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Modelling systemic COVID-19 impacts in cities

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The COVID-19 pandemic has impacted public health, the economy and society—both directly and indirectly. Few approaches exist to understand these complex impacts in a way that (1) acknowledges cross-sectoral interdependencies; (2) models how short-term shocks translate into impacts on longer-term outcomes; (3) builds in local, contextual variation; and (4) recognises a wide set of priorities. The Urban Systems Abstraction Hierarchy (USAH) is proposed as an approach with these capabilities, and applied to Edinburgh (UK) between March-October 2020 to identify city-level impacts of the pandemic and associated policy responses. Results show changing priorities in the system and suggest areas which should be targeted for future urban resilience planning in Edinburgh for both short-term shocks and long-term recovery. This makes both methodological contributions (in the form of testing a new complex systems approach) and practical contributions (in the form of city-specific results which inform different aspects of resilience) to urban science.

INTRODUCTION

Urban resilience is a polysemic concept that is defined in a variety of ways[1–3]. Increasingly, definitions of resilience encompass three aspects. The first aspect is bouncing back to the status quo, i.e., reactive resilience[3]. The second aspect is adapting or "adjust[ing] cities to a constantly changing context"[2] (p. 2), i.e., responsive resilience ("learning from shocks, to enact adjustments to social, environmental or physical components" in preparation for future events[3] (p. 4)). The third aspect is 'transforming' or "radically changing [cities] according to modified contexts and circumstances"[2] (p. 2), i.e., proactive resilience ("an ongoing process of foresight, experimentation, reflection and learning, requiring systemic perspectives and multi-scalar approaches involving norms, identities and values and potential need for radical change"[3] (p. 5)). For example, the 100 Resilient Cities (100RC) project encompasses these aspects by defining resilience as "the capacity of individuals, communities, institutions, businesses and systems to reduce their exposure to, prepare for, cope with, recover better from, adapt to and transform, as necessary, in response to the impacts of climate change"[4].

Urban resilience challenges cannot be successfully tackled without complexity-smart approaches that are compatible with all three of the above aspects. The high concentration of people and activities in cities make them particularly vulnerable to hazards such as a flood or pandemic. Interacting natural, social, and technical parts[5–8] create systemic impacts, which become difficult to trace to a single source or time period.

The COVID-19 pandemic has highlighted specific needs for a complex systems approach to city resilience in several ways. First, interconnections between urban functions (e.g., education, economy, healthcare) are complex[5,9]. For example, closing schools has directly impacted education[10], indirectly impacted economic output through lack of childcare and increased home-school requirements[11,12] and even more broadly impacted progress on gender equality[13,14]. Such knock-on impacts highlight the need to move beyond dealing with one sector or hazard at a time, or risks may be assessed and prioritized in a way that neglects interdependent impacts.

Second, in that the effects of the pandemic will be felt for many years to come[15]. To date, urban COVID-19 research has focused on understanding shorter-term tangible aspects of environmental quality, socio-economic impacts, management and governance, and transportation and urban design[16]. Some study interdependencies in the short-term, e.g., by reporting improvement in air and water quality during lockdown periods[17], and linking this to changes in transportation patterns and greenspace use[18–20]. However, little is known about the long-term impacts of COVID-19 interventions across different urban functions[21–23]. Even less is understood about how short-term interactions may translate to changes in longer-term city outcomes by which resilience is measured, for example the 100RC goals[4] or Sustainable Development Goal (SDG) indicators[6,24,25]. Assessments of potential government interventions should consider a range of time-scales[26]. Better understanding is required not only for responses to COVID-19, but also for future hazards which are likely to be exacerbated by pressures such as climate change, urbanisation and loss of natural habitats[6,7,27]. Such long-term visioning is a neglected area of research (in contrast to investigations of short-term emergency response) that is essential to building just, sustainable and resilient cities.

Third, there are significant differences in how cities have experienced and responded to COVID-19[28–30]. Holding constant the severity of the COVID-19 hazard (i.e., a precise threshold of cases per 100,000 people), urban responses and consequences still vary. There are similarities in intervention strategies globally (e.g., travel limits, school closures, workplace closures and a 'stay at home' mandate). However, differences in speed and severity of implementation may result in diverse longer-term outcomes for different cities[31]. Variation likely arises from not only the pattern and severity of interventions imposed, but also the context of a specific city, and its latent conditions prior to the pandemic. The pandemic has highlighted community resilience[32,33], and the influence of local and socio-cultural factors, as key to successful responses. Assessments of potential government interventions should acknowledge how underlying social contexts shape impacts[26]. McClymont et al.[34] argue that resilience is contextual

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Table 1. Example nodes for each USAH level.

