Appendix III: JRC Statistical Audit of the 2022 Network Readiness Index

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3.1 Introduction

The Networked Readiness Index (NRI) was first published in 2002 by the World Economic Forum as part of the Global Information Technology Report. Over the last two decades, the NRI has provided a holistic view of how economies can deploy technology to enhance development and global competitiveness.

In addition to the analysis on how economies have dealt with and continue to fare in the face of present-day challenges, the 2022 edition of the index (NRI 2022, henceforth) focuses on the role of younger generations in leading the world into the information age. As indicated by the developers, recent trends indicate that future-readiness will largely rely on three major currencies: data, talent, and learning. On all those fronts, we are only seeing the beginning of what tomorrow will bring. The future is still very young, and we all have a role to play in shaping it into the future we want.

The NRI 2022's overall structure is conceptually in line with respect to NRI 2021. The index consists of four pillars (Technology, People, Governance, and Impact) that make up the fundamental dimensions of network readiness. Each of the fundamental pillars is divided into additional sub-pillars, further subdivided in 59 indicators. The current version of the index has been subject to several adjustments. More precisely, the methodology of some indicators was revised, one new indicator was introduced without replacing the existing one, three indicators were dropped without replacement, four indicators were introduced to replace previous indicators, and five indicators changed code. Each pillar has the same weight in the computation of the index. All pillars are composed of three sub-pillars that are weighted equally. The number of indicators making up each sub-pillar may vary. Although they are equally weighted in their respective sub-pillars, different within-pillar numerosity of the indicators into different contribution of each individual indicator in the overall index. The inclusion of countries and indicators relied on a double threshold approach (70% coverage at the pillar level, and 40% coverage at the sub-pillar level), resulting in a total of 131 countries.

The European Commission's Competence Centre on Composite Indicators and Scoreboards (COIN) at the Joint Research Centre (JRC) has been invited for the second time to audit the index. As in previous edition, the present JRC-COIN audit focuses on the statistical soundness of the multi-level structure of the index as well as on the impact of key modelling assumptions on the results. The independent statistical assessment of the NRI 2022 provided by the JRC-COIN guarantees the transparency and reliability of the index for both policymakers and other stakeholders, thus facilitating more accurate priority setting and policy formulation in the respective field.

The JRC assessment of the NRI 2022 presented here focuses on two main issues: the statistical coherence of the structure, and the impact of key modelling assumptions. The statistical analysis is based on the adequacy of aggregating indicators into pillars, and pillars into the overall index.

As in past NRI report, the JRC-COIN analysis complements the reported country rankings for the NRI index 2022 with simulated intervals, in order to better appreciate the robustness of these ranks to the modelling choices. Finally, the JRC-COIN analysis includes an assessment of the added value of the NRII 2022 and a measure of distance to the efficient frontier of innovation by using data envelopment analysis.

3.2 Conceptual framework

The definition of a clear and transparent conceptual framework is one of the most important steps in the construction of a composite indicator. The NRI 2022 is a multidimensional index comprising four pillars: *Technology*; *People*; *Government*; and *Impact*. Each pillar is further partitioned into three sub-pillars, each containing a different number of indicators (for a total of 59).

The structure of the NRI 2022 is summarized in **Table 1**. The selection of indicators was based on their conceptual relevance, literature reviews, expert opinions, and country coverage. Compared to NRI 2021, the methodology of three indicators was revised, one new indicator was introduced without replacing an existing one, three indicators were dropped without replacement, four indicators were introduced to replace previous indicators, one indicator changed name, and six indicators changed code. The last column of **Table 1** provides a summary of adjustments to the NRI 2022 framework.

Even though the aim of this statistical audit is not to address the conceptual relevance of the indicators underpinning the framework, it is worth noting that the developers have used a parsimonious approach by selecting a rather balanced number of indicators across pillars/sub-pillars.

Table 1. Framework of the NRI 2022

Pillar	Sub-pillar	Indicator	Note
1. TECHNOLOGY	1.1 Access	1.1.1 Mobile tariffs	
		1.1.2 Handset prices	
		1.1.3 FTTH/building Internet subscriptions	Replaces "Internet access"
		1.1.4 Population covered by at least a 3G mobile network	Changed code
		1.1.5 International Internet bandwidth	
		1.1.6 Internet access in schools	
	1.2 Content	1.2.1 GitHub commits	
		1.2.2 Internet domain registrations	Changed code
		1.2.3 Mobile apps development	Changed code
		1.2.4 AI scientific publications	Methodology revised /Changed Code
	1.3 Future Technologies	1.3.1 Adoption of emerging technologies	
		1.3.2 Investment in emerging technologies	
		1.3.3 Robot density	
		1.3.4 Computer software spending	
2. PEOPLE	2.1 Individuals	2.1.1 Mobile broadband internet traffic within the country	Replaces "Active mobile broadband subscriptions"
		2.1.2 ICT skills in the education system	
		2.1.3 Use of virtual social networks	
		2.1.4 Tertiary enrollment	
		2.1.5 Adult literacy rate	
		2.1.6 AI talent concentration	New indicator
	2.2 Businesses	2.2.1 Firms with website	
		2.2.2 GERD financed by business enterprise	
		2.2.3 Professionals	Methodology revised
		2.2.4 Annual investment in telecommunication services	Changed code
		2.2.5 GERD performed by business enterprise	Changed code
	2.3 Governments	2.3.1 Government online services	
		2.3.2 Publication and use of open data	
		2.3.3 Government promotion of investment in emerging technologies	
		2.3.4 R&D expenditure by governments and higher education	
3. GOVERNANCE	3.1 Trust	3.1.1 Secure Internet servers	
		3.1.2 Cybersecurity	
		3.1.3 Online access to financial account	
		3.1.4 Internet shopping	
	3.2 Regulation	3.2.1 Regulatory quality	
		3.2.2 ICT regulatory environment	
		3.2.3 Regulation of emerging technologies	Changed name from "Legal framework's adaptability to emerging technologies."
		3.2.4 E-commerce legislation	
		3.2.5 Privacy protection by law content	
	3.3 Inclusion	3.3.1 E-Participation	
		3.3.2 Socioeconomic gap in use of digital payments	
		3.3.3 Availability of local online content	
		3.3.4 Gender gap in Internet use	
		3.3.5 Rural gap in use of digital payments	

Pillar	Sub-pillar	Indicator	Note
4. IMPACT	4.1 Economy	4.1.1 High-tech and medium-high-tech manufacturing	
		4.1.2 High-tech exports	
		4.1.3 PCT patent applications	
		4.1.4 Domestic market size	Replaces "GDP per person engaged"
		4.1.5 Prevalence of gig economy	
		4.1.6 ICT services exports	
	4.2 Quality of Life	4.2.1 Happiness	
		4.2.2 Freedom to make life choices	
		4.2.3 Income inequality	
		4.2.4 Healthy life expectancy at birth	
	4.3 SDG Contribution	4.3.1 SDG 3: Good Health and Well-Being	
		4.3.2 SDG 4: Quality Education	
		4.3.3 SDG 5: Women's economic opportunity	Replaces "Females employed with advanced degrees"
		4.3.4 SDG 7: Affordable and Clean Energy	
		4.3.5 SDG 11: Sustainable Cities and Communities	Methodology changed

Source: Developers of the index and the European Commission's Joint Research Centre, 2022.

3.3 Data quality and availability

3.3.1 Treatment of missing data

Regarding data coverage, the general practice is to establish a threshold above which an indicator is excluded from the framework. For the NRI 2022 development, the inclusion of countries and indicators is based on the "double threshold" approach. In terms of country coverage, this means that only countries with data available for at least 70% of all indicators are included in the NRI 2022. In addition, countries need to pass a sub-pillar level data availability of at least 40%. In terms of indicator coverage, only indicators with availability of at least 50% of countries are included in the NRI 2022, with only exception, namely the new indicator "AI talent concentration" (i2.1.6) characterized by a very high incidence of missing values (69%).

Despite the absence of an absolute golden standard, in the statistical assessment of the NRI 2021 index, the JRC-COIN suggested including only indicators with a maximum of one-third of missing values (33%). However, when an indicator represents a very specific and central concept, a looser threshold of 40% missing countries could also be integrated into the structure. In this respect, the newly added indicator (i2.1.6) still generates concerns since the incidence of missing values is very high and well above the suggested exceptional lower limit of 40%. In light of this evidence (and some additional concerns that will be raised in the rest of this statistical audit), the JRC – COIN suggests considering the exclusion of this indicator from future editions of the index, if data coverage cannot be improved since its role in the composite may be unpredictable.

Moreover, the following indicators should be taken under observation as well, with the aim of improving their coverage or excluding/modifying them in future editions of the index (% of missing values in parenthesis):

- i1.1.6 International Internet bandwidth (38.2%);
- i1.3.3. Robot density (57.3%); and
- i4.3.2. SDG4 Quality education (39.7%).

The audit also examined the presence of outliers that could potentially bias the effect of the indicators on the aggregates. JRC-COIN recommends an approach for outlier identification based on the values of skewness and kurtosis,[17] *i.e.,* when the variables simultaneously have an absolute skewness higher than 2.0 and a kurtosis higher than 3.5.

According to the developers, outliers were detected in 19 indicators, eight of which had fewer than five outliers and eleven had five or more outliers. Prior to normalisation, these were treated according to the following rule: indicators with no more than four outliers were winsorised; those with five or more outliers were transformed by natural logarithms. One indicator, namely "AI scientific publications" (i1.2.4) neither winsorisation nor multiplication by a given factor plus logarithmic transformation brought the series within the desired parameters. For this particular case, a variant of the Box-Cox transformation, defined as Yeo-Johnson, was applied.

The approach followed by developers to treat the outliers seems correct. Nevertheless, we observed some inconsistencies while examining the data. First, starting from the non-normalised data, we detect only 18 indicators with outliers. Second, after examining the normalized data, the JRC-COIN realized that there are still two indicators (i1.1.4 "Population covered by at least a 3G mobile network" and i2.2.4 "Annual investment in telecommunication services") with an absolute skewness higher than 2.0 and a kurtosis higher than 3.5 (**Table 2**). Both indicators show negative skewness, which suggests that the minimum value of the indicators is far away from the rest of the distribution.

