System Dynamics Society

Fair allocation of COVID-19 vaccines:

A system dynamics model for sub-prioritization of socioeconomically vulnerable populations

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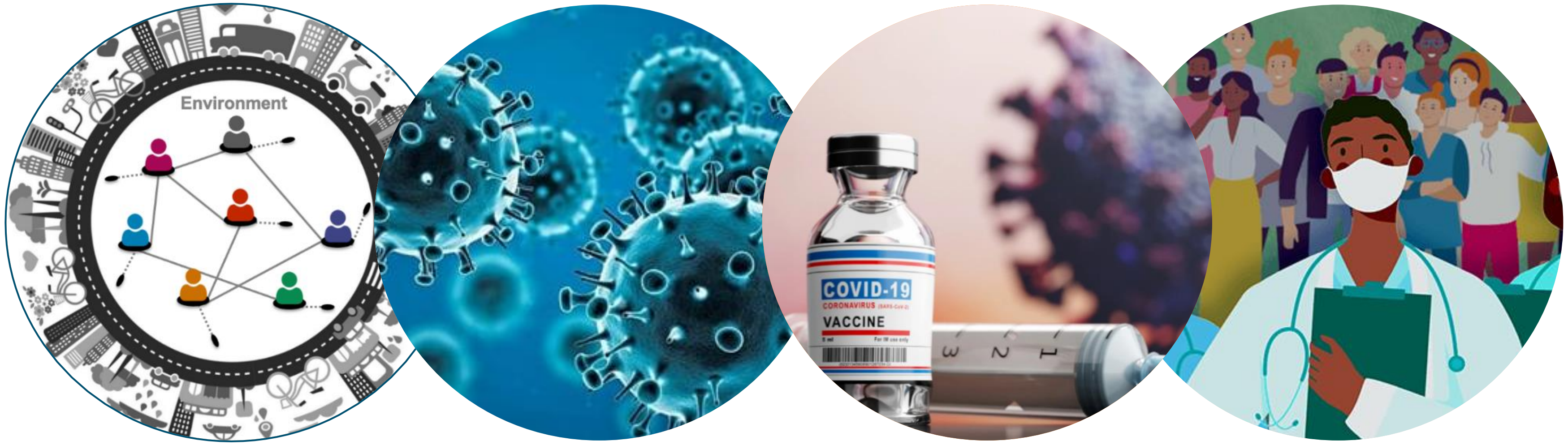

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Fair allocation of COVID-19 vaccines:

A system dynamics model for sub-prioritization of socioeconomically vulnerable populations

AGENDA

- Introduction
- Research question
- COVID-19 vaccine prioritization models
- Proposed strategy
- Methodology
- Data collection and validation
- Scenario analysis
- What-if analysis
- Conclusion

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INTRODUCTION

- Assessing health inequality has become crucial in health ethics during the pandemic [1].
- The pandemic highlighted the strong link between socioeconomic vulnerability and poorer health outcomes [2].
- England's vaccination guidelines are criticized as unfair. Political, economic, and social factors worsened health inequalities [3].
- Socioeconomically vulnerable individuals live in crowded areas with poor hygiene and depend on public transportation.
- Vaccine prioritization strategies focus only on health vulnerabilities, neglecting socioeconomic factors.
- To address health disparities, vaccination policies need to consider both medical and socio-economical vulnerabilities to ensure fairness.
- Addressing this issue is essential for fairer and more effective vaccine allocation in future pandemics.

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RESEARCH QUESTION

What is the impact of prioritizing <u>socioeconomically vulnerable people</u> (within age groups) on

a. **<u>fair vaccine allocation</u> and**

b. **the <u>overall COVID-19 mortality</u>?**

- **Socioeconomic vulnerability:** Vulnerable and non-vulnerable population percentages are defined according to the Index of Multiple Deprivation (IMD).
- **Fair vaccine allocation:** Outcome equity
  no health disparities between the burdens (=deaths) experienced by different population groups.
- **Overall COVID-19 mortality:** Total deaths
- **Case study:** England

VACCINE PRIORITIZATION MODELS

Why System Dynamics (SD)?

- **understanding how things change over time**
  epidemic curves, policy impact over time, long-term immunity trends, etc.
- **focusing on the feedback (loop) behavior of variables within the systems**
  vaccine uptake and herd immunity (+ feedback), death rates and public health measures (- feedback), etc.
- **dealing with complex systems**
  interacting demographics, public compliance, variant evolution, etc.
- **non-linearity and delay**
  infection-related delays (incubation, immunity loss), policy delays, non-linear epidemic spread, etc.

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VACCINE PRIORITIZATION MODELS

to compare different vaccine prioritization strategies based on two primary mechanisms:

(1) minimizing deaths

- seniors with comorbidities [5]
- seniors with another group with high contacts [6, 7]
- group with high contacts [8]
- essential workers [9, 10]
- group with high contacts with seniors (e.g., social carers) [11]

(2) minimizing cases:

- young and middle-aged [12, 13]
- young [14],
- young and children [6]
- essential workers [10, 15]
- individuals without antibodies(by serological testing)[16, 17]
- different geographical regions[18, 19]

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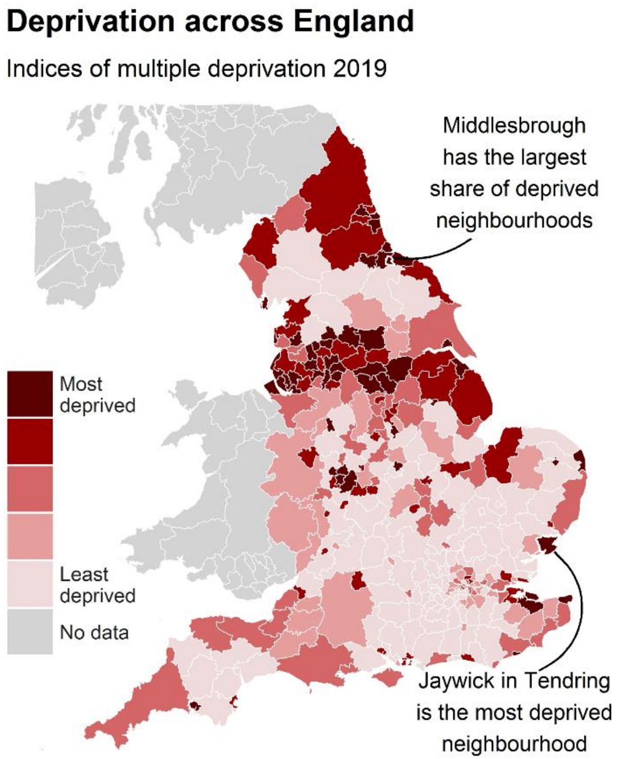
PROPOSED STRATEGY