Level		Description	Example nodes
1	Purposes	*Why does a city exist?* The fundamental reasons a city exists or is built – creates constraints at the most abstract level of the USAH.	*Physical settlement, Economic opportunity, Safety and security, Pooling of resources, Social opportunity and care*
2	Outcomes	*What are the measures of a successful city?* Criteria by which we can determine if the city is fulfilling its purposes; based on the 100RC goals	*Effective provision of critical services, Sustainable economy, Effective safeguards to human health and life, Integrated development and planning, Empowered stakeholders*
3	Tasks	*What are the key functions of a city?* What tasks and services can be accomplished by using specific processes; often representative of sectors	*Energy supply, Employment provision, Public health, Hydrometeorological hazard regulation, Tourism, Learning and education, Clean water*
4	Processes	*What do the objects do or afford?* All of the processes that each resource can physically do	*Act as access point for electricity, Provide employment, Provide life-threatening healthcare services, Support microclimate regulation, Facilitate leisure or recreation, Provide education services, Transport wastewater*
5	Resources	*What is in a city?* Objects within a city boundary – such as buildings, ecosystems, facilities, infrastructure – creates physical constraints at the most granular level of the USAH	*Eateries, Hospitals, Lakes and ponds, Parks, Schools, Wastewater treatment plants*

and pluralistic, whereby location-specific differences imply there are different ways of achieving resilience. Future approaches must therefore acknowledge local contextual factors.

Fourth, the pandemic has triggered a reflection on how cities are managed, planned and governed[28,35,36]. As recovery and learning from past city successes[35] continues, social and environmental considerations must be championed in addition to economic ones[16]. For example, Gatzweiler et al.[37] call for a systems approach for managing urban health, and highlight that effective and equitable management are critical to improving urban planning and sustainable development. Urban systems approaches need to acknowledge a wide set of priorities, including but not limited to economic outcomes. To 'build back better', academics and practitioners are looking to what approaches have been missing and how to incorporate them. The design of city infrastructure and services post-COVID-19 must recognize complexity[38], and we need tools to help us understand cities as complex systems.

In pursuit of these more complex forms of resilience, the panarchy[39] – a conceptual approach from social-ecological systems theory – may be a useful frame. The panarchy is a nested set of adaptive cycles operating at discrete ranges of scale, however its practical applications remain "primarily descriptive and abstract"[40] (p. 578). A method to meet the above needs could also be well-suited as a tool to test panarchy concepts.

In this paper, we present the Urban Systems Abstraction Hierarchy (USAH)[7,41] as an appropriate tool to understand cities as complex systems and capture systemic impacts. This paper demonstrates how the USAH approach (1) acknowledges cross-sectoral interdependencies; (2) models how short-term shocks translate into long-term impacts; (3) builds in local, contextual variation; and (4) recognises a wide set of priorities (e.g., including wellbeing alongside economic outcomes). Each of these methodological capabilities means that practical findings have the potential to improve reactive and responsive resilience, and even support discussions around proactive resilience.

To date, the USAH has been developed as a generic template to support systems thinking around any UK city, with a view to adapting the model for specific cities and hazards. This paper applies the USAH to Edinburgh (UK) during the COVID-19 pandemic, hence demonstrating one application of how the approach can meet the above needs in a wide range of locations and scenarios. Thus, this paper makes both methodological contributions (in the form of testing a new complex systems approach that meets the four above needs) and practical

contributions (in the form of city-specific results) to urban sustainability science.

The USAH is a systems map designed to model the interconnectedness of cities by including social, technical, and natural functionality in a single framework. It is an application of the abstraction hierarchy method[42] from the discipline of human factors. Originally developed as a method to improve the design of safety-critical work systems (e.g., a nuclear power plant), this application of the abstraction hierarchy has been scaled up to the entirety of the urban system[7,41].