In the statistical assessment of the NRI 2021 index, this problem has already been emphasized. At that time, it concerned four different indicators. The JRC-COIN then focused on two of them (one of which is actually the indicator i1.1.4, "Population covered by at least a 3G mobile network") and performed a sensitivity analysis comparing the official NRI 2021 rankings and the ones that would have been obtained from the exclusion of the two variables. The difference between the two models did not seem to be particularly large. As a result, the JRC-COIN suggested considering these indicators as good candidates for further refinement of the index. Following this suggestion, we still believe it is reasonable to take this advice into account for next Network Readiness Index updates.

3.3.2 Normalisation

The indicators are rescaled to a 0-100 scale, with higher values denoting better performances. This is a common and usually desired practice in the construction of composite indicators. The normalisation is done using all of the countries for which data are available in order to reflect more closely the global situation for each indicator. The reverse normalization formula is applied to indicators where higher values imply worse outcomes. For the NRI 2022 edition of the index, reverse normalisation was needed for three indicators: i4.2.3 ("Income inequality"), i4.3.4 ("SDG 7: Affordable and clean energy") and i4.3.5 ("SDG 11: Sustainable Cities and Communities").

Table 2. Summary statistics of indicators comprised in the NRI 2022

Indicator	N	Missing	Mean	Min	Max	Std	Skew	Kurt
i1.1.1	131	0	56.9	0	100	23.1	-0.355	-0.605
i1.1.2	131	0	54.7	0	100	21.9	0.0549	-0.435
i1.1.3	105	19.8	30.1	0	100	19.5	0.761	0.679
i1.1.4	131	0	96.2	0	100	11.1	-6.07	46
i1.1.5	130	0.8	70.2	0	100	12.6	-1.31	6.77
i1.1.6	81	38.2	62.3	0	100	38.3	-0.381	-1.5
i1.2.1	130	0.8	18.3	0	100	25.3	1.65	1.84
i1.2.2	131	0	16	0	100	24.4	1.9	3
i1.2.3	131	0	75.1	0	100	19.7	-1.08	1.51
i1.2.4	99	24.4	51.6	0	100	23.8	-0.112	-0.79
i1.3.1	126	3.8	49.9	0	100	22.7	0.266	-0.441
i1.3.2	130	0.8	44.6	0	100	20.9	0.616	-0.24
i1.3.3	56	57.3	19.1	0	100	22.6	1.9	4.2
i1.3.4	122	6.9	22.4	0	100	18	1.14	1.83
i2.1.1	118	9.9	17.3	0	100	20	1.82	3.58
i2.1.2	131	0	47.2	0	100	22.5	0.0491	-0.65
i2.1.3	131	0	56.5	0	100	27.7	-0.783	-0.706
i2.1.4	127	3.1	31.6	0	100	20.9	0.299	-0.442
i2.1.5	106	19.1	82.6	0	100	21.8	-1.76	2.81
i2.1.6	41	68.7	27.6	0	100	25.7	1.87	3.05
i2.2.1	121	7.6	52.5	0	100	25.9	-0.0839	-1.07
i2.2.2	105	19.8	39.4	0	100	29.1	0.155	-1.16
i2.2.3	130	0.8	38.7	0	100	25.1	0.359	-0.965
i2.2.4	112	14.5	77.9	0	100	10.5	-3.54	26.1
i2.2.5	96	26.7	17.3	0	100	22.3	1.74	2.92
i2.3.1	130	0.8	65.6	0	100	21.5	-0.65	-0.124
i2.3.2	105	19.8	37.2	0	100	26.1	0.731	-0.271
i2.3.3	126	3.8	41.7	0	100	22	0.5	-0.179
i2.3.4	111	15.3	35.3	0	100	25.5	0.549	-0.553
i3.1.1	131	0	56.3	0	100	23.5	-0.0512	-1.04
i3.1.2	130	0.8	67.6	0	100	30.7	-0.748	-0.867
i3.1.3	123	6.1	35.4	0	100	24.9	0.806	-0.25
i3.1.4	114	13	36	0	100	29.9	0.518	-1.12

Indicator	N	Missing	Mean	Min	Max	Std	Skew	Kurt
i3.2.1	131	0	47.3	0	100	23.6	0.236	-0.843
i3.2.2	131	0	77.7	0	100	17	-1.59	3.94
i3.2.3	118	9.9	47.6	0	100	24.4	0.0518	-0.821
i3.2.4	130	0.8	84.1	0	100	26	-1.72	2.48
i3.2.5	131	0	62.9	0	100	20.8	-0.631	0.0653
i3.3.1	130	0.8	66.3	0	100	23.1	-0.518	-0.572
i3.3.2	127	3.1	69.7	0	100	23.8	-0.545	-0.554
i3.3.3	131	0	59.4	0	100	23.7	-0.284	-0.771
i3.3.4	106	19.1	64.3	0	100	19.4	-1.97	4
i3.3.5	123	6.1	59.1	0	100	19.8	-0.888	0.381
i4.1.1	107	18.3	33.6	0	100	24.3	0.543	-0.622
i4.1.2	122	6.9	31.1	0	100	26.3	0.711	-0.415
i4.1.3	116	11.5	17.3	0	100	25.4	1.75	2.2
i4.1.4	131	0	52.4	0	100	17.8	0.0637	0.127
i4.1.5	126	3.8	44.6	0	100	22.2	0.279	-0.453
i4.1.6	130	0.8	29.9	0	100	20.1	0.723	0.443
i4.2.1	127	3.1	61.2	0	100	20.5	-0.43	-0.286
i4.2.2	127	3.1	70.7	0	100	19	-1.1	1.71
i4.2.3	117	10.7	64.4	0	100	20.3	-0.746	0.349
i4.2.4	130	0.8	68.3	0	100	20.6	-0.801	0.0223
i4.3.1	130	0.8	65	0	100	24	-0.648	-0.502
i4.3.2	79	39.7	50	0	100	21.5	-0.204	-0.666
i4.3.3	131	0	72.5	0	100	22.1	-1.21	1.57
i4.3.4	131	0	73.5	0	100	20	-1.69	3.14
i4.3.5	130	0.8	63.8	0	100	22.7	-0.306	-0.732

Note: The cells with the percentage of missing values exceeding 33%, as well as those with the values of skewness and kurtosis simultaneously exceeding the threshold are written in light red.

3.4 Statistical coherence

The assessment of statistical coherence consists of a multi-level analysis of the correlations of indicators, and a comparison of NRI 2022 rankings with their constituent goals.[18]

3.4.1 Correlation analysis

The statistical coherence of an index should be considered a necessary but not sufficient condition for a sound index. Given that the statistical analysis is mostly based on correlations, the correspondence of every index to a real-world phenomenon needs to be critically addressed by developers and experts, because "correlations do not necessarily represent the real influence of the individual indicators on the phenomenon being measured" (OECD and JRC, 2008).[19] This influence relies on the interplay between both conceptual and statistical soundness. The degree of coherence between the conceptual framework and the statistical structure of the data is an important factor for the reliability of an index.

Correlation analysis is used to assess the extent to which the observed data supports the conceptual framework. Within each level of the index, there should ideally be positive significant correlations. The JRC-COIN recommends a correlation threshold of 0.3 above which the correlation is considered high enough to say that two elements share a significant amount of their variability. The framework should avoid redundancy, which can be identified by very high correlations (>=0.92). This is due to the fact that if two indicators are collinear, and it may result in double counting (and thus over-weighting) of the same phenomenon.

In what follows, we report the correlations between indicators in the same pillar, between indicators and their aggregates (sub-pillar, pillars, and NRI 2022), and finally between sub-pillars, pillars and the NRI 2022 index.

Correlation analysis between indicators and aggregates

Figure 1 shows the correlation coefficients between indicators within the same pillar. Boxes within each pillar identify indicators grouped into respective sub-pillars. The correlations within the "Technology pillar" (i1), as well as in the respective sub-pillars, are mostly positive and significant, and above the threshold level (0.30), with the exception of the "Content" (i1.1) sub-pillar, where the correlation of i.1.1.3 ("FTTH/building Internet subscriptions") is significantly different from zero only with the indicators i1.1.1 ("Mobile tariffs") and 1.1.5 ("International Internet bandwidth"). This evidence may suggest that the i1.1.3 indicator does not fully cooperate with the others, which could reduce the impact of the aggregate to which it belongs in the following aggregation steps. Indeed, as emerges from **Figure 2**, the correlation between i.1.1.3 and its corresponding pillar and NRI 2022 is lower than the other (around 0.30).

As for the "People pillar" (i2), the correlation structure for two indicators within the "Individuals" sub-pillar (i2.1) is weak and often not significantly different from zero. Moreover, the indicator i2.1.6 ("AI talent concentration") negatively correlates with i2.1.5 ("Adult literacy rate") and does not significantly differ from zero for the other indicators, with the exception of i.2.1.1 ("Mobile broadband internet traffic within the country"), where it is positive and statistically significant.

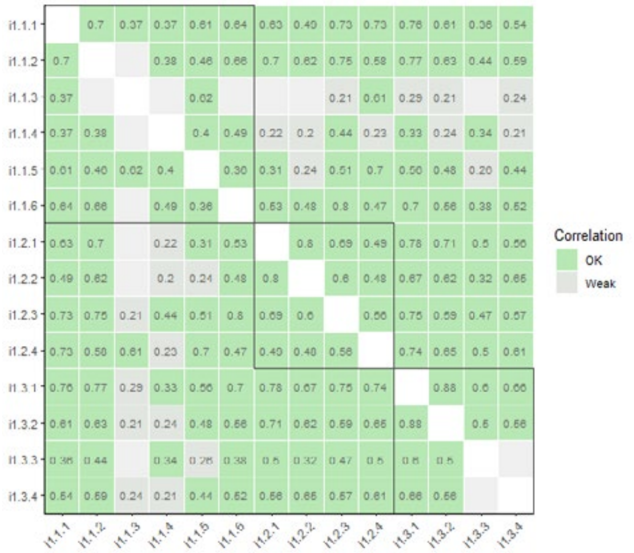
A strong negative correlation between the two aforementioned indicators suggests that they are related to each other but in in a conflicting way. Furthermore, statistically insignificant correlations suggest that i2.1.6 does not entirely cooperate with the other indicators in the respective sub-pillar. However, when looking at the correlations between the indicators and their aggregates (**Figure 2**), the performance of i2.1.6 is generally good at the sub-pillar and pillar level, while it does not seem to contribute to the overall index. Indeed, the correlation between i2.1.6 and NRI 2022 is not statistically different from zero. It is worth noting, however, that the interpretation of this result should be taken with caution since the share of missing values associated to this indicator is extremely high (68.7%).