1. Defining socioeconomic vulnerability:

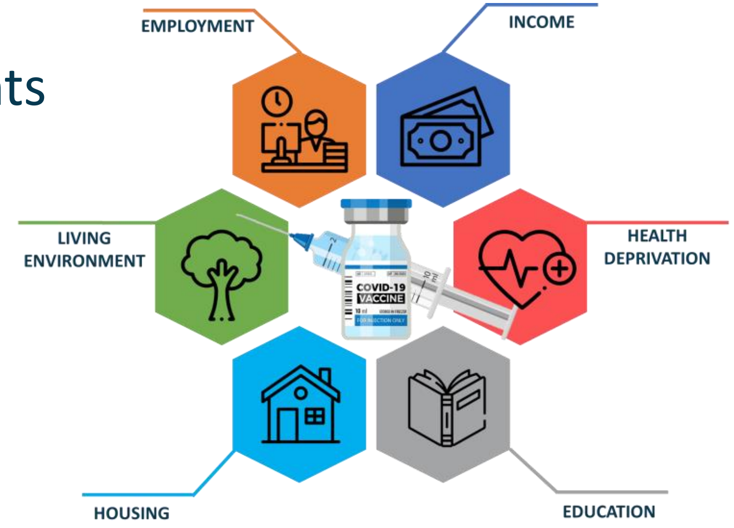
- 2 groups for simplicity: vulnerable vs non-vulnerable (BUT it can be extended)
- Based on the Index of Multiple Deprivation (IMD)



(32,844 small areas or neighborhoods)

Index of Multiple Deprivation (IMD): a measure of multiple deprivation based on seven distinct domains

1. Living Environments
2. Income,
3. Employment,
4. Education,
5. Health,
6. Crime,
7. Housing [4].



- Aggregated COVID death data for comparing IMD quintiles

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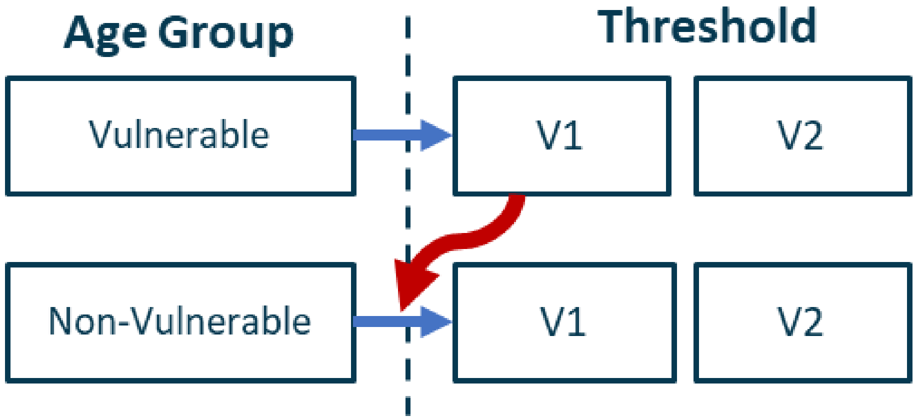
PROPOSED STRATEGY

2. Threshold approach:

- The first dose for a non-vulnerable group starts once a certain threshold is reached for the vulnerable group.
- No threshold for the second dose as the interval is specified by authorities.
- Formulation:
  1. the vaccinated population % of each group for each dose is calculated per time unit.
  2. comparing this % with the threshold, a binary matrix (eligibility) for each time unit.



Eligibility[Age Group, nonvulnerable]= IF THEN ELSE(V1 fraction[Age Group,Vulnerable]>Threshold value, 1, 0)

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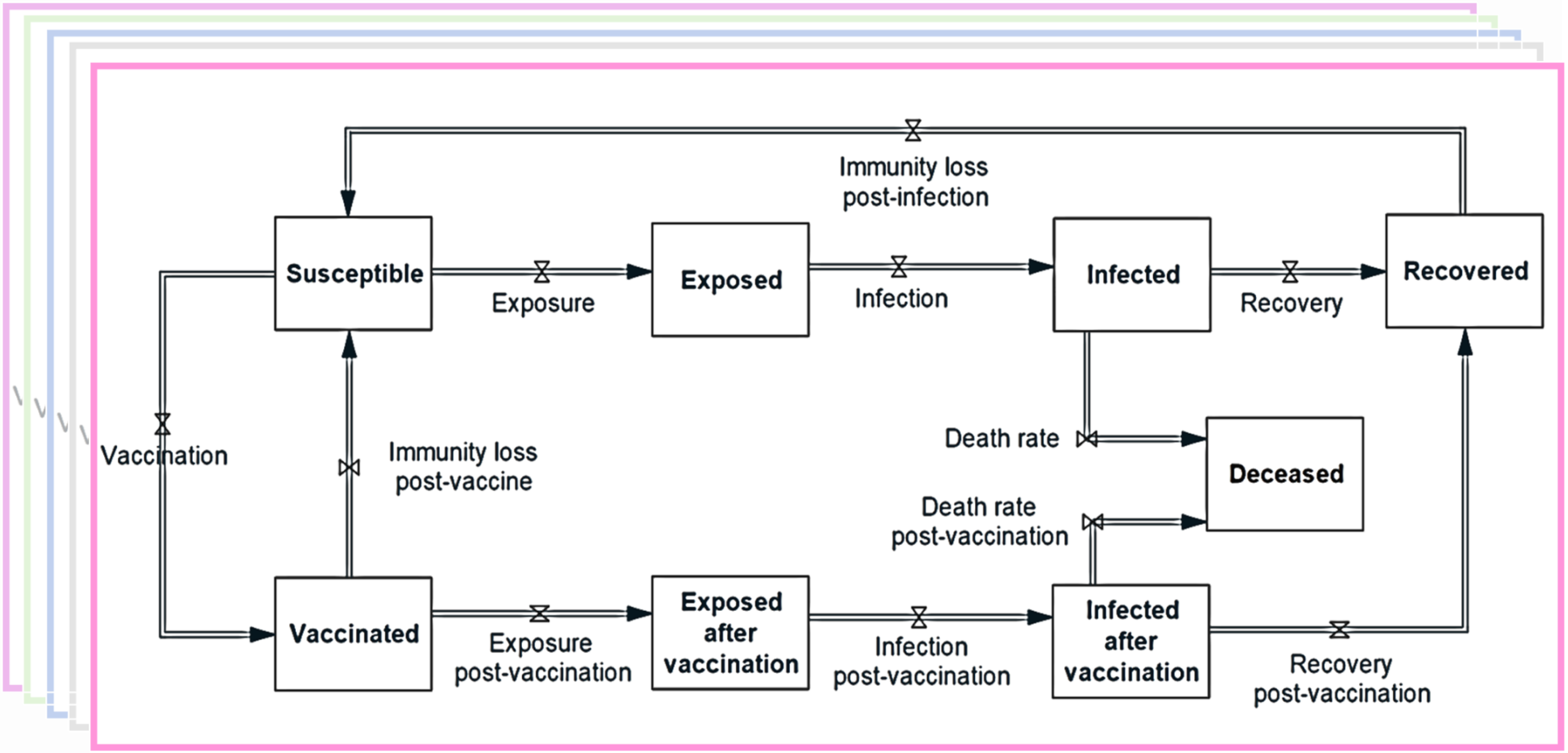
METHODOLOGY

