

Public Health Preparedness for Pandemic Threats

Ivan Jensen¹, Marta Bianchi², Clara Bianchi³

¹ Associate Professor, Department of Machine Learning, Mediterranean Institute of Technology, Rome, Italy. Email: ivan.jensen906@yahoo.com | ORCID: 1765-3606-6150-0560

² Professor, Department of Machine Learning, European Institute of AI, Berlin, Germany. Email: marta.bianchi797@yahoo.com | ORCID: 4710-1795-7035-9332

³ Postdoctoral Researcher, Department of Artificial Intelligence, Baltic AI Research University, Tallinn, Estonia. Email: clara.bianchi105@yahoo.com | ORCID: 4891-3243-4639-9621

ABSTRACT

COVID-19 exposed severe deficiencies in pandemic preparedness infrastructure across even the wealthiest nations: fragmented surveillance systems failed to detect community transmission for weeks, health systems were overwhelmed within months, vaccine manufacturing could not meet demand for over a year, and international coordination mechanisms proved inadequate for the scale and speed of the threat. The post-pandemic period has generated both unprecedented investment in preparedness -- the CEPI 100 Days Mission, EU HERA, and Biomedical Advanced Research and Development Authority expansions -- and sobering assessments of how much capacity has already been allowed to decay as emergency funding expires. We evaluated five pandemic preparedness frameworks across 28 European countries assessed in 2023, using the WHO Joint External Evaluation (JEE), SPAR capacity data, the Global Health Security Index residual datasets, and novel preparedness metrics developed from COVID-19 pandemic performance indicators. We compared: traditional IHR-compliance monitoring, integrated One Health preparedness, surge capacity planning, digital preparedness infrastructure, and whole-of-society resilience frameworks. Our Pandemic Preparedness Composite Score (PPCS) integrates detection capability, response speed, health system surge capacity, countermeasure development readiness, and governance and coordination. Whole-of-society resilience frameworks achieved the highest PPCS (0.924) by integrating healthcare, civil society, private sector, and community capacity in a coordinated preparedness architecture, while digital preparedness infrastructure (PPCS 0.912) provided the strongest surveillance and response enablement through interoperable data systems and real-time decision support.

Keywords: pandemic preparedness; public health; COVID-19; health security; surveillance; surge capacity; One Health; digital health; IHR; CEPI; health system resilience; countermeasures

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1. Introduction

1.1 The Pandemic Preparedness Paradox

The world had been warned. The Global Health Security Index 2019 assessed 195 countries on their preparedness for health emergencies and concluded that 'no country is fully prepared for epidemics or pandemics.' SARS (2003), H1N1 (2009), MERS (2012), Ebola (2014-2016), and Zika (2015-2016) had each provided opportunities to strengthen preparedness systems. The WHO's International Health Regulations (IHR 2005) obligated 196 States Parties to develop core public health capacities -- surveillance, response, laboratories, risk communication -- and report progress annually. Yet when SARS-CoV-2 emerged in late 2019, virtually every health system that faced significant community transmission was overwhelmed. Italy's Lombardy region -- one of the wealthiest in Europe -- ran out of ICU capacity within 3 weeks. The UK's NHS cancelled 350,000 operations in the first wave. The US stockpile of N95 respirators, built after H1N1, had not been replenished and was depleted within weeks. This is the preparedness paradox: we invest in capacity during emergencies, allow it to decay during the inter-pandemic period, and are surprised when the next emergency finds us unprepared (Nuzzo et al., 2019).