The relationship between indicators within the remaining two pillars is generally satisfactory. Most of the correlations are above 0.30 and below 0.92, and no indicator is negatively correlated with the other elements of the respective sub-pillar, which suggests that most of the sub-pillars in the "Governance" (i3) and "Impact" (i4) pillars are statistically consistent. The only exception is the sub-pillar "SDG Contribution" (i4.3), where the indicator i4.3.4 ("SDG 7: Affordable and Clean Energy") weakly correlates with the other indicators, but not in a critical way.

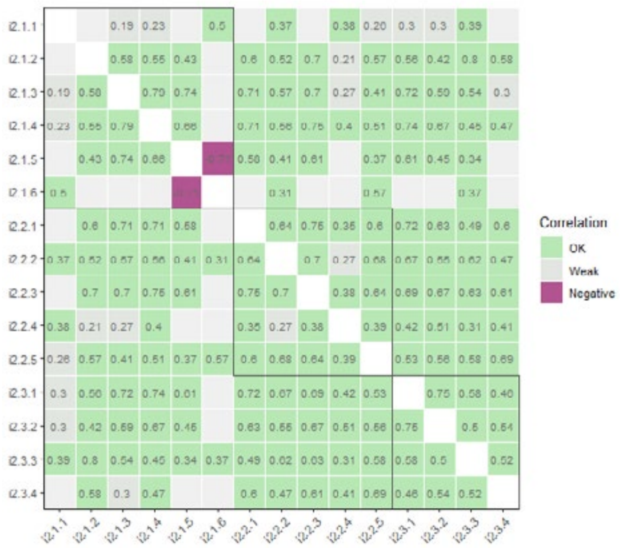
A general suggestion would be to continue monitoring the indicators with very low and statistically insignificant correlations and their position in the framework for future index editions in order to check their behaviour and, if necessary, modify or substitute them. Particular attention is suggested to the "People pillar" (i2) and the indicator i2.1.6 showing a negative and non-significant correlation. We would particularly suggest its substitution with another indicator that would fit conceptually into the pillar, unless a better data coverage is available and it determines an improved association with the other indicators.

Figure 1. Correlation between indicators in the same pillar

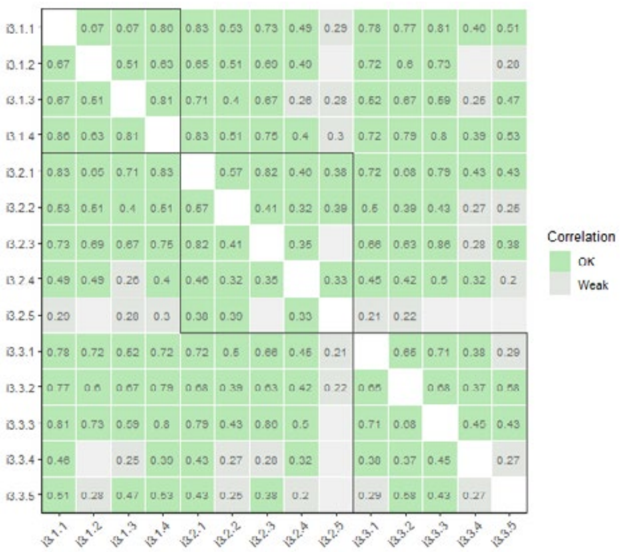
Technology pillar (i1)



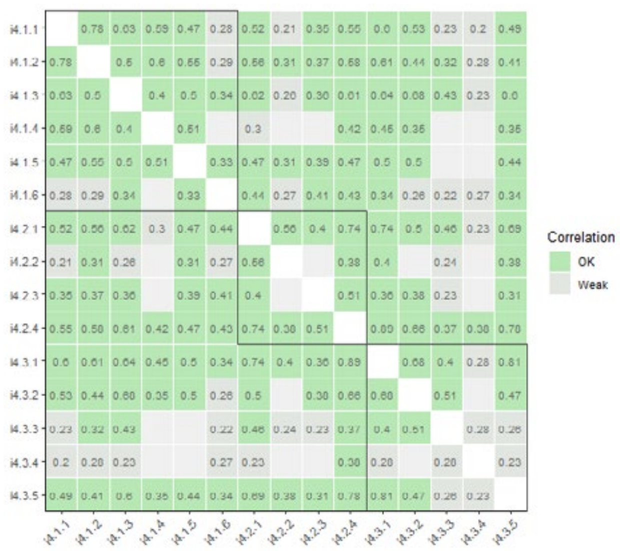
People pillar (i2)



Governance pillar (i3)



Impact pillar (i4)

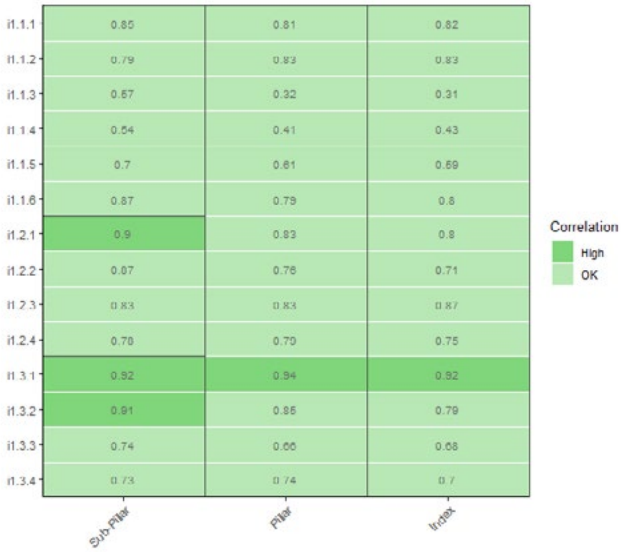


Source: European Commission's Joint Research Centre, 2022.

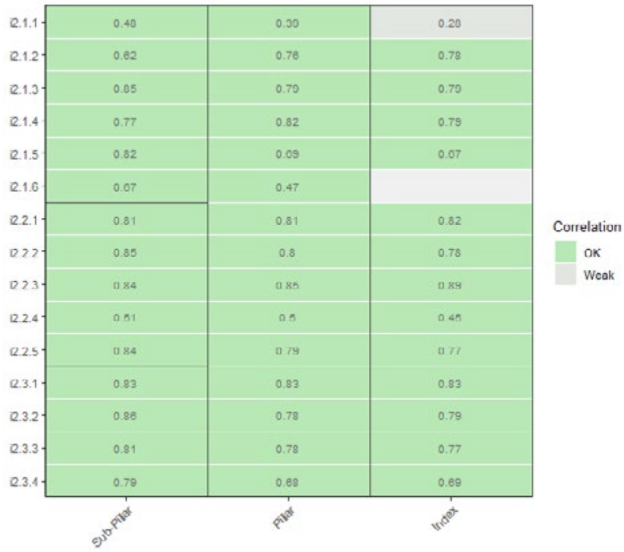
Note: Numbers represent the Pearson correlations coefficients. Good correlations (i.e., Pearson correlation coefficients between 0.30 and 0.92) are highlighted in green. Weak correlations (lower or equal than 0.30) are written in grey. Statistically insignificant correlations are those with the Pearson correlation coefficients lower than 0.17 and are displayed as empty cells.

Figure 2. Correlations between indicators and their aggregates (sub-pillars, pillars and index)

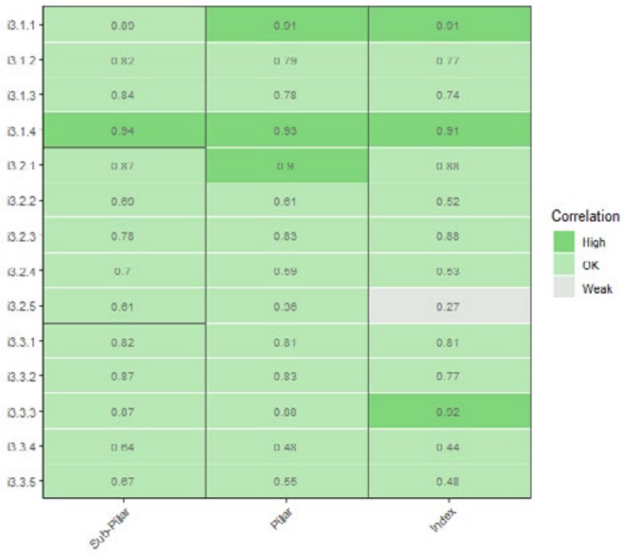
Technology pillar (i1)



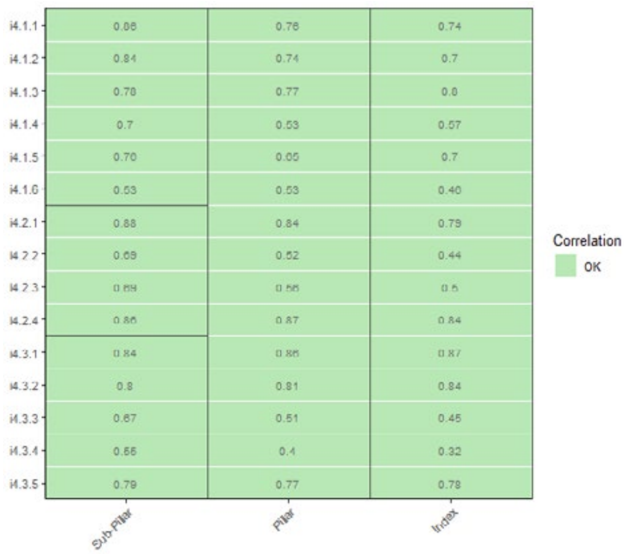
People pillar (i2)



Governance pillar (i3)



Impact pillar (i4)



Source: European Commission's Joint Research Centre, 2022.