SEIRD (Susceptible, Exposed, Infectious, Recovered, Dead) framework



18 population groups:
vaccine status (3)*
age group (3)*
SE vulnerability (2)

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MODEL PROPERTIES

Properties	To specify
Vaccine status	Protection level for different doses
Variants	Different disease characteristics
Vulnerability	Different socioeconomic groups
Age groups	Different age groups
Vaccine dose	Dose characteristics
Vaccine type	Protection levels of vaccines

Vaccine status		Explanation
No V	No vaccine	Initial condition
V1	Received dose 1	Protection of dose 1
V2	Received dose 1	Protection of dose 2

Age groups
Old 75+
Middle 55-74
Young 18-54

Variants
Original
Alpha
Delta

Vaccine doses
Dose 1
Dose 2

Vulnerability
Vulnerable
Non-vulnerable

Vaccine type
mRNA

- **Age:** susceptibility, severity, and mortality indicator (medical vulnerability)
- **Vaccine status:** to track vaccinated population, estimate vaccine demand, and apply vaccine-induced protection
- **Vulnerability:** sub-priority group within the age group for a fairer allocation
- **Variants:** time-dependent changes in virus properties

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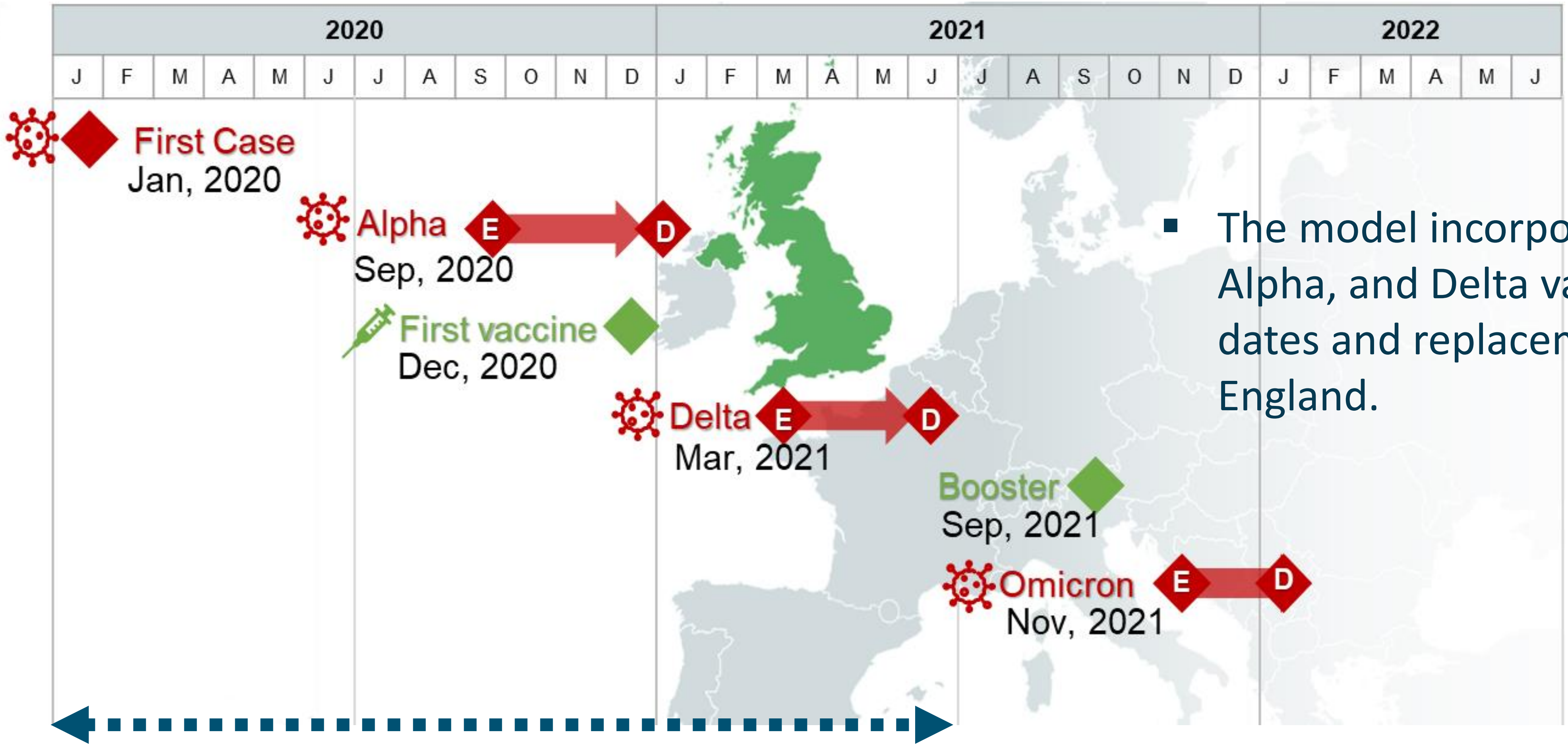
SIMULATION TIME HORIZON



- The model incorporates the wild type, Alpha, and Delta variants' emergence dates and replacement time frames in England.

Simulation duration= 600 days

Time unit= day

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ASSUMPTIONS AND SIMPLIFICATIONS

Vaccine demand and administration:

- Two-dose mRNA vaccines
- No immunity loss after the second dose
- 3rd vaccine doses are not considered.
- Susceptible demand for vaccine.
- 1st recipients will demand the 2nd dose.
- Daily vaccine capacity = real applied doses.
- Vaccine hesitancy varies by group but remains constant throughout the simulation.

Population and risk:

- Individuals aged 18+ (no children).
- Infection Fatality Rate (IFR) is equal for vulnerable and non-vulnerable groups.
- Testing and hospitalization are excluded.
- Responsiveness (sensitivity to the perceived risk of death) is the same across groups.
- Older individuals have slower risk perception decreases and faster increases (high-risk group).

