumptions of dependence structure between cancer and vascular mortality are risky

- Focusing on cancer and vascular, we propose non-parametric bounds of net(true) cancer mortality, which contain all possible dependence structures between cancer and vascular, i.e., no additional assumptions -- Peterson Bounds(Peterson, 1976)

- Peterson Bounds of net cancer mortality (1) are expressed in central mortality rate ($m^S_{x,t}$) (2) can account for uncertainty that originates from the potential dependence between cancer and vascular , (3) evaluate the potential best estimates of net (true) cancer mortality within the Peterson Bounds

Extension: Peterson Bounds

Given the Peterson Bounds in Competing Risk Framework (Peterson, 1976):

$$S_{CM}^{crude}[t] + S_{VM}^{crude}[t] \leqslant S_{CM}^{net}(t) = Pr[T_{CM} \geqslant t] \leqslant S_{CM}^{crude}[t] + (1 - p_{CM})$$

Where

$$j \in \{CM, VM\}$$

$$S_j^{crude}(t) = \mathbb{P}(T_j > t, min(T_{CM}, T_{VM}) = T_j)$$

$$S_j^{net}(t) = \mathbb{P}(T_j > t)$$

$$p_{CM} = Pr(T_{CM} = min_{j \in \{CM,VM\}} T_j)$$

We approximate the bounds in terms of $m_{x,t}^{s,v}$, the observed cause-specific mortality data

$$\frac{m_{x,t}^{CM,crude}}{m_{x,t}^{C\&V,crude}} m_{x,t}^{CM,crude} \leqslant m_{CMx,t}^{net} \leqslant m_{CM\ x,t}^{crude} + m_{VM\ x,t}^{crude}$$

where

No additional assumption on the cancer-vascular dependence structure!