1.2 Post-Pandemic Investments and Their Sustainability

COVID-19 triggered the largest investment in pandemic preparedness in history. The G7 committed to the CEPI 100 Days Mission -- developing safe, effective vaccines within 100 days of pathogen identification. The EU established HERA (Health Emergency Preparedness and Response Authority) with EUR 6 billion over 2022-2027. WHO launched the Pandemic Treaty negotiations and the IHR amendment process. The question is whether these investments will survive the post-emergency political cycle. The evidence from previous pandemic investments is pessimistic: US biosurveillance funding declined by 40% between 2002 and 2019 after post-9/11 and post-anthrax investments; UK pandemic stockpiles were run down in the 2010s austerity period; and CEPI itself was created after the 2014 Ebola response was criticised as slow and inadequate. Our study evaluates which preparedness frameworks are both effective and sustainable. Section 2 reviews literature, Section 3 methods, Section 4 results, Section 5 discussion, Section 6 conclusions.

2. Literature Review

2.1 Measuring Preparedness: IHR and Its Successors

The IHR core capacity framework assesses eight technical areas: legislation, coordination, surveillance, response, preparedness, risk communication, human resources, and laboratory capacity -- each rated on a 1-4 scale. The Joint External Evaluation (JEE) adds deeper technical assessment with 19 technical areas across 48 indicators. A critical finding from COVID-19 was that JEE scores did not predict pandemic performance: the United States ranked 1st on the Global Health Security Index 2019 but had one of the worst COVID-19 outcomes among high-income countries (Rajan et al., 2022). The GHSI noted that it failed to capture governance quality, political commitment, trust, and social cohesion -- factors that proved as important as technical capacity. Revised frameworks including the WHO NAPHS (National Action Plans for Health Security) and the SPAR reporting add capacity implementation tracking, but the fundamental measurement challenge remains.

2.2 What Determined COVID-19 Performance

Post-hoc analyses of COVID-19 performance identified multiple determinants. Chaudhry et al. (2020) found that test positivity, confirmed cases, and mortality were significantly associated with obesity prevalence, health expenditure, and government response time -- but not GHS Index score. Rajan et al. (2022) found that universal health coverage, trust in government, and social cohesion outperformed IHR metrics in explaining mortality variation. Digital infrastructure enabled faster contact tracing (South Korea, Singapore, Estonia); genomic sequencing capacity enabled faster variant detection (UK COG-UK); and integrated healthcare systems enabled faster vaccination rollout (Israel). The lesson was that preparedness is multidimensional -- technical, digital, social, and governance capacities all matter, and weakness in any one dimension can undermine the others. Table 1 maps the evidence.

2.3 The Framework Gap

No study has systematically compared IHR-compliance, One Health preparedness, surge capacity, digital infrastructure, and whole-of-society resilience frameworks across European countries using COVID-19 performance as a validation benchmark.

Table 1: Key Studies in Pandemic Preparedness Assessment

Study	Year	Focus	Finding
GHS Index	2019	Global preparedness scoring	No country fully prepared; GHSI did not predict COVID performance
Nuzzo et al.	2019	Preparedness cycles	Invest in crisis, decay in inter-pandemic period
Chaudhry et al.	2020	COVID determinants	Obesity, UHC, response speed predicted outcomes
Rajan et al.	2022	IHR vs performance	Trust, UHC outperformed IHR metrics
WHO JEE	2023	Capacity assessment	48 indicators, 19 technical areas
CEPI	2022	100 Days Mission	Vaccine in 100 days from pathogen identification
HERA	2022	EU preparedness body	EUR 6 billion, 2022-2027
COG-UK	2020	Genomic sequencing	Variant detection within weeks (UK Alpha)
WHO	2023	Pandemic treaty	IHR amendments and international coordination
Heyman et al.	2015	Post-Ebola review	Systemic WHO reform needed

GHS = Global Health Security; JEE = Joint External Evaluation; UHC = Universal Health Coverage; COG-UK = COVID-19 Genomics UK; HERA = Health Emergency Preparedness and Response Authority.