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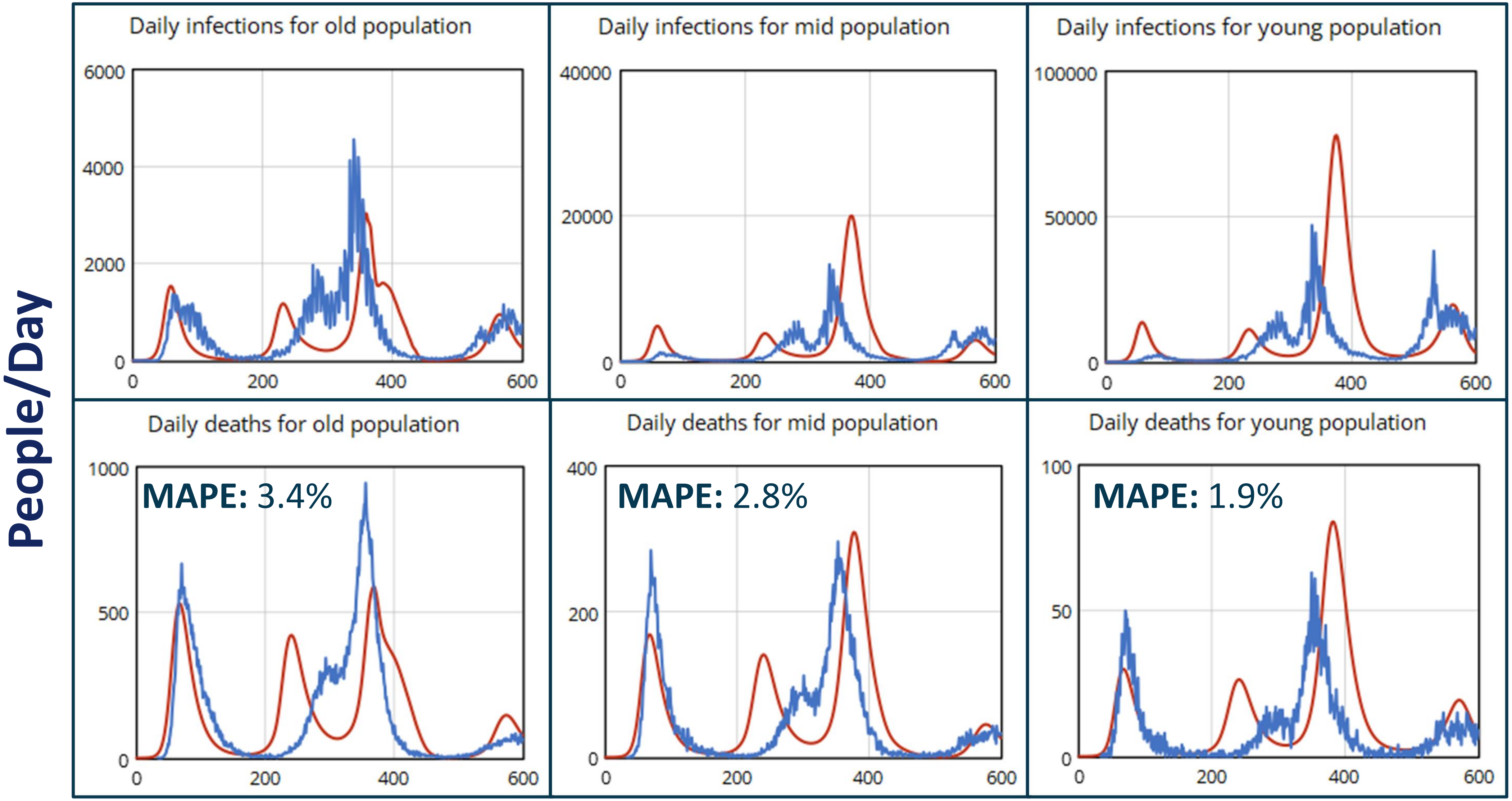
VALIDATION



Day

Reference Data

Simulation Output

Data collection:

- Gov.uk
- ONS

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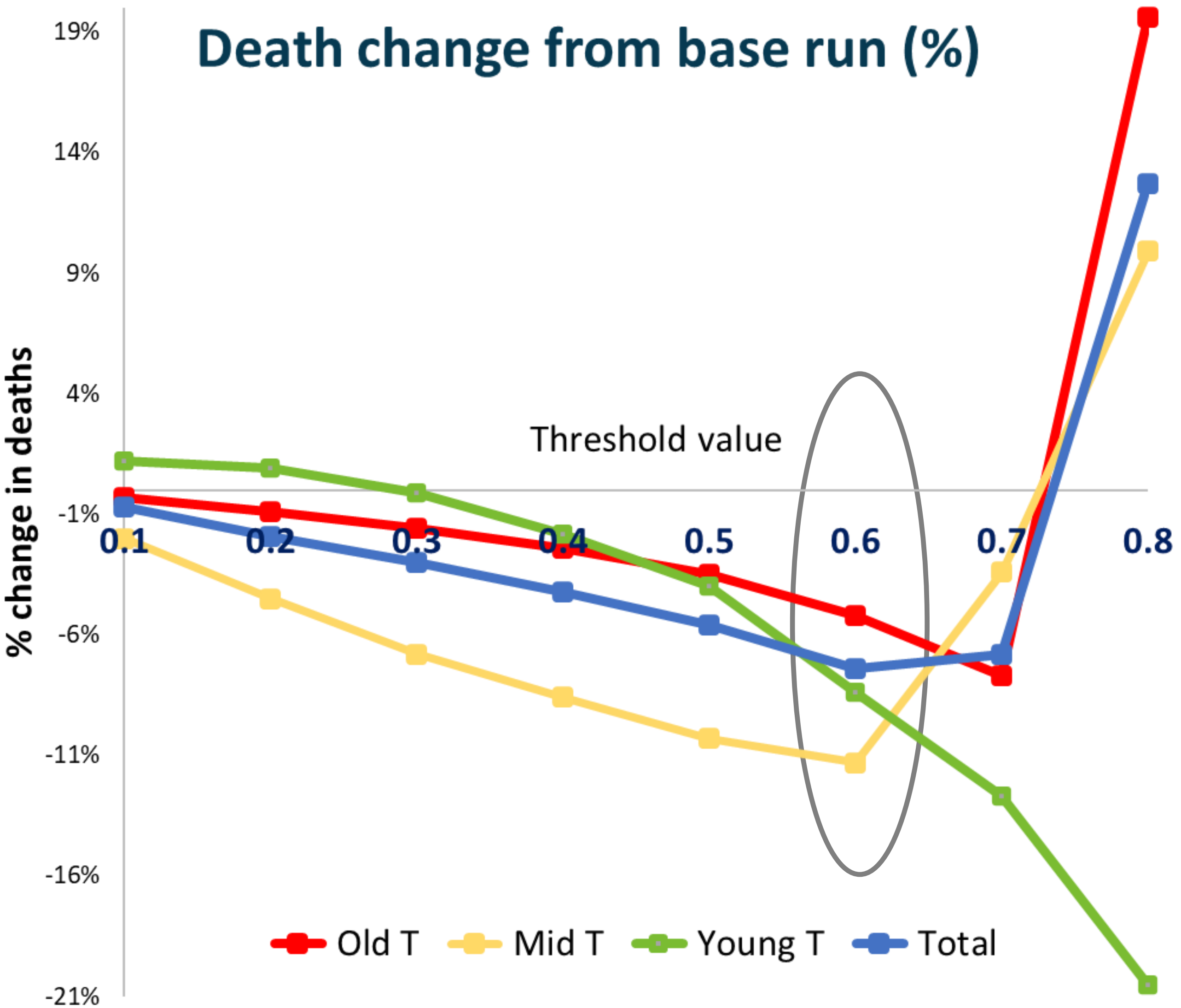
SCENARIO ANALYSIS: Best threshold