Note: Numbers represent the Pearson correlations coefficients. Good correlations (i.e., Pearson correlation coefficients between 0.30 and 0.92) are highlighted in green. Weak correlations (lower or equal than 0.30) are written in grey.

Correlations between sub-pillars, pillars and NRI 2022

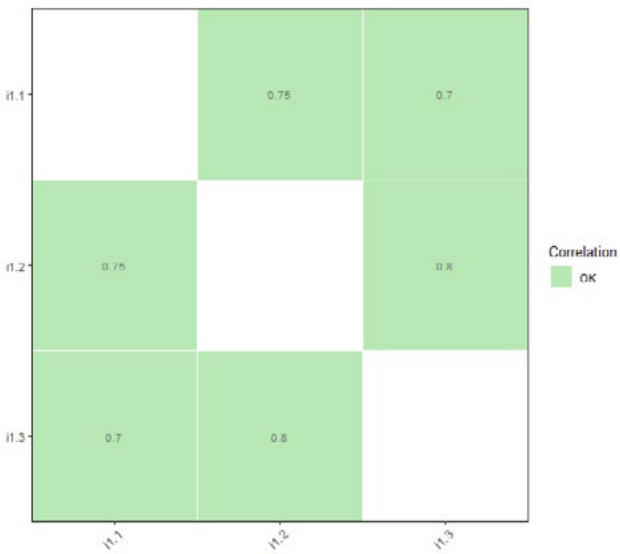
The correlation between the aggregates represents the most important element of the analysis of statistical coherence as it reflects the relations between the defined concepts. The evidence from **Figure 3**, **Figure 4** and **Figure 5** suggests that all pillars appear consistent, with the sub-pillars being well correlated with each other. The NRI 2022, therefore, has a generally satisfactory correlation structure, as evidenced by strong correlations between the sub-pillars, pillars, and the index.

Nevertheless, a note of caution is necessary. Some sub-pillars tend to be extremely correlated with their respective pillars. More precisely, the sub-pillars "Content" (i1.2), "Governments" (i2.3), "Trust" (i3.1) and "Inclusion" (i3.3) are highly correlated with their pillars (correlations exceeding 0.92), suggesting that there may be a risk of redundancy at the pillar level. This is partly mitigated at the index level (**Figure 4**), where two pillars, namely i1.2 and i3.3 show good positive correlations that do not exceed the 0.92 set threshold.

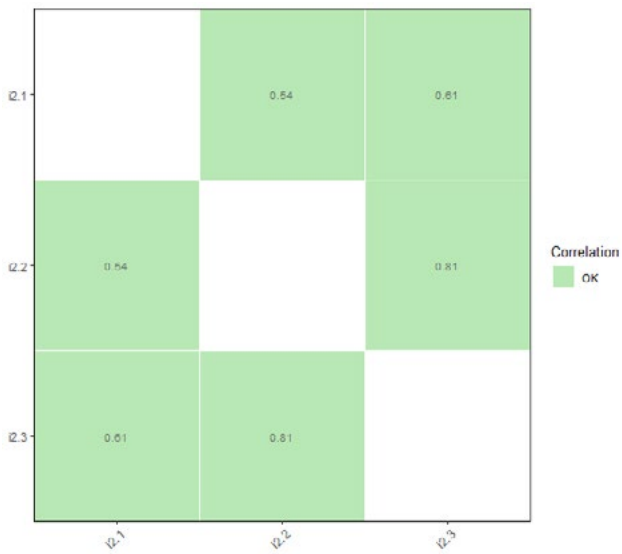
The highest aggregation steps, between pillars and from pillars to NRI, also display very high correlations, all above 0.9. High statistical reliability among the main components can be the result of redundancy of information. Overall, NRI indicators, pillars, and sub-pillars seem to be measuring similar phenomena. The exclusion of some elements from the framework will probably have a small effect on the final result. Keeping in mind the importance of parsimony, the reduction in the number of indicators could be an interesting option that the JRC-COIN suggests to consider for future editions.

Figure 3. Correlations between sub-pillars in the same pillar

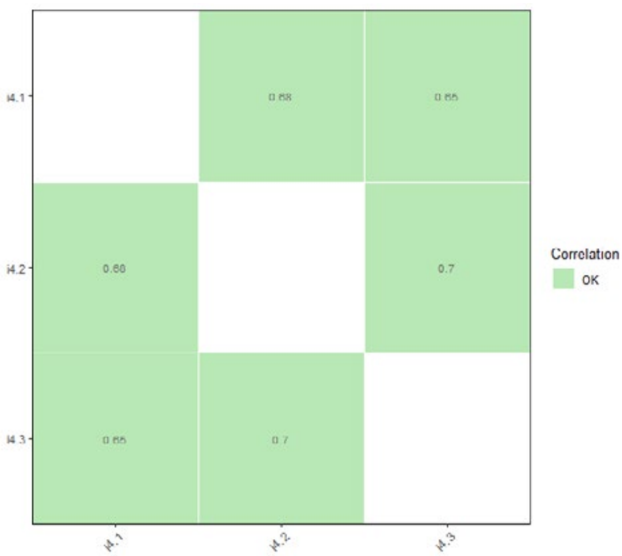
Technology pillar (i1)



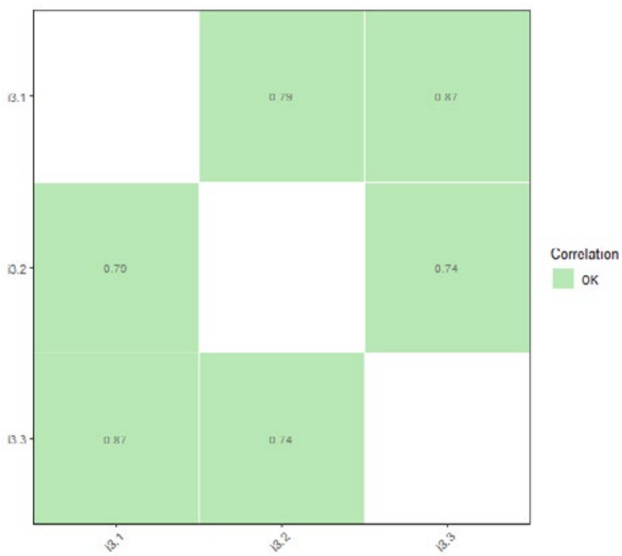
People pillar (i2)



Governance pillar (i3)



Impact pillar (i4)

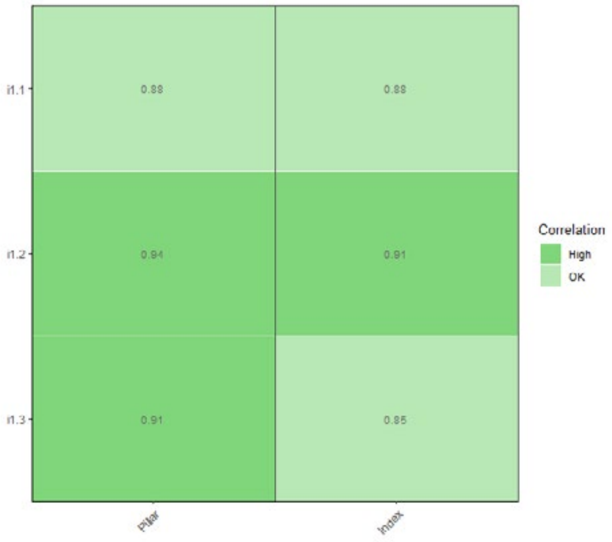


Source: European Commission's Joint Research Centre, 2022.

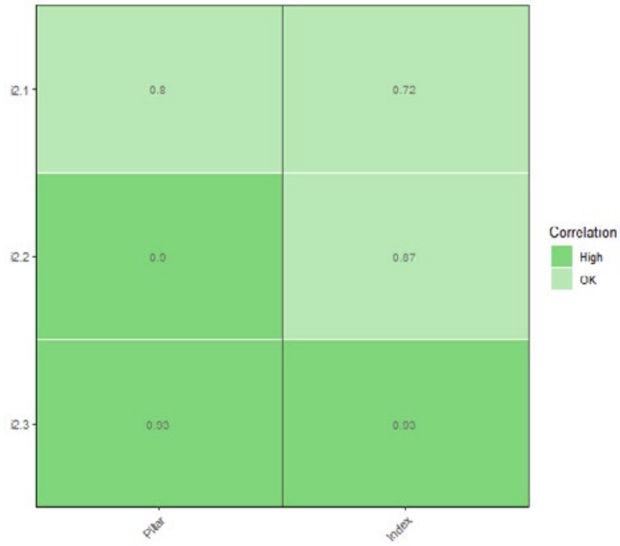
Note: Numbers represent the Pearson correlations coefficients. Good correlations (i.e., Pearson correlation coefficients between 0.30 and 0.92) are highlighted in green.