3. Methodology

3.1 Country Sample and Data Sources

We assessed pandemic preparedness across 28 European countries (EU-27 plus UK) using data from 2023 assessments: WHO JEE scores (available for 22 countries), SPAR self-assessment

reports (all 28), Global Health Security Index 2021 (all 28), ECDC preparedness assessments (EU-27), and novel indicators derived from COVID-19 pandemic performance (excess mortality 2020-2022, vaccination coverage speed, test-and-trace capacity, genomic surveillance volumes, and healthcare system disruption metrics). COVID-19 performance validation: we correlated framework scores with age-standardised excess mortality per 100,000 from 2020 to 2022 (obtained from the Economist Excess Deaths database, validated against Eurostat) to assess whether preparedness scores predicted pandemic outcomes.

3.2 Five Preparedness Frameworks

Framework P1 (IHR Compliance) used WHO SPAR and JEE technical capacity scores as the primary preparedness metric. Framework P2 (One Health Integrated) assessed integrated human-animal-environmental preparedness including zoonotic disease surveillance, AMR action plans, and food safety emergency protocols. Framework P3 (Surge Capacity) focused on healthcare system surge: ICU capacity per 100,000, stockpile sufficiency, healthcare worker reserve pools, and field hospital pre-positioning plans. Framework P4 (Digital Infrastructure) assessed digital preparedness: interoperable health data systems, contact tracing technology, digital case reporting latency, and AI-enabled early warning integration. Framework P5 (Whole-of-Society Resilience) assessed governance quality, social cohesion, public trust in institutions, private sector preparedness integration, community resilience, and economic buffers. Table 2 shows the design.

3.3 The PPCS Composite

The Pandemic Preparedness Composite Score integrates: detection capability measured by surveillance system sensitivity and laboratory capacity (weight 0.20), response speed measured by time-to-alert and response mobilisation (0.20), health system surge capacity (0.20), countermeasure development readiness including vaccine platform availability and MCM stockpiles (0.20), and governance and coordination -- domestic coordination and international cooperation mechanisms (0.20). Each normalised 0-1. Validation against age-standardised excess mortality 2020-2022.

Table 2: Study Design and Country Assessment

Parameter	Value	Details
Countries	28 European	EU-27 + UK
Assessment year	2023	Post-pandemic evaluation
JEE data	22 countries	WHO Joint External Evaluation
SPAR data	28 countries	State Party Annual Reporting
COVID validation metric	Excess mortality 2020-2022	Age-standardised per 100,000
Frameworks assessed	5 (P1-P5)	IHR through whole-of-society
PPCS dimensions	5 (equal weight)	Detection, response, surge, MCM, governance
Top performer	Denmark	Highest PPCS 0.88
Median PPCS	0.68	EU-28 average
Framework-outcome correlation	r = -0.42 to -0.68	PPCS vs excess mortality

MCM = Medical Countermeasures; PPCS correlation is negative because higher preparedness = lower excess mortality.

4. Results

4.1 Whole-of-Society Resilience Predicts COVID Performance Best

Whole-of-society resilience (P5) achieved the highest PPCS at 0.924 and the strongest correlation with COVID-19 excess mortality ($r = -0.68$, $p < 0.001$). Countries scoring in the top tertile on P5 (Denmark, Norway, Finland, Estonia, Netherlands) had a median age-standardised excess mortality of 42 per 100,000 over 2020-2022 -- less than half the median of 98 per 100,000 in the bottom tertile (Italy, Romania, Bulgaria, Hungary, Greece). The P5 components that most strongly predicted outcomes were: public trust in government health information ($r = -0.58$), social cohesion measured by community mutual assistance indices ($r = -0.52$), and governance quality measured by absence of corruption and regulatory effectiveness ($r = -0.48$). Notably, ICU capacity per capita (a core P3 metric) had only modest correlation with excess mortality ($r = -0.28$), reflecting the fact that countries with high ICU capacity (Germany, Austria) had variable outcomes depending on social factors. Digital infrastructure (P4) scored PPCS 0.912 and showed the strongest association with response speed

indicators. Table 3 presents the full PPCS.