- Deaths after vaccine start
- **Best threshold:** 0.6 (7.4% decrease)
- Mid-group dominates total deaths (e.g., 0.7)
- increased threshold values lead to more vaccine waste after 0.6
- Total vaccination (real data): 76 M
- **Vaccine waste in the model:** vaccines to already infected or naturally immune
- **Assumption:** vaccines are applied only to the susceptible

Threshold	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Vax waste	-2.8%	-5.8%	-8.3%	-10.7%	-12.1%	-12.6%	**11.8%**	**284.6%**

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SCENARIO ANALYSIS: Best threshold

$$Dead\ pop\ \% = \frac{deaths\ after\ vaccine\ start}{initial\ population}$$

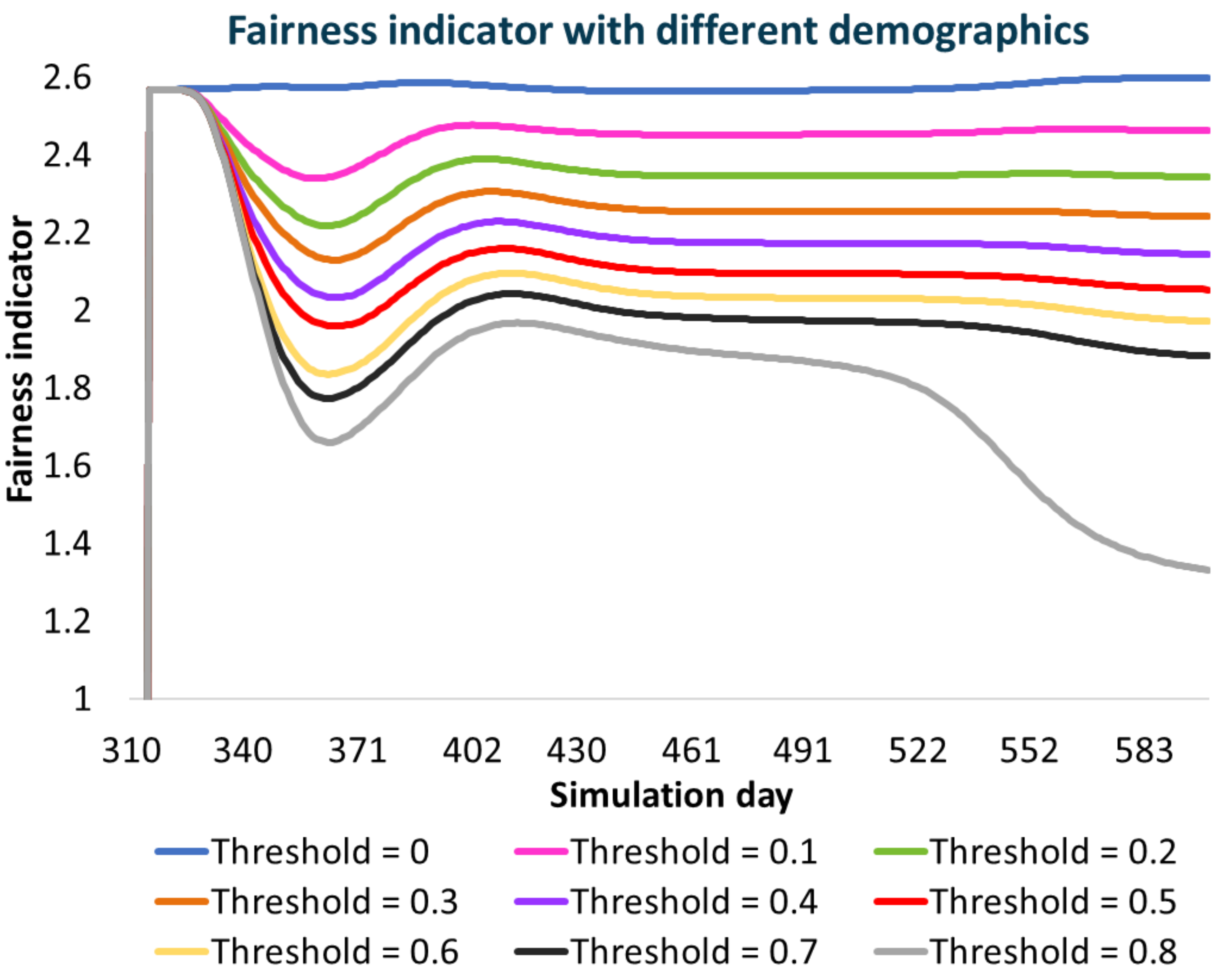
$$Fairness\ indicator = \frac{dead\ pop\ \%\ vulnerables}{dead\ pop\ \%\ nonvulnerables}$$

Desired value: 1

Fairness indicators and thresholds

	Age group			
Threshold	**Old**	**Mid**	**Young**	**Total**
Base run	3.4	3.4	3.2	2.6
0.1	3.2	3.1	3	2.5
0.2	3.1	3	2.7	2.3
0.3	3	2.7	2.5	2.2
0.4	3	2.6	2.2	2.1
0.5	2.9	2.4	2.1	2.1
0.6	2.8	2.3	1.9	2
0.7	2.8	2	1.7	1.9
0.8	1.9	1.5	1.6	1.3

increased threshold leads to less health inequality



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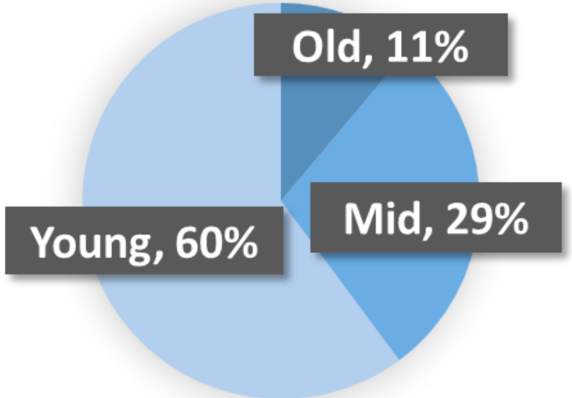
WHAT-IF ANALYSIS: Demographics

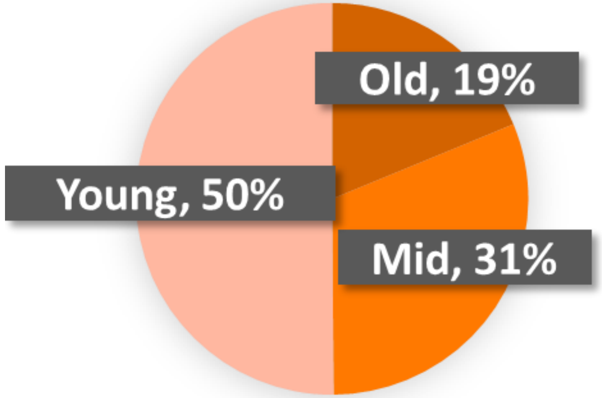
1. What would happen if the **demographics** of England were different?