Figure 4. Correlations between sub-pillars, pillars and NRI 2022

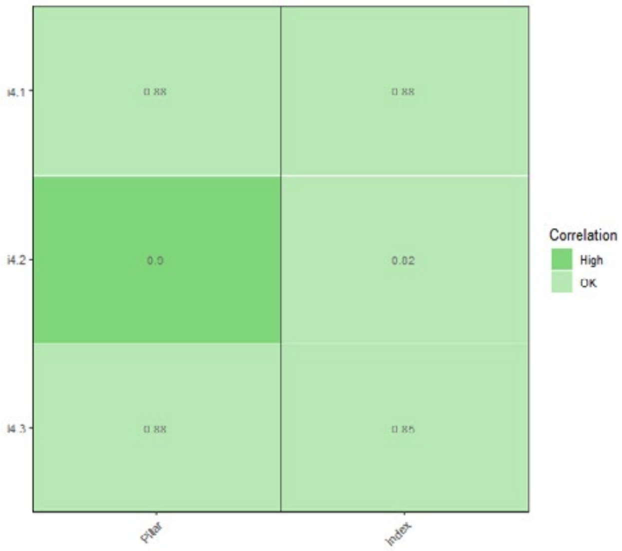
Technology pillar (i1)



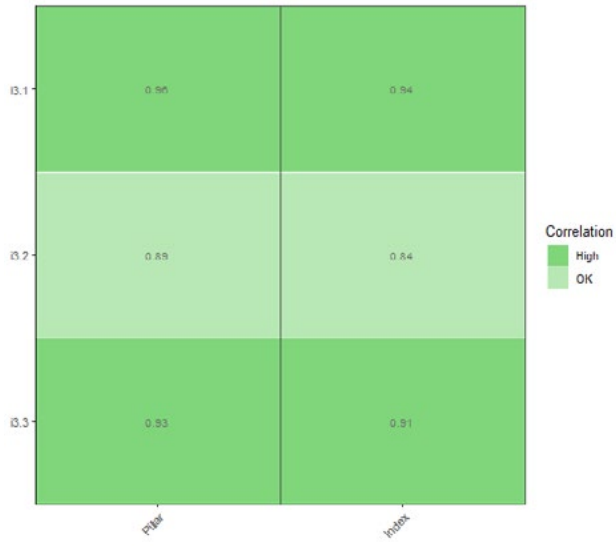
People pillar (i2)



Governance pillar (i3)



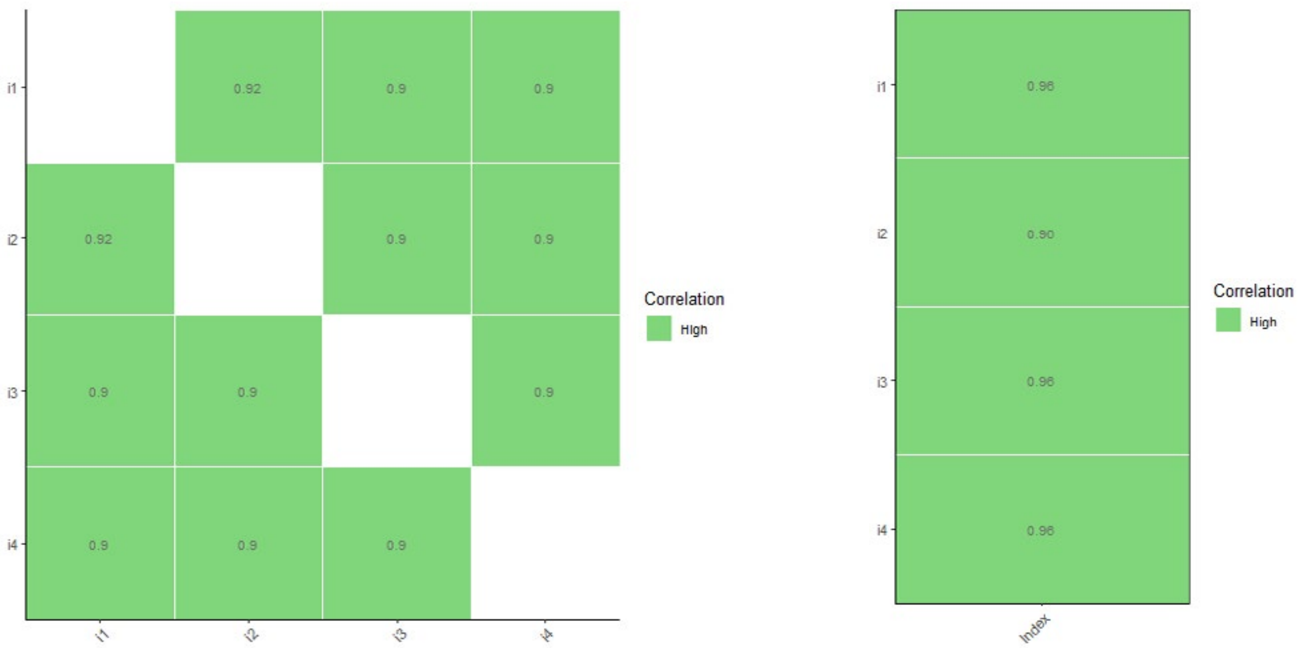
Impact pillar (i4)



Source: European Commission's Joint Research Centre, 2022.

Note: Numbers represent the Pearson correlations coefficients. Good correlations (i.e., Pearson correlation coefficients between 0.30 and 0.92) are highlighted in green.

Figure 5. Correlations between pillars, and between pillars and NRI 2022



Source: European Commission's Joint Research Centre, 2022.

Note: Numbers represent the Pearson correlations coefficients. Good correlations (i.e., Pearson correlation coefficients between 0.30 and 0.92) are highlighted in green.

Figure 5 shows the correlation between the pillars and between the pillars and NRI 2022. This is the most important level of aggregation because it represents the consistency of the overall concept. All correlations are significant and positive (> 0.30). "Technology" (i1) and "People" (i2) pillars are highly correlated (0.92), suggesting that there may be a risk of redundancy at the pillar level. This issue does not appear to be alleviated at the index level, where correlations are even higher (0.96), and exceeding the redundancy threshold (set at 0.92). Also, the remaining pillars show very high correlations with the index. This is not surprising evidence given the high correlations between sub-pillars, pillars, and index reported in **Figure 4**. Although not a critical issue for the reliability of the NRI, this should be taken into account in the Index's upcoming revisions.

3.4.2 Principal components analysis of the NRI 2022

As a further step in the analysis of statistical coherence, we perform a principal component analysis (PCA). The aim of principal component analysis is to assess to what extent the conceptual framework is confirmed by statistical approaches. The objective is to observe only one principal component with an eigenvalue greater than 1, or able to explain more than 70% of the total variance. The achievement of these thresholds suggests the presence of a common, unidimensional phenomenon underlying the pillars.

The four pillars share a single statistical dimension that summarizes 92.6% of the total variance (**Table 3**). Moreover, the four loadings (correlation coefficients) of these pillars are almost equal (0.96). This similarity suggests that the four pillars make roughly equal contributions to the variation of the NRI 2022. The second principal component is much less influential since it accounts for only 2.85% of the total variance.

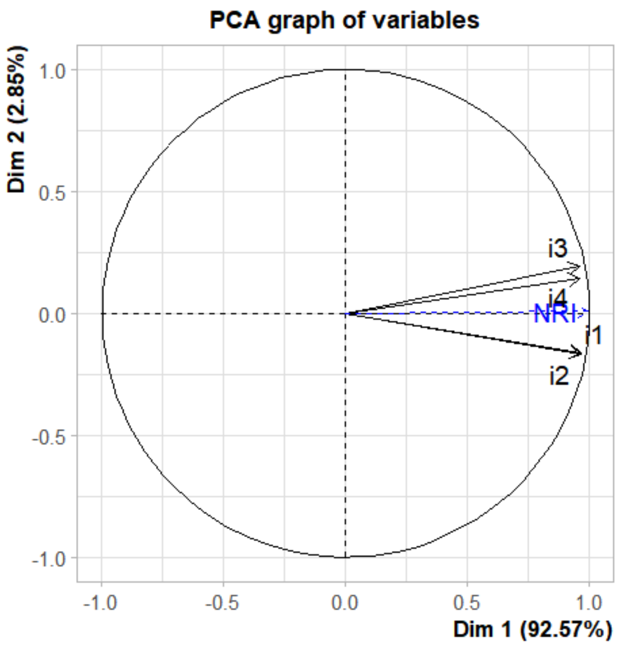
Table 3. Eigenvalues and explained variance for the first ten principal components

PC	Eigenvalue	% of variance	Cumulative % of variance
PC1	3.70	92.57	92.57
PC2	0.11	2.85	95.42
PC3	0.10	2.59	98.00
PC4	0.08	1.99	100

Source: European Commission's Joint Research Centre, 2022.

Figure 6 illustrates the projections of the pillars onto the plane spanned by the first two principal components in a "factor map". The correlation between each pillar and the principal component is given by the projection of the NRI 2022 vector onto the component axis. The trajectories of pillars i1 and i2 overlap, while the remaining two pillars are very close to each other, suggesting that there may be a risk of redundancy at the index level, which offers a significant room for simplification. This is not a surprising evidence and is in line with the results obtained in the correlation analysis.

Figure 6. Factor map of the four pillars and comparison with the overall NRI 2022



Source: European Commission's Joint Research Centre, 2022.

Table 4. Distribution of differences between pillars and NRI 2022 rankings

Shift respect to NRI	Technology	People	Governance	Impact
More than 30 positions	0.80%	0.80%	0.00%	1.50%
16 to 30 positions	11.50%	13.00%	11.50%	17.60%
More than 15 positions	12.30%	13.80%	11.50%	19.10%
6 to 15 positions	34.40%	37.40%	45.80%	34.40%
Up to 5 positions	45.00%	44.30%	39.70%	40.50%
0 positions	8.40%	4.60%	3.10%	6.10%

Source: European Commission's Joint Research Centre, 2022.

Moreover, PCA results also confirm the presence of a single latent dimension in each of the four pillars (one component with an eigenvalue greater than 1) that captures between close to 77% ("People pillar") up to 87% ("Governance pillar") of the total variance in the three underlying sub-pillars.