The USAH is a network consisting of five levels of increasing abstraction. At the bottom of the hierarchy are the City Resources (Level 5 – Physical Objects) e.g., *Hospitals*. These object types are linked to Processes they support (Level 4 – Object-Related Processes) e.g., *Provide life-threatening healthcare services*, then to Tasks they achieve (Level 3 – Generalised Functions) e.g., *Public health*, then to Outcomes (Level 2 - Values & Priority Measures) e.g., *Effective safeguards to human health and life*, and finally to System Purposes (Level 1 – Functional Purposes) e.g., *Social opportunity and care*. Table 1 provides an explanation of each USAH level with example nodes. These system parts are network of nodes which are linked between levels through their functionality, connecting the physical to the abstract through a hierarchical network. Moving upward through the levels the nodes are connected by asking 'why the node exists'; moving downward levels the nodes are connected by asking 'how a node is afforded'. These links represent "the 'means' that a system can use in order to achieve defined 'ends'"[43] (p. 203), explicitly connecting the physical and abstract. Figure 1a shows a sample section of the USAH, highlighting all nodes directly connected to the Object-Related Process *Provide life-threatening healthcare services*.

The USAH has been developed and validated with input from subject matter experts[41] and embeds the 12 outcomes from the 100RC framework[4] at Level 2 (e.g., a *Sustainable economy*, or *Effective provision of critical services*). The resulting USAH model (for a generic UK city) is a hierarchical network consisting of 5 levels which can be modified to explore the interconnected impacts of a hazard within a particular urban system (e.g., Edinburgh). In the USAH approach, urban resilience is addressed in direct and explicit terms, via the individual Outcome nodes at Level 2. These are the system criteria or 'schema' targeting the achievement of specific urban resilience goals, as laid out by the 100RC project[4]. Their inclusion recognises a wide set of priorities ranging across wellbeing, economic, and environmental aspects. However, resilience is also addressed structurally through links and subsequent network analysis.
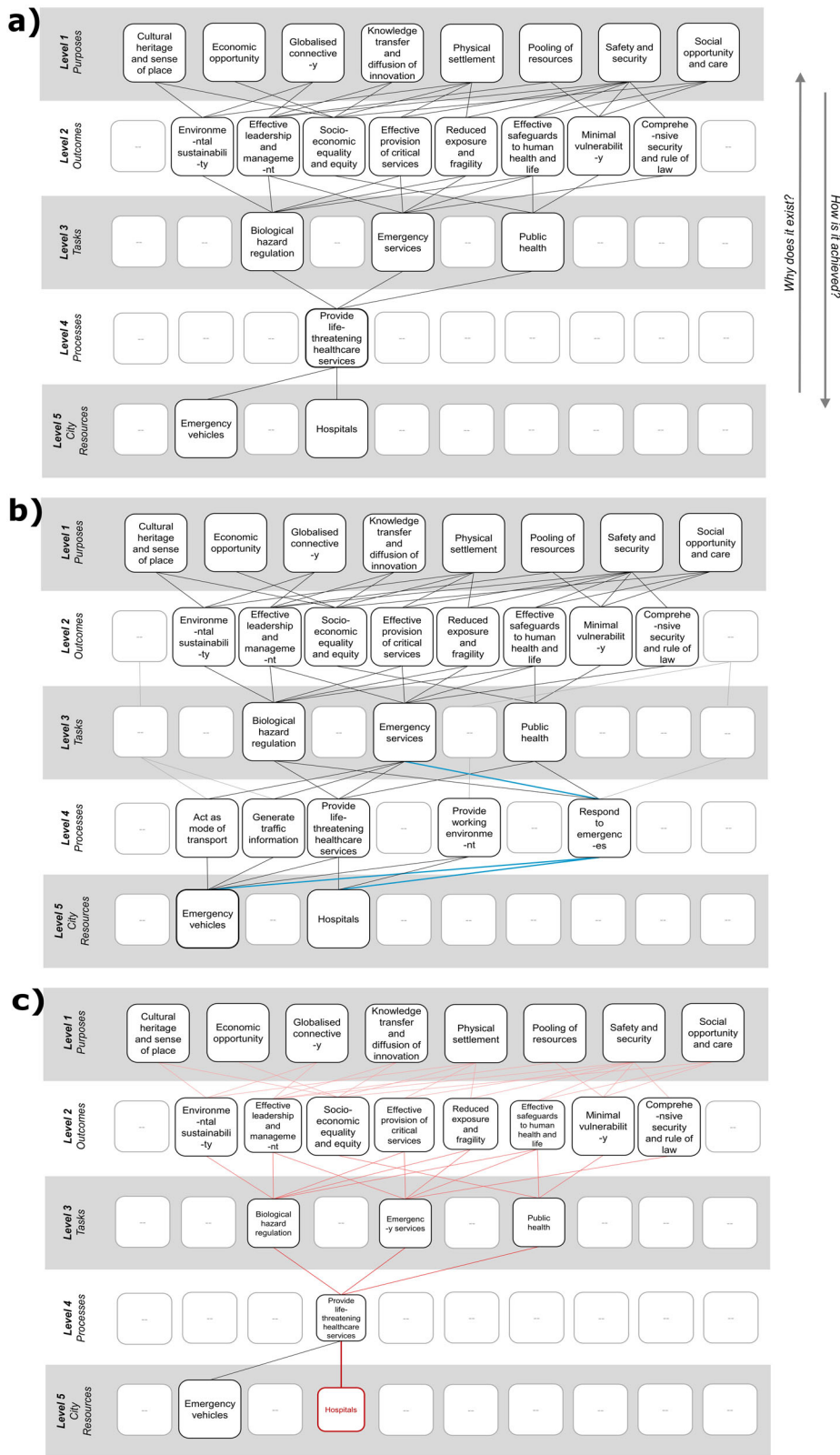
Fig. 1 Simplified excerpts of the USAH. a Simplified excerpt of the USAH using *Provide life-threatening healthcare services* as an example. **b** Example of Processes connected to *Hospitals* and *Emergency vehicles*, illustrating within-scale interactions and response diversity. **c** Example of an affected USAH link between *Hospitals* and *Provide life-threatening healthcare services*, and the potential cascading cross-scale impacts to connected Outcomes.