- **Total population:** England
- **Vulnerability ratio:** England
- **Daily vaccinations:** England
- Age group distribution change
- Adjust vaccine allocation by age

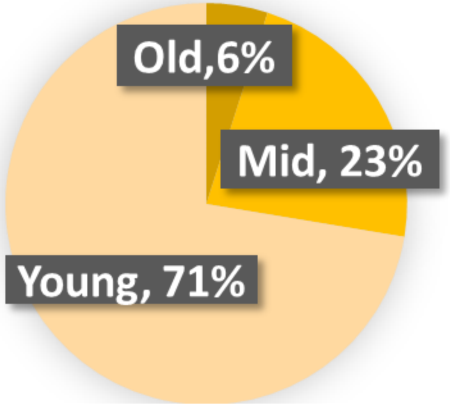
England



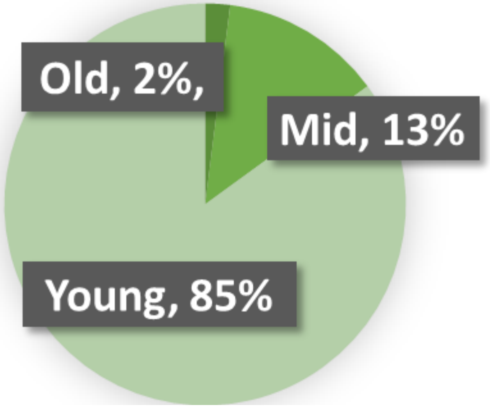
Japan (the oldest country)



World average



Niger (the youngest country)



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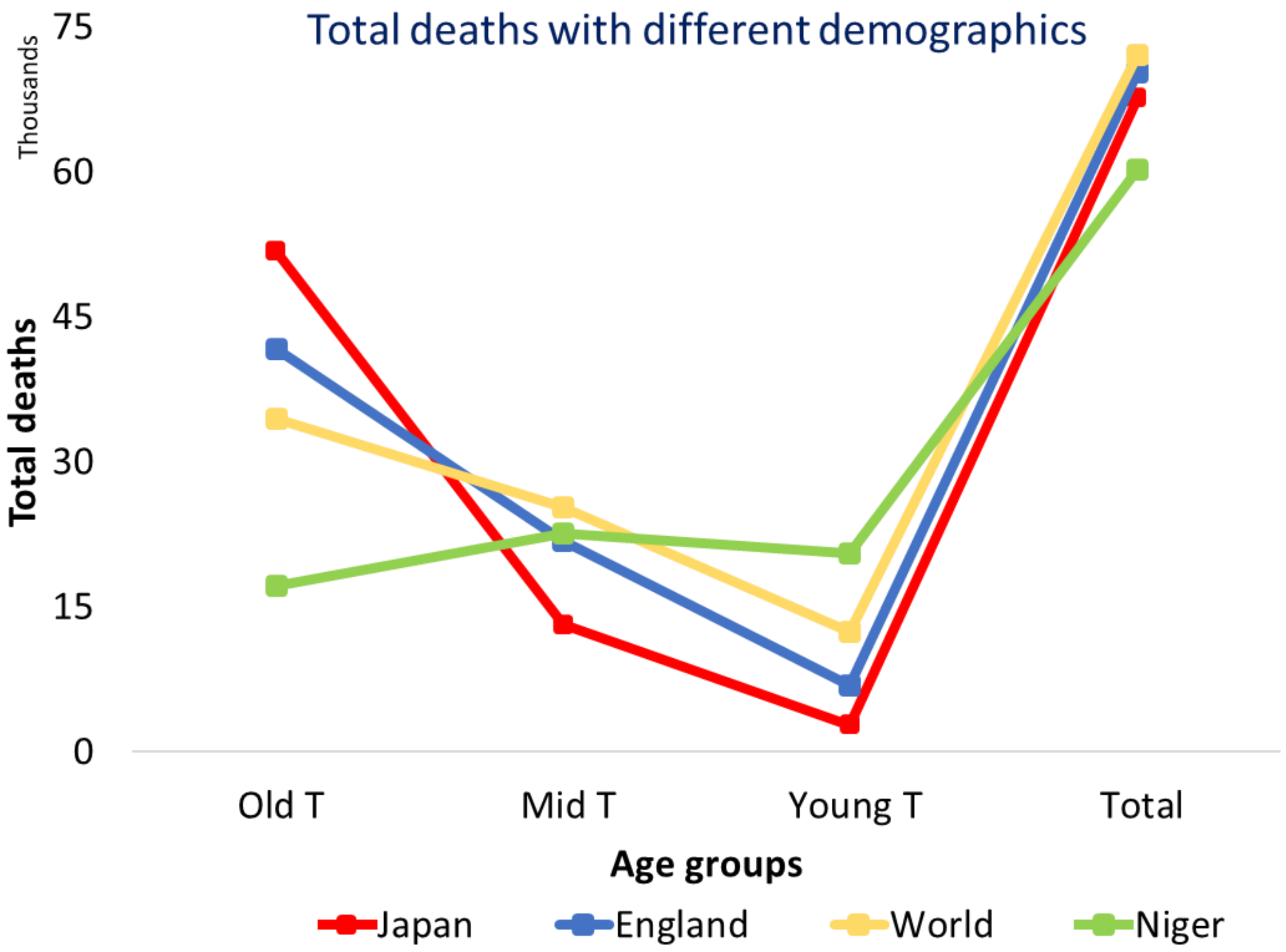
WHAT-IF ANALYSIS: Demographics

1. What would happen if the demographics of England were different? (th:0.6)



- Japan's demographics have the highest number of **old deaths** due to its large old population.
- Niger's demographics have the lowest number of **old deaths** due to its young population.
- Mid-age deaths do not follow this pattern.
- Total deaths (max to min):
  1. World average
  2. England
  3. Japan
  4. Niger