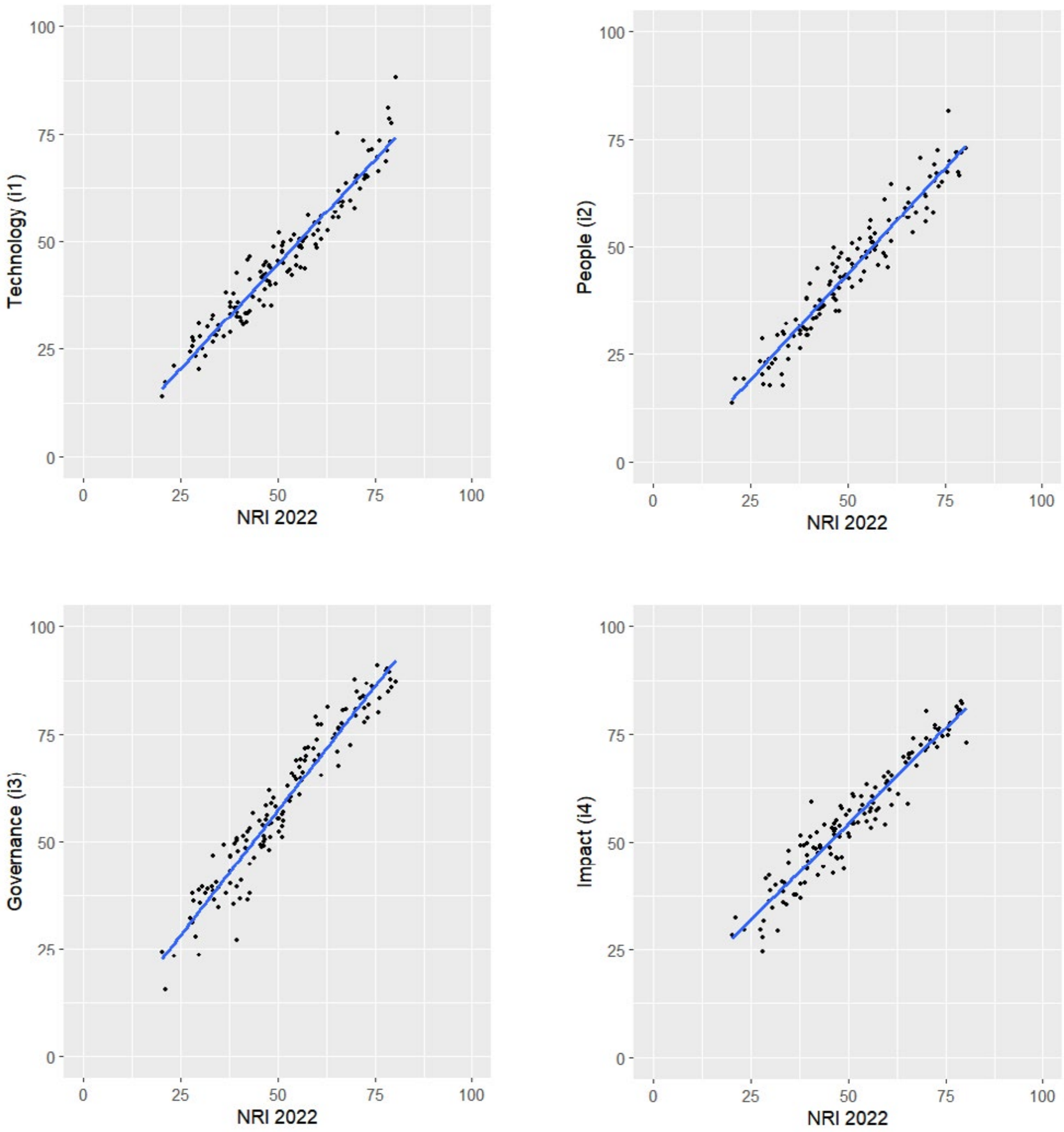
3.4.3 Added value of the NRI 2022

High statistical reliability among the main components of an index can be the result of redundancy of information. The main objective of this exercise is to test whether the NRI 2022 rankings highlight aspects of countries' network readiness that do not emerge by looking into the three pillars separately. In other words, NRI 2022 should tell us more about the underlying concept than each of the four pillars alone.

The results in **Table 3** suggest that the percentage of countries where the NRI 2022 rankings differ by 15 or more positions with respect to the pillars ranges from 11.5% in the case of i3 ("Governance") to 19.10% in the case of i4 ("Impact"). In other words, NRI 2022 rankings depict aspects of countries' network readiness that do not emerge from each of the four single pillars for less than 20% of the countries considered. **Figure 7** represents graphically the relationship between the NRI 2022 and its constituent elements. In line with the evidence in **Table 3** and the correlation coefficients reported in **Figure 5**, the four pillars appear linearly associated with the index.

Even though the presence of a strong concordance among the aggregates does not represent a problem "per se", it offers a room for simplification. Therefore, in order to improve readability, the developers may consider excluding some elements of the index without jeopardising the integrity of the pillars or the overall index.

Figure 7. Relationship between the pillars and the NRI 2022



Source: European Commission's Joint Research Centre, 2022.

3.5 Impact of modelling assumptions on the NRI 2022 results

3.5.1 Uncertainty analysis

A fundamental step in the statistical analysis of a composite indicator is to assess the effect of different modelling assumptions on the country rankings. Despite the efforts in the development process, there is an unavoidable subjectivity (or uncertainty) in the resulting choices. This subjectivity can be explored by comparing the results obtained under different alternative assumptions. The literature on this topic[20] suggests assessing the robustness of the index by means of a *Monte Carlo simulation* and by applying a multi-modelling approach. This also assumes "error-free" data as possible errors have already been corrected in the preliminary stage of the index construction before the audit.

This Index analysed in this document, like most composite indicators, is the outcome of several choices. Among other things, these choices usually include: (i) the underlying theoretical framework; (ii) the indicators selected; (iii) the imputation of missing values; (iv) the weights assigned; and (v) the aggregation method. Some of these choices may be based on expert opinion or other consideration driven by statistical analysis or the need to ease communication or draw attention to specific issues.

This section aims to test the impact of varying some of these assumptions within a range of plausible alternatives in an uncertainty analysis. The objective is therefore to try to quantify the uncertainty in the ranks of NRI 2022, which can demonstrate the extent to which countries can be differentiated by their scores and ranks. The modelling issues considered in the robustness assessment of the NRI 2022 are:

- the aggregation formula; and
- the pillars' weights.

The following paragraphs deal with each of these in turn.

Aggregation formula

The developers of the NRI 2022 opted for the arithmetic mean with equal weight for the four pillars, which implies a strong compensability allowing for an outstanding performance in some aspects to balance the weaknesses in others and vice-versa. In other words, arithmetic averaging treats countries with outstanding high and low results in the same way as it treats a more "balanced" countries showing average results.

To assess the impact of this compensability issue, the JRC-COIN relaxed the strong perfect substitutability assumption inherent in the arithmetic average and considered instead the geometric average, which is a partially compensatory approach that rewards economies with balanced profiles and motivates economies to improve in the NRI pillars in which they perform poorly, and not just in any NRI pillar. The comparison of the two aggregation approaches, hence, should be able to highlight countries with unbalanced profiles.

Weights

Weights. Monte Carlo simulation comprised 1 000 runs of different sets of weights for the four pillars. The weights are the result of a random extraction based on uniform continuous distributions centred in the reference values (0.25) plus or minus 20% of these values.

As summarised in **Table 5**, four models were tested comparing the different aggregation formulas, the different imputation methods and applying the 1,000 runs of different sets of weights resulting in a total of 2,000 runs of simulations.

The main results obtained from the robustness analysis are shown in **Figure 8**, with median ranks and 90% intervals computed across the 2,000 Monte Carlo simulations. Countries are ordered from best to worst according to their NRI 2022 rank, where the blue dots represent the median rank among the simulations. For each country, the error bars represent the 90% interval across all simulations, that is, from the 5th to the 95th percentile of the country's rank among all the simulations.

The NRI 2022 ranks are shown to be representative of a plurality of scenarios and extremely robust to changes in the assumptions. Considering the median rank across the simulated scenarios as being representative of these scenarios, the fact that the NRI 2022 rank is close to the median rank (less than three positions away) for 100% of the countries suggests that NRI 2022 is a suitable and stable summary measure. Furthermore, the majority of the countries' ranks (124 out of 131) hardly vary across simulations (5 positions or less). Only Croatia, Mauritius, Jamaica, Kenya, Albania, Lebanon, and Laos are showing a simulated interval larger than 5 positions but still smaller than 10. This result is a direct effect of the correlation structure among pillars and the index. It makes the NRI 2022 rankings very stable for all countries.

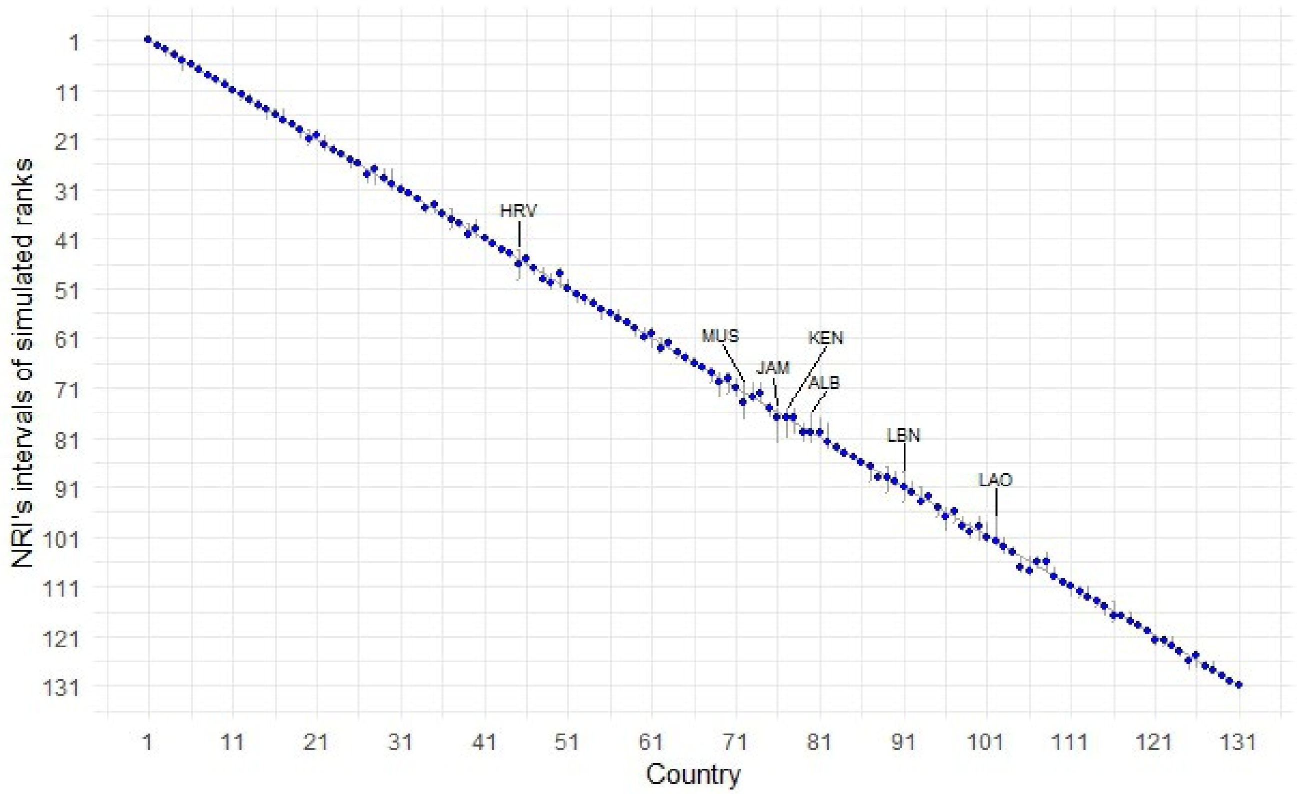
Finally, **Table 6** reports the NRI 2022 country ranks along with the simulated intervals (the central 90 percentiles observed among the 2,000 scenarios) for full transparency and information, in order to better appreciate the robustness of these ranks to the computation methodology and to facilitate analysis of the behaviour of specific countries in response to perturbations.