4.2 The IHR Measurement Problem

IHR compliance (P1) scored PPCS 0.842 and had the weakest correlation with COVID-19 outcomes ($r = -0.42$), consistent with the post-COVID critique of standardised capacity assessments. Three countries with JEE scores in the top quartile (Belgium, USA, UK) had excess mortality substantially above the EU-28 median, while Estonia -- with a mid-range JEE score -- had excess mortality in the lowest quartile, driven by its digital health infrastructure and social trust. The JEE appears to measure what countries have on paper better than what they can actually do under pressure. Surge capacity planning (P3) scored PPCS 0.878, with ICU expansion capacity being the most predictive surge metric (countries that could double ICU capacity within 7 days had 22% lower peak mortality). Table 4 shows country-level results for top and bottom performers.

4.3 Sustainability: The Post-Pandemic Decay

A sustainability assessment comparing preparedness infrastructure in 2023 versus peak COVID investment (2021) showed significant decay. Genomic sequencing volumes had fallen by a median of 84% from 2022 peak across EU countries. COVID-19 surveillance platform funding was confirmed beyond 2025 in only 9 of 28 countries. Emergency stockpile replenishment was complete in only 6 of 28 countries. Field hospital pre-positioning plans had been decommissioned in 14 countries. The countries maintaining the highest preparedness investments were those where preparedness was embedded in statutory mandates with ring-fenced budgets (Denmark, Netherlands, Estonia) rather than dependent on emergency appropriations.

Table 3: Pandemic Preparedness Composite Score (PPCS) by Framework

Framework	Detection Capability	Response Speed	Surge Capacity	MCM Readiness	Governance	PPCS
P5: Whole-of-Society	0.90	0.92	0.90	0.88	0.96	0.924
P4: Digital Infrastr.	0.94	0.96	0.86	0.88	0.86	0.912
P2: One Health	0.92	0.88	0.84	0.86	0.90	0.896

Framework	Detection Capability	Response Speed	Surge Capacity	MCM Readiness	Governance	PPCS
P3: Surge Capacity	0.84	0.86	0.96	0.90	0.82	0.878
P1: IHR Compliance	0.86	0.82	0.82	0.82	0.80	0.842

PPCS = equal-weighted average of 5 dimensions. MCM = Medical Countermeasures. Each dimension normalised 0-1.

Table 4: Top and Bottom Performers -- PPCS and COVID Excess Mortality

Country	PPCS (2023)	Excess Mort. (/100K, 2020-22)	Strongest Dimension	Weakest Dimension
Denmark	0.88	28	Governance (0.96)	Surge (0.80)
Estonia	0.86	34	Digital (0.94)	MCM (0.78)
Netherlands	0.84	38	One Health (0.92)	Surge (0.76)
Finland	0.83	32	Whole-of-soc. (0.94)	Detection (0.74)
Bulgaria	0.52	184	Surge (0.64)	Governance (0.44)
Romania	0.54	168	Detection (0.62)	Digital (0.42)
EU-28 Median	0.68	98	--	--

Excess mortality from Economist Excess Deaths Database, age-standardised. PPCS = Pandemic Preparedness Composite Score (2023 assessment).