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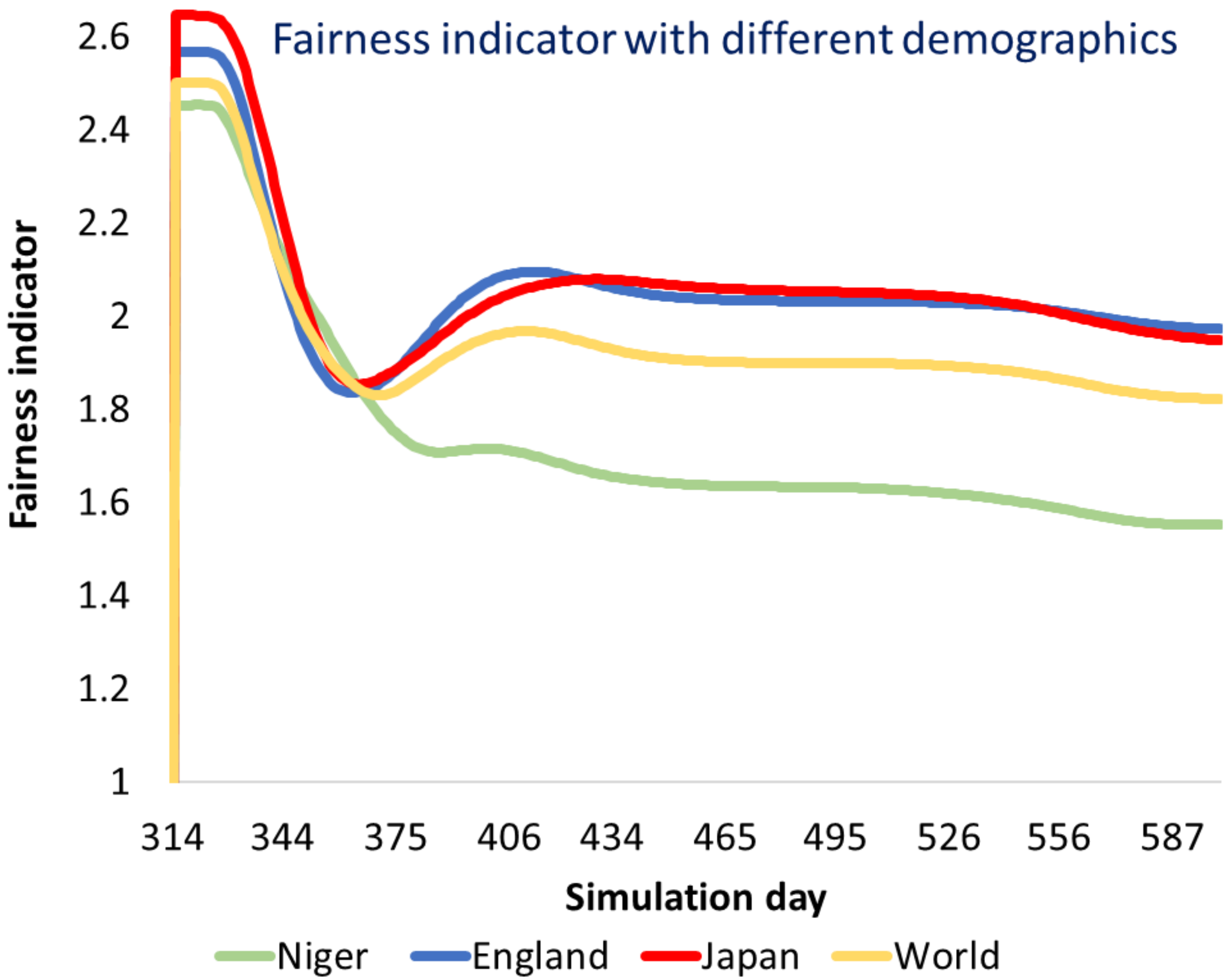
WHAT-IF ANALYSIS: Demographics

1. What would happen if the demographics of England were different? (th: 0.6)

- Larger elderly populations increase inequity as they are most affected by death. (e.g., Japan)
- Niger shows the greatest fairness improvement with threshold application, as high-risk elderly are a minority and under-vaccinated.
- Similarly, world demographics display the second-best improvement in fairness.
- Vaccine prioritization alone is insufficient for outcome equity (desired fairness indicator: 1).
- Hygiene and social distancing are also essential.



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WHAT-IF ANALYSIS: Vulnerability

2. What would happen if the vulnerable population ratio of England were different?

- **Total population:** England
- **Age group distribution:** England
- **Daily vaccinations:** England
- **Vulnerability ratio:** -/+ 5%, 10%, 20%, and 50%
- In the base model, vulnerable portions are determined according to the IMD for England.
  - ✓ **Young population:** 21% vulnerable
  - ✓ **Mid population:** 16% vulnerable
  - ✓ **Old population:** 14% vulnerable

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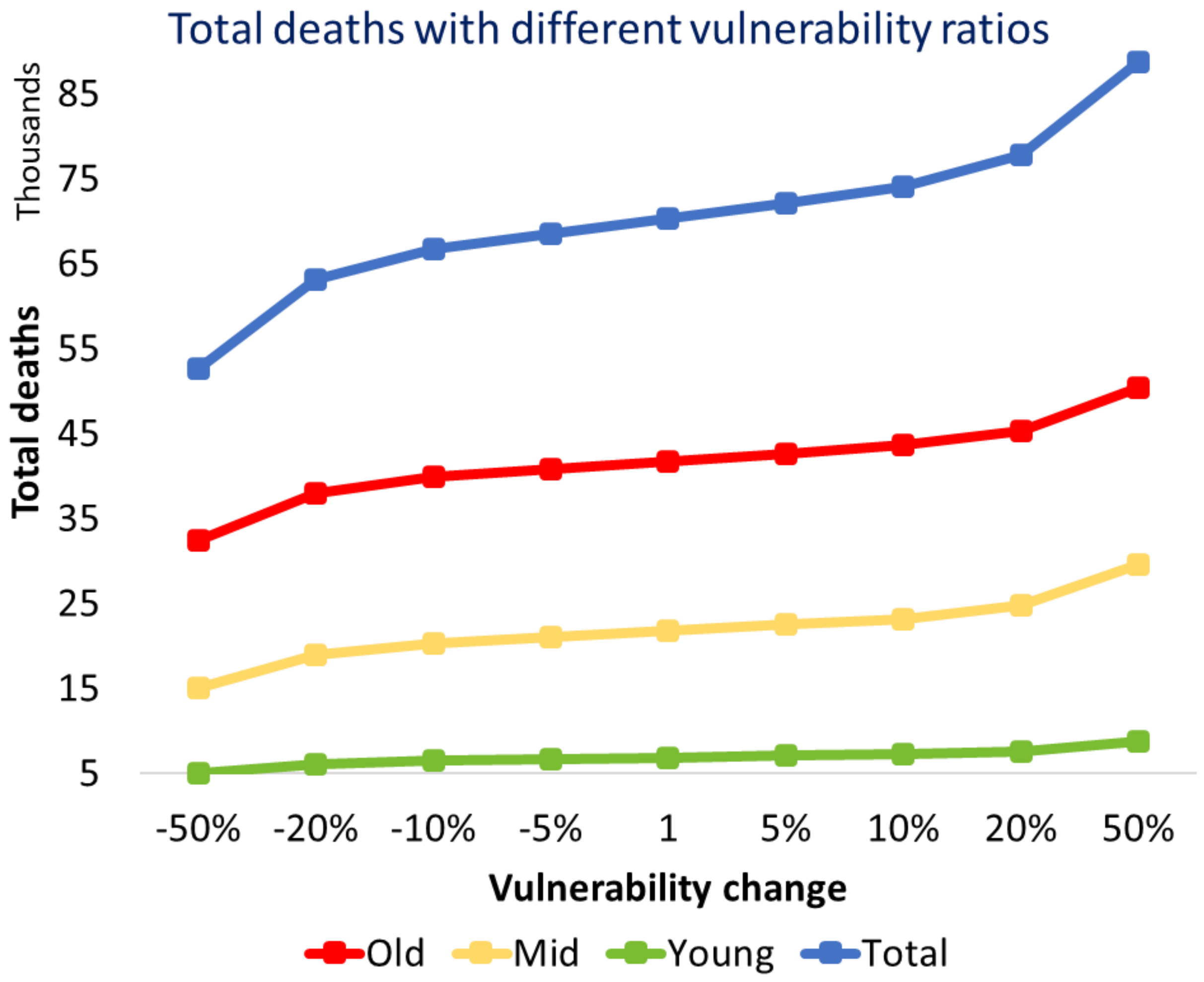
WHAT-IF ANALYSIS: Vulnerability