Table 5. Alternative assumptions considered in the analysis

	Reference	Alternative
I. Aggregation formula	Arithmetic average	Geometric average
II. Weighting system	Equal weights	Varying
Technology	0,25	U [0.2; 0.3]
People	0,25	U [0.2; 0.3]
Governance	0,25	U [0.2; 0.3]
Impact	0,25	U [0.2; 0.3]

Source: European Commission's Joint Research Centre, 2022.

Figure 8. Robustness analysis: NRI 2022 rank vs median rank and 90% intervals.



Source: European Commission's Joint Research Centre, 2022.

Table 6. NRI 2022 ranks and 90 percent confidence intervals

ISO	Index	interval	ISO	Index	interval	ISO	Index	interval
USA	1	[1-1]	HRV	45	[43-49]	PAK	89	[87-92]
SGP	2	[2-2]	THA	46	[45-46]	BIH	90	[88-91]
SWE	3	[3-4]	URY	47	[46-48]	LBN	91	[88-94]
NLD	4	[3-5]	TUR	48	[47-50]	TTO	92	[90-92]
CHE	5	[4-7]	GRC	49	[48-51]	PRY	93	[91-94]
DNK	6	[5-6]	UKR	50	[47-51]	CPV	94	[93-94]
FIN	7	[6-7]	BGR	51	[49-51]	KGZ	95	[95-97]
DEU	8	[8-9]	ROU	52	[52-54]	SLV	96	[95-100]
KOR	9	[8-10]	OMN	53	[52-54]	BOL	97	[95-98]
NOR	10	[9-10]	BHR	54	[53-54]	SEN	98	[97-100]
CAN	11	[11-11]	SRB	55	[55-57]	CIV	99	[98-101]
GBR	12	[12-13]	CRI	56	[55-57]	DZA	100	[97-102]
JPN	13	[12-14]	ARG	57	[55-57]	RWA	101	[98-102]
AUS	14	[13-15]	KAZ	58	[58-58]	LAO	102	[97-103]
ISR	15	[14-17]	IDN	59	[59-61]	GHA	103	[101-104]
FRA	16	[15-16]	MEX	60	[59-62]	KHM	104	[103-105]
LUX	17	[15-18]	IND	61	[59-63]	HND	105	[105-108]
AUT	18	[17-18]	VNM	62	[61-64]	GTM	106	[105-109]
NZL	19	[19-21]	KWT	63	[61-63]	TZA	107	[105-107]
IRL	20	[19-22]	ARM	64	[63-65]	BWA	108	[104-108]
BEL	21	[19-21]	MNE	65	[64-66]	NGA	109	[107-109]
EST	22	[20-23]	COL	66	[65-66]	BEN	110	[110-110]
CHN	23	[22-23]	MDA	67	[67-68]	TJK	111	[111-113]
ISL	24	[24-24]	ZAF	68	[67-70]	NPL	112	[111-113]
CZE	25	[25-27]	MKD	69	[68-73]	ZMB	113	[111-114]
ESP	26	[25-26]	JOR	70	[68-72]	CMR	114	[113-115]
SVN	27	[27-30]	PHL	71	[69-73]	NAM	115	[115-117]
ARE	28	[26-30]	MUS	72	[70-77]	UGA	116	[114-118]
PRT	29	[27-30]	EGY	73	[70-74]	GMB	117	[116-117]
HKG	30	[27-31]	AZE	74	[70-74]	ZWE	118	[116-118]
MLT	31	[30-31]	GEO	75	[74-77]	MWI	119	[119-119]
ITA	32	[32-32]	JAM	76	[75-82]	MDG	120	[120-120]
LTU	33	[33-33]	KEN	77	[75-81]	MLI	121	[121-123]
POL	34	[34-36]	PER	78	[75-80]	BFA	122	[121-123]
SAU	35	[34-36]	MAR	79	[78-82]	ETH	123	[121-123]
MYS	36	[35-37]	ALB	80	[76-82]	GIN	124	[124-125]
SVK	37	[35-39]	LKA	81	[77-81]	MOZ	125	[125-128]
CYP	38	[37-39]	IRN	82	[78-83]	SWZ	126	[124-127]
LVA	39	[38-41]	PAN	83	[82-84]	LSO	127	[126-128]
RUS	40	[37-41]	TUN	84	[83-85]	AGO	128	[126-128]
HUN	41	[40-41]	DOM	85	[84-85]	COD	129	[129-129]
QAT	42	[42-42]	ECU	86	[86-87]	BDI	130	[130-130]
CHL	43	[43-44]	MNG	87	[86-90]	TCD	131	[131-131]
BRA	44	[43-45]	BGD	88	[88-90]			

Source: European Commission's Joint Research Centre, 2022.

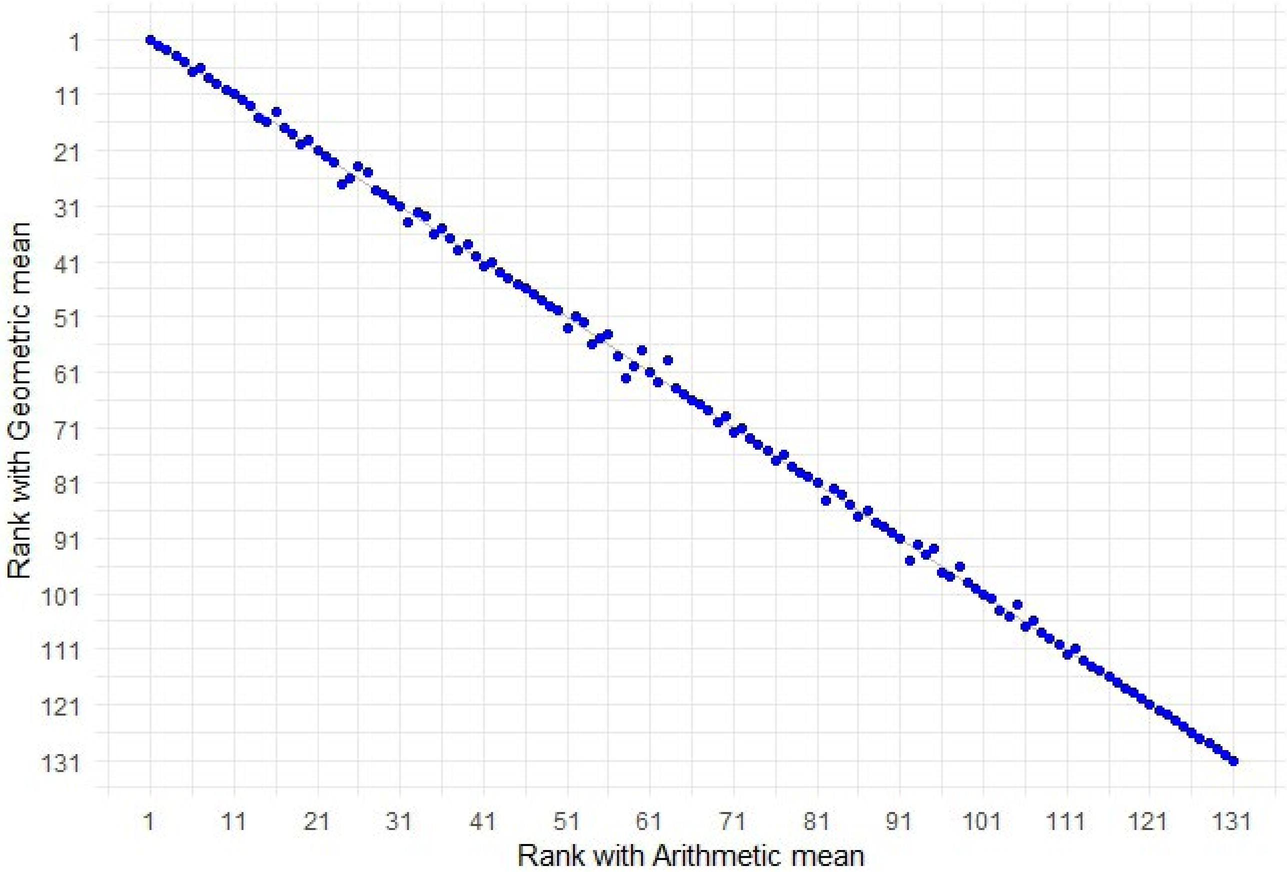
3.5.2 Sensitivity analysis

Complementary to the uncertainty analysis, sensitivity analysis has been used to identify which of the modelling assumptions have the highest impact on certain country ranks.

Figure 9 compares the ranks derived from NRI 2022 with those that would have been obtained by changing the aggregation procedure from arithmetic to geometric mean. This comparison allows us to inquire whether the variability in the rank intervals is originating from the modelling assumptions underlying the aggregation procedure or by the weights' perturbation. When countries are placed under the main diagonal their values are worse in rank positions when computed with the geometric mean. This is probably the case of countries penalised by the geometric mean because of their unbalanced profiles.

In any case, the aggregation formula does not significantly affect the NRI 2022 ranks. This result is a direct consequence of the very strong correlation structure described in Section 4. Basically, when the pillars are strongly correlated it is difficult to have countries with unbalanced values, hence the result obtained from the arithmetic and geometric means do not differ much.

Figure 9. Sensitivity Analysis: Comparison of ranks according to arithmetic and geometric mean.



Source: European Commission's Joint Research Centre, 2022.

3.6 Efficiency frontier in the NRI by data envelopment analysis

Is there a way to benchmark economies' multidimensional performance on network readiness without imposing a fixed and common set of weights to the four pillars of the NRI - Technology, People, Governance, Impact - that may not be fair to a particular country/economy?