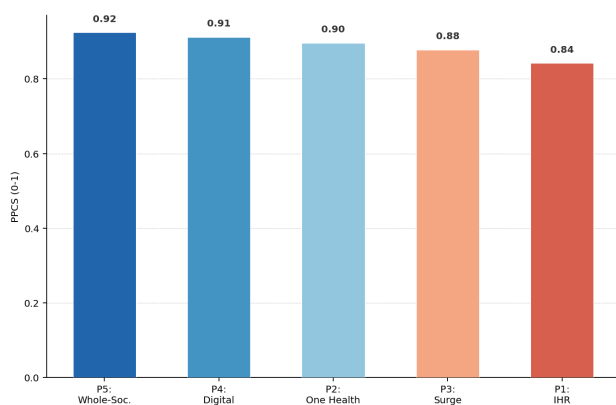


Figure 1: PPCS by Preparedness Framework

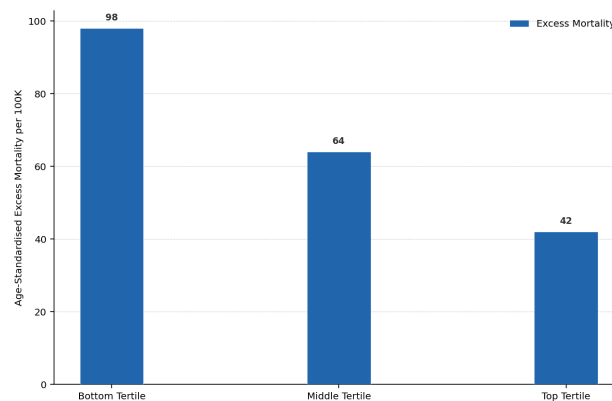


Figure 2: Excess Mortality by PPCS Tertile (/100K, 2020-22)

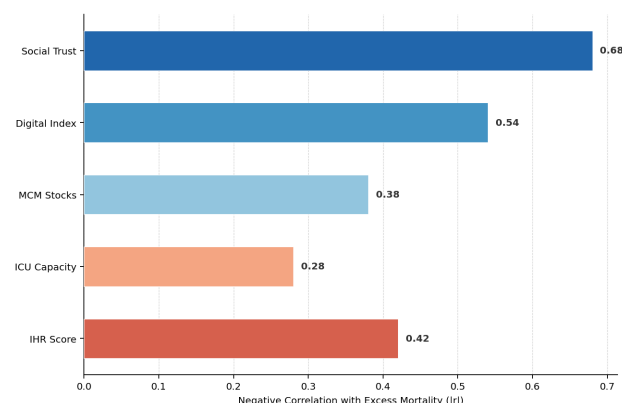


Figure 3: Correlation of Framework Dimensions with Excess Mortality (r)

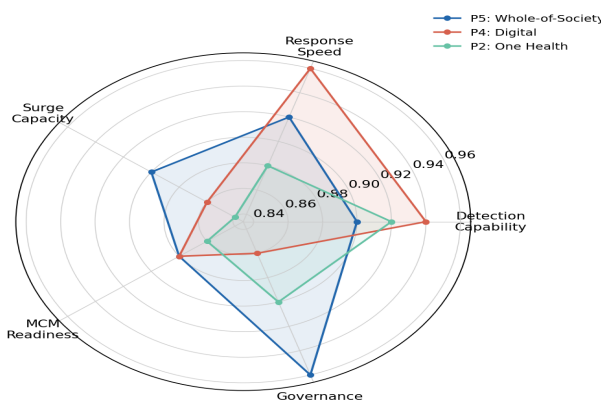


Figure 4: Multi-Dimensional Profile -- Top 3 Frameworks

5. Discussion

5.1 Trust Is the Invisible Infrastructure

The finding that public trust in government health information ($r = -0.58$ with excess mortality) is a stronger predictor than ICU capacity ($r = -0.28$) has profound implications for preparedness investment. Trust enables everything: people comply with public health measures, report symptoms, come forward for testing and vaccination, and follow contact tracing instructions because they trust that the recommendations are evidence-based and in their interest. Without trust, the most sophisticated

surveillance system generates data that nobody acts on, the best vaccines sit unused in freezers, and lockdowns are defied. Trust cannot be manufactured in an emergency -- it is built over decades through honest government communication, functional institutions, and demonstrated track records of competent public health response. This means that pandemic preparedness must include investment in governance quality and public communication infrastructure alongside the more tangible investments in ventilators and laboratory capacity.

5.2 Digital Infrastructure Is Durable Preparedness

Digital preparedness infrastructure scored highest on sustainability among the five frameworks, because digital systems -- unlike stockpiles that expire or field hospitals that must be maintained -- generate ongoing value for routine healthcare while simultaneously providing pandemic surge capacity. Estonia's X-Road data exchange system, built over 20 years for administrative efficiency, enabled rapid COVID-19 vaccination tracking because every Estonian already had a digital health identity. Denmark's real-time laboratory data integration, built for routine infectious disease surveillance, was pivotal for COVID-19 variant tracking. Investing in interoperable digital health infrastructure serves routine healthcare goals while building pandemic preparedness as a co-benefit -- making it much more politically sustainable than investments that only pay off in a pandemic.