2. What would happen if the vulnerable population ratio of England were different?



- Increased vulnerability leads to higher total deaths due to greater infection risk in socioeconomically disadvantaged groups.
- This increase is most pronounced in the middle-aged and elderly, while less noticeable in the young population due to lower death rates.

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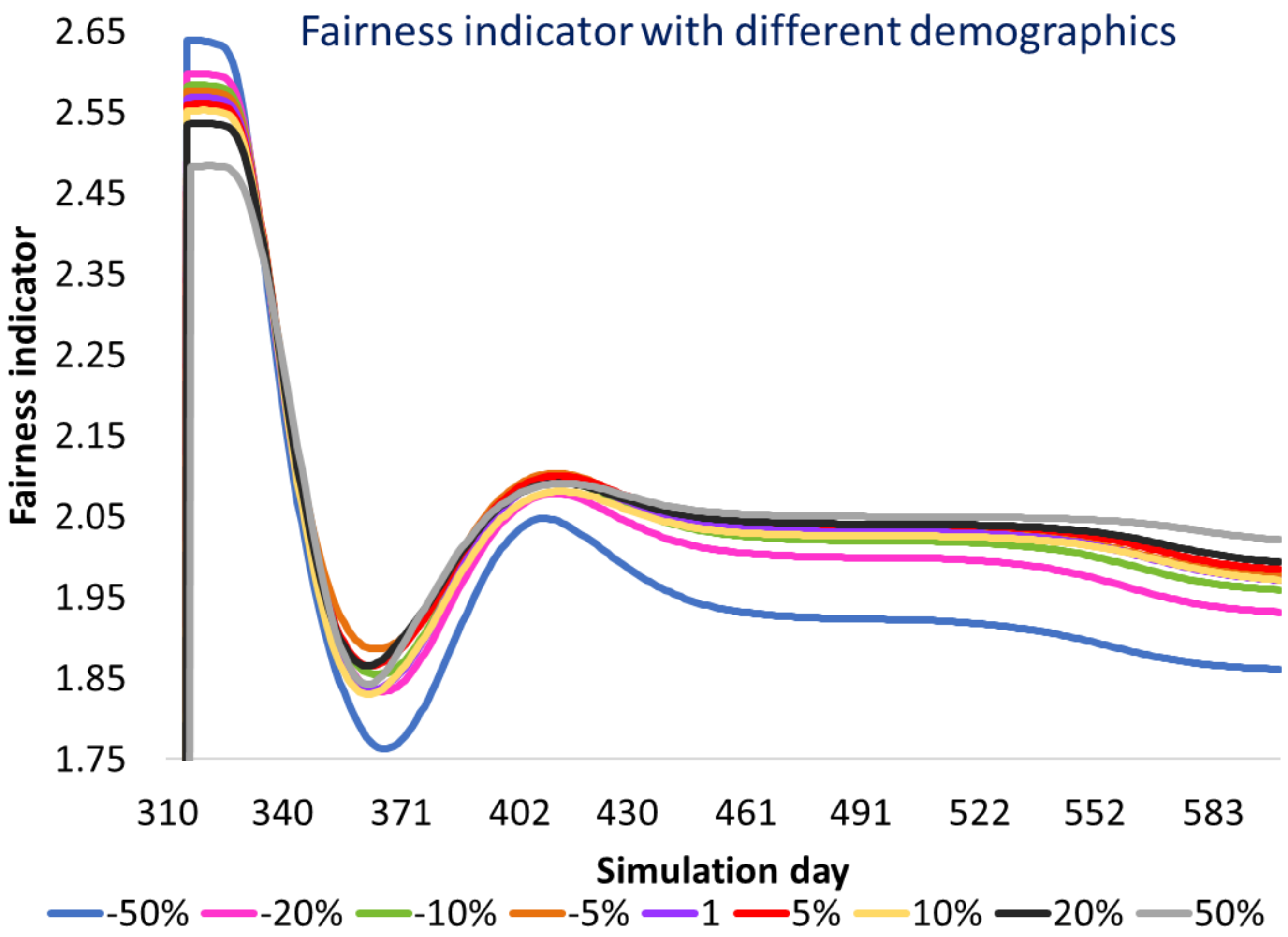
WHAT-IF ANALYSIS: Vulnerability

2. What would happen if the vulnerable population ratio of England were different?

- As the vulnerable population increases, the fairness indicator decreases (fairness improves).
- Vulnerable individuals become less visible, making them even more of a minority when thresholds are not applied.
- Applying thresholds improves fairness more when the vulnerable population is smaller.
- Vaccine prioritization alone is insufficient for outcome equity (desired fairness indicator: 1).
- Hygiene and social distancing are also essential.



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CONCLUSION

Optimal Threshold Value:

- 0.6 improves fairness and reduces total deaths.
- Higher values lead to more vaccine waste, as vaccines are given to those already immune or infected.

Policy Improvement:

- Threshold alone is insufficient, enhancing conditions for vulnerable groups (e.g., contact, hygiene) is crucial.

Demographic Patterns:

- **Elderly Population Increase:** more elderly deaths and greater inequity (e.g., Japan).
- **Young Population Increase:** more young deaths (e.g., Niger).
- **Mid-age Deaths:** Do not follow the same pattern as young and elderly deaths.
- Niger shows the greatest improvement with thresholds due to the minority of high-risk elderly.

Vulnerability:

- Greater vulnerability increases total deaths due to higher infection risks.
- Fairness improves with higher thresholds, especially when the vulnerable population is smaller.
- Vulnerable individuals become less visible without thresholds, making them more marginalized.

THANKS FOR LISTENING

Questions and feedback?

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