$$m_{c,t}^{CM,crude} + m_{c,t}^{VM,crude} = m_{c,t}^{C\&V,crude}$$

Extension: Peterson Bounds

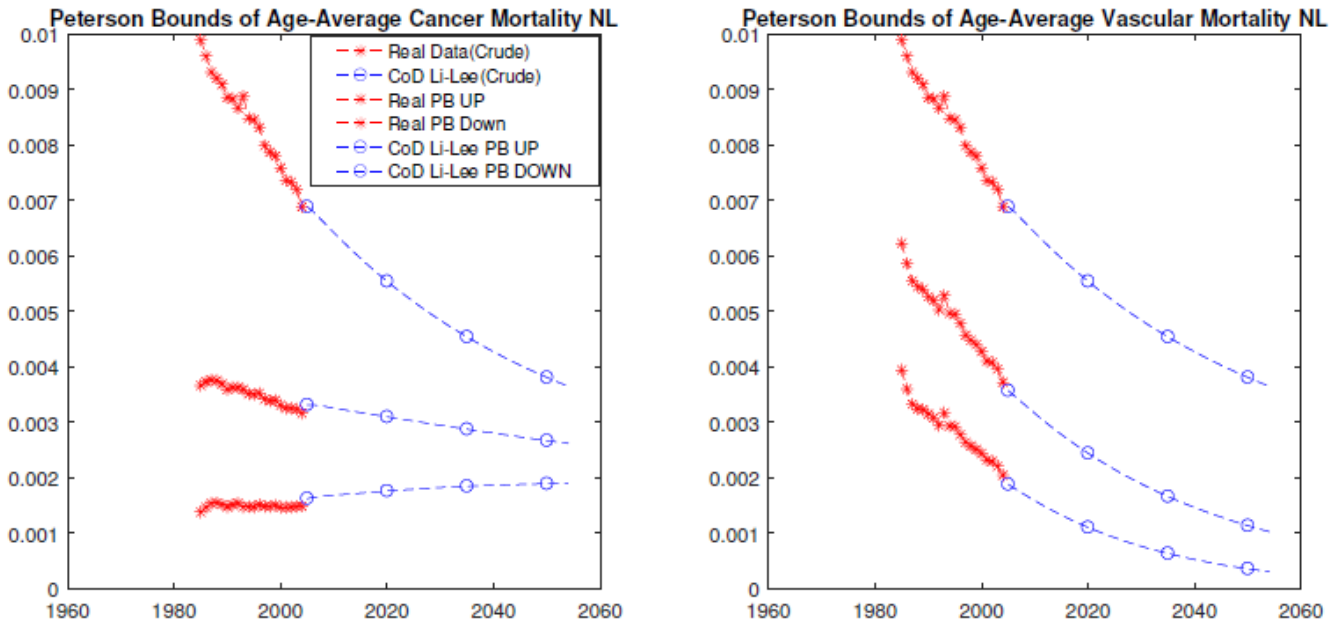


Figure 5: Peterson Bounds of Age-Average Cancer Mortality of Dutch Male

- The uncertainty that only originates from the potential dependence structure between cancer and vascular mortality is not negligible.
- Such uncertainty of cancer mortality becomes smaller as CVD mortality become less.
- Next steps:……

Main Takeaways

- CoDLi-Lee that incorporates international convergence between similar countries(Assumption 1, A1), produces comparable in-sample fit and out-of-sample forecasts in short run
- nestedCoDLi-Lee that incorporates international convergence between similar countries (A1) and the convergence between cancer and CVD (A2), produces comparable in-sample fit and better out-of-sample forecasts in long run
- NestedCoDLi-Lee model suggests 8% more capital reserve for a 75-year-old-male pensioner so as to account for the potential mortality improvement of cancer
- Next step: Non-parametric Peterson Bounds to avoid dependence assumptions like nestedCoDLi-Lee model, to assess the uncertainty that originates from the dependence structure and potential alternatives of best estimates of net(true) cause-specific mortality.

Additions: Assumptions

How do assumptions of the convergence solve the pessimism?

Why Pessimism ?

- Wilmoth (1995) assumes the cause specific mortality are independent both between causes and between similar countries, slow-improving cancer mortality of one country will be maintain its slow pace forever, leading to pessimism

How to solve?

- CVD that improve much faster than cancer. CVD and Cancer are exposed to same risk factors. The convergence between cancer and CVD based on the evidence above, leading cancer to improve faster in long run.

Additions: Assumptions

◆How do assumptions of the convergence deal with the dependence?

- Only consider the dependence between cancer and CVD, as Honore 2006 and many other literature

➢ Complex dependence originates in the competing nature between causes

- The observed cancer mortality ≠ The true cancer mortality because of cancer-vascular subsititution.Since CVD improve faster than cancer, more relative risk exposures are shifted from CVD to cancer.
- Such dependence structure is not identifiable (Tsiatis 1975)

➢ The sum of cancer and vascular mortality is net of such a cancer-vascular substitution

- We derive the long-run cancer-vascular common trend from the cancer-vascular sum.

➢ Cancer-Vascular convergence means “Observed = true” in long run

- Long-run observed(true) cancer mortality converge to the common trend

Thank you !

Proof of Approximation of Peterson Bounds

Given the Peterson Bounds of crude cause-specific mortality in Peterson (1976)

$$S_{CM}^{crude}[t] + S_{VM}^{crude}[t] \leqslant S_{CM}^{net}(t) = Pr[T_{CM} \geqslant t] \leqslant S_{CM}^{crude}[t] + (1 - p_{CM}) \tag{30}$$

where

$$p_{CM} = Pr(T_{CM} = min_{j\in\{CM,VM\}} T_j) \tag{31}$$

Let $t = 1$ and make the following approximation for each cohort:

(1) $S_{CM}^{net}(t) \approx \exp(-m_{c,t}^{CM,net})$ with $t = 1$

(2)$S_{CM}^{crude}(t) \approx \exp(-m_{c,t}^{CM,crude})\frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude}+m_{c,t}^{VM,crude}}$, meaning the crude survival probability of cancer conditions on the event that observed cause of death of the cohort is cancer

(3) $S_{C\&V}(t) = S_{CM}^{Crude}[t] + S_{VM}^{Crude}[t] = Pr(T_{CM} > t|T_{CM} < T_{VM}) + Pr(T_{VM} > t|T_{VM} < T_{CM}) = Prob(min(T_{CM}, T_{VM}) > t) \approx \exp(-(m_{c,t}^{CM,net} + m_{c,t}^{VM,net}))$, meaning the probability of cohort c to survive from cancer and vascular disease.