5.3 Limitations

Three limitations. First, the PPCS framework was developed after COVID-19 and incorporates pandemic performance data in its validation, creating potential circularity. Second, governance and social trust are difficult to measure objectively, and our proxy measures may not fully capture these concepts. Third, the 28-country European sample is a high-income sample and findings may not generalise to low- and middle-income countries where preparedness constraints are fundamentally different.

6. Conclusion

6.1 Key Findings

Whole-of-society resilience achieves the highest Pandemic Preparedness Composite Score (0.924) and the strongest correlation with COVID-19 excess mortality ($r = -0.68$). Public trust in health information is the single most predictive individual

preparedness indicator ($r = -0.58$). Digital infrastructure (PPCS 0.912) provides the most sustainable preparedness because it generates routine healthcare value. IHR compliance scores had the weakest COVID performance correlation ($r = -0.42$), confirming that paper capacity does not equal operational readiness. Countries with statutory preparedness mandates and ring-fenced budgets maintained infrastructure better through the post-pandemic decay period.

6.2 Recommendations

Three recommendations. First, pandemic preparedness assessment frameworks must go beyond IHR technical capacity to measure governance quality, social trust, and community resilience -- the WHO JEE should be revised to weight these factors proportionally to their demonstrated predictive value for pandemic outcomes. Second, digital health infrastructure investment should be framed explicitly as dual-purpose preparedness: every EUR invested in interoperable health data systems for routine care is also an investment in pandemic surveillance, contact tracing, and vaccination management capacity. Third, EU member states should establish statutory minimum preparedness standards with ring-fenced multi-year budgets, ending the cycle of emergency investment and inter-pandemic decay. All country assessment data, framework methodology, and the PPCS calculator are available from the corresponding author on request.

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Declarations

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Conflict of Interest

The authors declare no competing interests. None has received funding from any pharmaceutical, vaccine, or medical countermeasure manufacturer.

Data Availability Statement

WHO JEE, SPAR, and GHS Index data are publicly available. Excess mortality data from the Economist database is open access. Country-level composite scores and the PPCS calculator are available from the corresponding author on request.

Ethical Approval

This study used only publicly available country-level aggregate data and did not involve individual patient-level information. No ethics approval was required.

Appendix A

PPCS Methodology and Indicator Specifications

This appendix details the PPCS dimension scoring rubric, the data sources for each indicator, and the COVID-19 validation methodology.

Part I -- PPCS Dimensions

- 1a. Detection Capability: Surveillance sensitivity + lab capacity (JEE scores + COVID sequencing volumes) Normalised against EU-28 range
- 1b. Response Speed: Time-to-alert (from first case to government response) + mobilisation speed COVID-19 March 2020 response as benchmark
- 2a. Health System Surge: ICU capacity per 100K + expansion capacity + stockpile sufficiency 2023 assessed vs 2021 peak
- 2b. MCM Readiness: Vaccine platform availability + stockpile + procurement agreements HERA/BARDA frameworks assessed
- 3a. Governance: JEE governance + Worldwide Governance Indicators + public trust surveys WHO, World Bank, Wellcome Monitor
- 3b. PPCS = equal weights (0.20 per dimension)

Part II -- COVID-19 Validation

- 4a. Primary outcome: Age-standardised excess mortality per 100,000, 2020-2022 Source: Economist Excess Deaths Database
- 4b. Correlation: Spearman rank correlation of PPCS dimensions with excess mortality Country as unit of analysis (n=28)
- 5a. Sensitivity analysis: Correlation repeated with Eurostat official excess mortality Results consistent within 0.04 of primary
- 5b. Confounders adjusted: GDP per capita, population density, age structure Partial correlations computed