As a whole, the USAH generic template has been built at the spatial scale of an urban area. Each level is disaggregated to a different resolution and corresponds to a different temporal scale. For example, links between Resources (Level 5) and Processes (Level 4) are disaggregated at the finest resolution and correspond to a short-term timescale (hours or days or weeks;[44] links between Tasks (Level 3) and Outcomes (Level 2) correspond to a medium-term timescale (months or years[44]). By linking the short-term physical reality in each city (i.e., the tangible resources and processes) with longer-term target outcomes, cascading impacts of hazards (and interventions) can be better understood within specific cities. This models how short-term shocks impact physical resources and translates these into impacts on longer-term resilience outcomes.

The full generic USAH template was created in a UK context and consists of 481 nodes and 4463 links. To create the generic USAH template, a pilot USAH was created by Beevers et al.[43], modified and tested by McClymont et al. (2021)[45], then robustly validated by subject-matter experts in McClymont et al. (2022)[41]. Validation included input from experts from diverse disciplines (both academia and public sector) to determine which nodes should be included or excluded, via a Delphi questionnaire. This was followed by over 50 h of discussion and consensus building to construct appropriate links between nodes. To explore a full, interactive model with definitions for each node, see Visser-Quinn et al.[46]. For further examples of how links are constructed, see Bedinger et al.;[7] for a full description of the USAH construction and validation process, see Supplementary Methods and McClymont et al.[41].

The USAH can illustrate the functionality of the healthcare system, but also crucially recognises other processes which collectively contribute to public health, and how the healthcare system is interdependent with other city Tasks and Outcomes. As such the Abstraction Hierarchy integrates "partial view(s)"[47] of any system under study (p. 79), acting as a single point of reference for different stakeholders to explore multiple perspectives across disciplines[48]. The USAH structure is event-independent such that the urban system can also be understood outside of typical operation, even for unanticipated events[49]. This acknowledges cross-sectoral interdependencies.