(4) $p_{CM} \approx \frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude}+m_{c,t}^{VM,crude}}$, meaning the probability of cohort c to die from cancer conditioning on only dying from cancer or vascular.

Taking the logs and multiplying by -1, the equation (30) becomes the following:

$$\begin{aligned} &-\log(\exp(-m_{CM\ c,t}^{crude})\frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude} + m_{c,t}^{VM,crude}} + (1 - \frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude} + m_{c,t}^{VM,crude}})) \leqslant m_{CM\,c,t}^{net} \\ &\leqslant -\log[\exp(-(m_{CM\ c,t}^{crude} + m_{VM\ c,t}^{crude})] \end{aligned} \tag{32}$$

The upper bound is straightforward: $m_{CM\ c,t}^{crude} + m_{VM\ c,t}^{crude}$. We focus on the lower bound $-\log(\exp(-m_{CM\ c,t}^{crude})\frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude}+m_{c,t}^{VM,crude}} + (1 - \frac{m_{c,t}^{CM,crude}}{m_{c,t}^{CM,crude}+m_{c,t}^{VM,crude}}))$.

Let $m_{c,t}^{CM,crude} + m_{c,t}^{VM,crude} = m_{c,t}^{C\&V,crude}$, the lower bound LHS of equation 34 can be expressed as the following:

$$\begin{aligned} LHS &= \log(m_{c,t}^{C\&V,crude}) - \log(m_{c,t}^{C\&V,crude} + (\exp(-m_{CM\ c,t}^{crude}) - 1)m_{c,t}^{CM,crude}) \\ &\approx \log(m_{c,t}^{C\&V,crude}) - (\log(m_{c,t}^{C\&V,crude}) + \frac{1}{m_{c,t}^{C\&V,crude}}(\exp(-m_{CM\ c,t}^{crude}) - 1)m_{CM\ c,t}^{crude}) \\ &= \frac{m_{c,t}^{CM,crude}}{m_{c,t}^{C\&V,crude}}(1 - \exp(-m_{c,t}^{CM,crude})) \approx \frac{m_{c,t}^{CM,crude}}{m_{c,t}^{C\&V,crude}}m_{c,t}^{CM,crude} \end{aligned} \tag{33}$$

For the second part of equation (33), we apply Taylor series approximation around $m_{c,t}^{CM,crude} = 0$ in the first approximation. In the second approximation, we replace $1 - \exp(-m_{c,t}^{CM,crude})$ by $m_{c,t}^{CM,crude}$. Given $m_{c,t}^{CM,crude}$ is normally 0.01-0.02, both approximations are reasonable.

In sum, the Peterson bounds in equation (30) can be approximated by the following:

$$\frac{m_{c,t}^{CM,crude}}{m_{c,t}^{C\&V,crude}}m_{c,t}^{CM,crude} \leqslant m_{CM\,c,t}^{net} \leqslant m_{CM\ c,t}^{crude} + m_{VM\ c,t}^{crude} \tag{34}$$

After that, we can transform the cohort mortality to age-period mortality by the following rule.

$$m_{j\ c,t}^{crude} = m_{CM\ x,t}^{crude}, x = t - c \tag{35}$$

In sum, we obtain final Peterson Bound for cancer mortality rate

$$\frac{m_{x,t}^{CM,crude}}{m_{x,t}^{C\&V,crude}}m_{x,t}^{CM,crude} \leqslant m_{CM\,x,t}^{net} \leqslant m_{CM\ x,t}^{crude} + m_{VM\ x,t}^{crude} \tag{36}$$

where

$$m_{x,t}^{C\&V,crude} = m_{x,t}^{CM,crude} + m_{x,t}^{VM,crude} \tag{37}$$

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