Several network readiness-related policy issues at the national level entail an intricate balance between global priorities and economy-specific strategies. Comparing the multidimensional performance on network readiness by subjecting all 131 economies included in the NRI to a fixed and common set of weights of the four NRI pillars may prevent acceptance of the index on the grounds that a given weighting scheme might not be fair to a particular economy. An appealing feature of the data envelopment analysis (DEA) applied in real decision-making settings is the determination of endogenous weights that maximize the overall score of each country in a given dataset.

In this type of analysis, the assumption of fixed pillar weights common to all 131 economies is relaxed, whereby country-specific weights that maximize a country's network readiness score are determined endogenously by DEA.[21] In theory, each country/economy is free to decide on the relative contribution of each network readiness pillar to its score, so as to achieve the best possible score in a computation that reflects its strategy for network readiness. In practice, the DEA method assigns a higher (or lower) contribution to those pillars in which a country/economy is relatively strong (or weak). Reasonable constraints are applied to the weights to preclude the possibility of an economy achieving a perfect score by assigning a zero weight to weak pillars: for each economy, the share of each pillar score (i.e., the pillar score multiplied by the DEA weight over the total score) has upper and lower bounds of 10 percent and 40 percent, respectively. The DEA score is then measured as the weighted average of all four network readiness pillar scores, where the weights are the economy-specific DEA weights, compared to the best performance among all other economies with those same weights. The DEA scores, ranging between 0 (lowest) and 1 (highest) can be interpreted as a measure of the "distance to the efficiency frontier."

Table 7 presents the pillar shares and DEA scores for the top 25 economies in the NRI 2022, next to the NRI 2022 ranks. All pillar shares are in accordance with the starting point of granting leeway to each economy when assigning shares, while not violating the upper and lower bounds (10 percent and 40 percent). The pillar shares are quite diverse, reflecting the different national strategies for network readiness. These pillar shares can also be seen to reflect different economies' comparative advantage in certain NRI pillars vis-à-vis all other economies and all pillars. For example, seven countries – the United States of America, Singapore, Sweden, the Netherlands, Switzerland, Denmark, and Finland - obtain a perfect DEA score of 1.00 and hence they are all on the frontier of efficiency when it comes to network readiness. In the case of the United States, this is achieved by assigning 36-37 percent of its DEA score to the Technology and People pillars, while 14 percent of the USA's DEA score comes from the Governance and Impact pillars. Having different strengths, Singapore has assigned 32 percent and 40 percent of its DEA score to the People and Impact pillars, while just 11 percent and 16 percent of its DEA score comes from the Technology and Governance pillars. The top seven countries are closely followed by the Rep. of Korea (0.99) and Norway (0.97) in terms of efficiency. **Figure 10** shows how close the DEA scores and the NRI 2022 scores are for all 131 economies (Pearson correlation of 0.999).

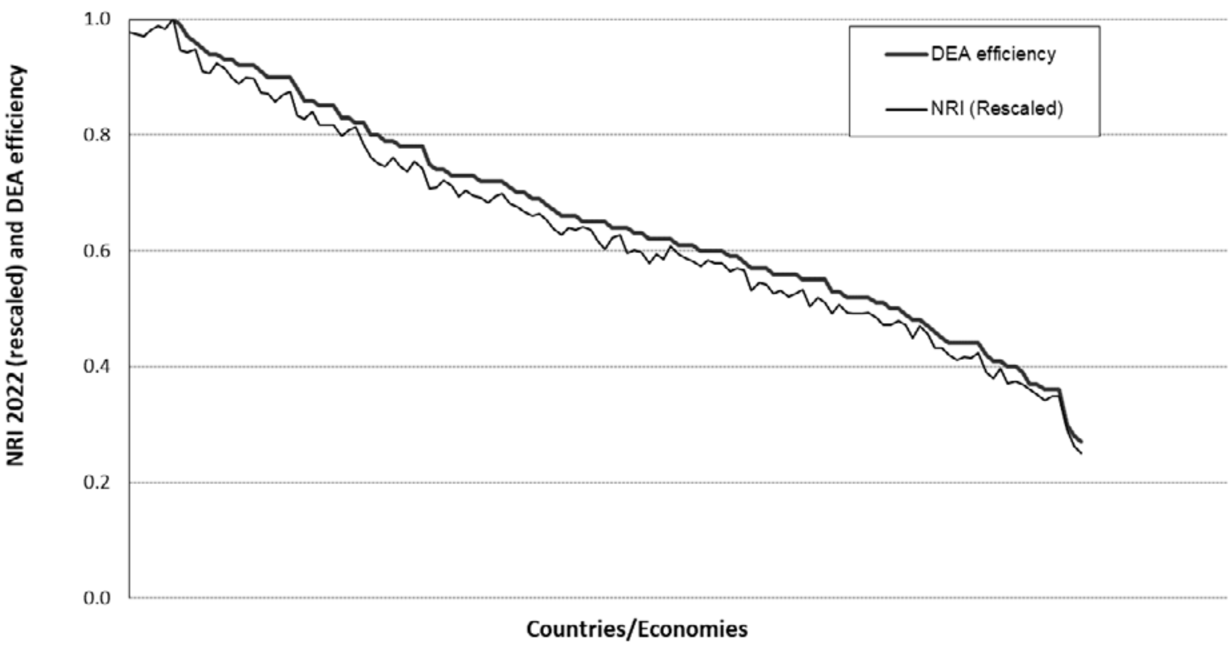
Table 7. Pillar shares and efficiency scores for the top 25 economies in the NRI 2022

	Technology	People	Governance	Impact	Efficient frontier score (DEA)	Efficient frontier rank (DEA)	NRI rank	Difference from NRI rank
United States	0.37	0.36	0.14	0.14	1.00	1	1	0
Singapore	0.11	0.32	0.16	0.40	1.00	1	2	1
Sweden	0.10	0.23	0.27	0.40	1.00	1	3	2
Netherlands	0.17	0.10	0.34	0.39	1.00	1	4	3
Switzerland	0.31	0.10	0.19	0.40	1.00	1	5	4
Denmark	0.10	0.32	0.40	0.18	1.00	1	6	5
Finland	0.10	0.30	0.40	0.20	1.00	1	7	6
Korea, Rep.	0.10	0.40	0.17	0.33	0.99	8	9	1
Norway	0.10	0.32	0.40	0.18	0.97	9	10	1
Germany	0.13	0.40	0.24	0.23	0.96	10	8	-2
Japan	0.10	0.40	0.10	0.40	0.95	11	13	2
Canada	0.17	0.16	0.40	0.27	0.94	12	11	-1
Australia	0.10	0.32	0.40	0.18	0.94	12	14	2
United Kingdom	0.17	0.11	0.31	0.40	0.93	14	12	-2
Israel	0.10	0.40	0.10	0.40	0.93	14	15	1
France	0.10	0.10	0.40	0.40	0.92	16	16	0
Luxembourg	0.23	0.10	0.40	0.27	0.92	16	17	1
Austria	0.10	0.31	0.40	0.19	0.92	16	18	2
Ireland	0.10	0.10	0.40	0.40	0.91	19	20	1
New Zealand	0.13	0.10	0.40	0.37	0.90	20	19	-1
Belgium	0.10	0.10	0.40	0.40	0.90	20	21	1
Estonia	0.10	0.30	0.40	0.20	0.90	20	22	2
China	0.10	0.40	0.10	0.40	0.90	20	23	3
Czechia	0.10	0.10	0.40	0.40	0.88	24	25	1
Iceland	0.17	0.16	0.40	0.27	0.86	25	24	-1
Spain	0.10	0.10	0.40	0.40	0.86	25	26	1

Source: European Commission's Joint Research Centre, 2022.

Note: The results are based on Data Envelopment Analysis. Pillar shares are expressed in percentages, bounded by 0.10 and 0.40 for all four pillars of network readiness - Technology, People, Governance, Impact. Instead, in the NRI 2022, the four pillars each have a fixed weight of 0.25. Darker colors represent a higher contribution of those pillars to the overall DEA score as a result of an economy's stronger performance in those pillars, which may help to provide evidence for economy-specific strategies. Economies are ordered by their Efficient Frontier score.

Figure 10. NRI 2022 scores and DEA "distance to the efficiency frontier" scores



Source: European Commission's Joint Research Centre, 2022.

Note: For comparison purposes, the NRI scores were rescaled by dividing them by the result of the best performer in the overall NRI 2022 (the United States).

3.7 Conclusions

The JRC statistical audit delves into the extensive work carried out by the developers of the NRI 2022 to suggest improvements in terms of data characteristics, structure and methods used. The analysis aims to ensure the transparency of the index methodology and the reliability of the results.

The NRI 2022 represents a sound index in terms of conceptual and statistical consistency. It shows that ICT deployment is a multifaceted phenomenon where technology, users, and several aspects of ICT regulation go hand in hand. The data coverage of the framework is generally satisfactory. Most indicators contain an acceptable level of missing values. Nevertheless, four indicators are characterized by the remarkable presence of missing values, two of which are well above the suggested exceptional limit of 40%. The statistical audit of the previous edition of the NRI contains additional analysis on the role of missing data in the framework. The developers decided not to impute them. This is common practice in relevant contexts and justified on grounds of transparency and replicability. However, JRC-COIN suggests to pay particular attention to the aforementioned indicators in future editions of the index.

The index is statistically well balanced with respect to its indicators, sub-pillars, and pillars. Correlations between each pillar and the respective sub-pillar are mostly significant and positive. Most of the indicators are meaningfully correlated with the index and relative pillars. The very strong correlations between some NRI 2022 components and between the four pillars and the index may be a sign of redundancy of information in the NRI 2022. This possibility is further confirmed by the analysis of added value of the NRI 2022 rankings. The suggestion is to use the index's very stable and correlated structure to explore and open up to the simplification of the framework or to some even more specific aspects of the network economy.

Finally, JRC-COIN analysed the robustness of the index respect to the selected weights and aggregation formula at pillars level. The results of the uncertainty analysis show that NRI 2022 is a robust summary measure.

All things considered, the present JRC-COIN audit findings confirm that the NRI 2022 is a reliable tool with a statistically coherent framework and acknowledge the important efforts made by the developers' team.

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