Network analysis of the USAH can be applied to explore not only dependencies across the system, but also diversity (City Resources with unique sets of processes) and redundancy (City Resources with one or more shared processes). Ahern[50] argues that a system is more resilient to a shock if the same function is provided by distributed components of the system. Response diversity is created through functional redundancy, i.e., different components in a system have overlapping functions but respond to shocks differently[51–54]. Understanding a system's diversity and redundancy characteristics is critical to resilience planning in order to target responsive resilience which requires understanding the capacities of different actors, or proactive resilience which calls for acknowledging "the importance of redundancy, flexibility and proactively working to shape complex, non-linear, dynamic and context specific change processes"[3] (p. 5). For example, Fig. 1b replicates the USAH excerpt in Fig. 1a, highlighting how two similar City Resources (Hospitals and Emergency vehicles) are connected to overlapping yet unique sets of Processes. Response diversity as a result of within-scale interactions can be explored with the USAH.

Cross-scale interactions can also be explored with the USAH. In a panarchy framework, the conceptualisation of the system is "different from typically envisioned hierarchies in that control is not just exerted by larger-scale, top-down processes, but can also come from small scale or bottom-up processes"[40] (p. 578). The USAH approach takes the same bidirectional view. As such it can go beyond reactive resilience—which "often assume[s] the need for top-down command and control or unsupported actions undertaken by local people"[3] (p. 4)—to target responsive resilience that is "multifaceted, encompassing different actors, interests and capacities as part of an ongoing process of change"[3] (p. 4). Thus the USAH deals with cross-sectoral interdependencies and recognizes a wide set of priorities. Whilst reactive resilience can be addressed by the USAH through a focus on returning Resources and Processes to 'normal', responsive resilience can be addressed by a focus on returning Tasks and Outcomes to 'normal' and an openness to discussion around how more tangible levels operate to achieve this. Proactive resilience can be pursued by tracking Tasks and Outcomes, and more deeply evaluating whether their baseline or new positions reflect the desired state.

While achieving resilience within a panarchy context requires an understanding of complex dynamics between multiple actors or levels, it also requires understanding the added dimension of dynamics through time[40]. For example, approaches that understand regime changes[39] that occur when a system's resilience threshold is crossed or the processes responsible for a system's structure and function change and create new self-organized structures. The USAH approach is one way to explore possible future regime changes, by grappling with connections between the immediate shocks (days to weeks) and the medium-term stressors (months to years) within cities[41]. Through network analysis, the structural properties of the USAH can be explored to understand not only diversity and redundancy at lower levels of the hierarchy, but also how changing conditions cascade across scale to the Outcomes level.

For example, Fig. 1c replicates the USAH excerpt in Fig. 1a, going one step further to assume the ability of Hospitals to Provide life-threatening healthcare services has been affected. A loss in shorter-term functionality causes a link degradation between this Resource and Process, which cascades upward to potentially change the relative importance of the Tasks and Outcomes connected at higher levels of the USAH, e.g., Effective safeguards to human health and life vs. Environmental sustainability. The extent to which various Tasks and Outcomes are affected by such a scenario may indicate when and how the urban system is approaching its current limits, and thus indicate that functional changes will likely occur in the future, whether 'designed' or self-organized.

The aim of this paper is to demonstrate how the USAH approach (1) acknowledges cross-sectoral interdependencies; (2) models how short-term shocks translate into long-term impacts; (3) builds in local, contextual variation; and (4) recognises a wide set of priorities (e.g., including wellbeing alongside economic outcomes). Points 1, 2, and 4 are inherent capabilities of the USAH template, while point 3 is demonstrated via a real-world application: the pandemic and associated interventions for containing the spread of the virus (e.g., 'stay at home' mandates, school closures) in Edinburgh (UK). Thus, this paper presents not only the USAH's ability to capture systemic impacts in general, but also Edinburgh-specific findings of the impact of the pandemic.

A full description of the methodology can be reviewed in the Methods section below. A broad overview is detailed in Fig. 2. The method followed involved the creation of a city-specific Edinburgh model; modifying that model 30 times to reflect distinct weeks during the COVID-19 pandemic; and comparing network analysis results to the pre-pandemic Edinburgh scenario, to track changes (see Fig. 2).

The USAH template is transferable to more specific regions or cities by applying a spatial boundary using open software OSMtidy[55] and AHgen[56]. In this work, a city-specific USAH for Edinburgh (UK) was created by identifying all Resources present within the city council boundary. This boundary is 271.82 km^2 and includes the 17 council wards within Edinburgh. The physical boundary identified the City Resources to be considered for Level 5 of the hierarchy. Those within the boundary were included, and those outside the boundary were excluded. For example, the
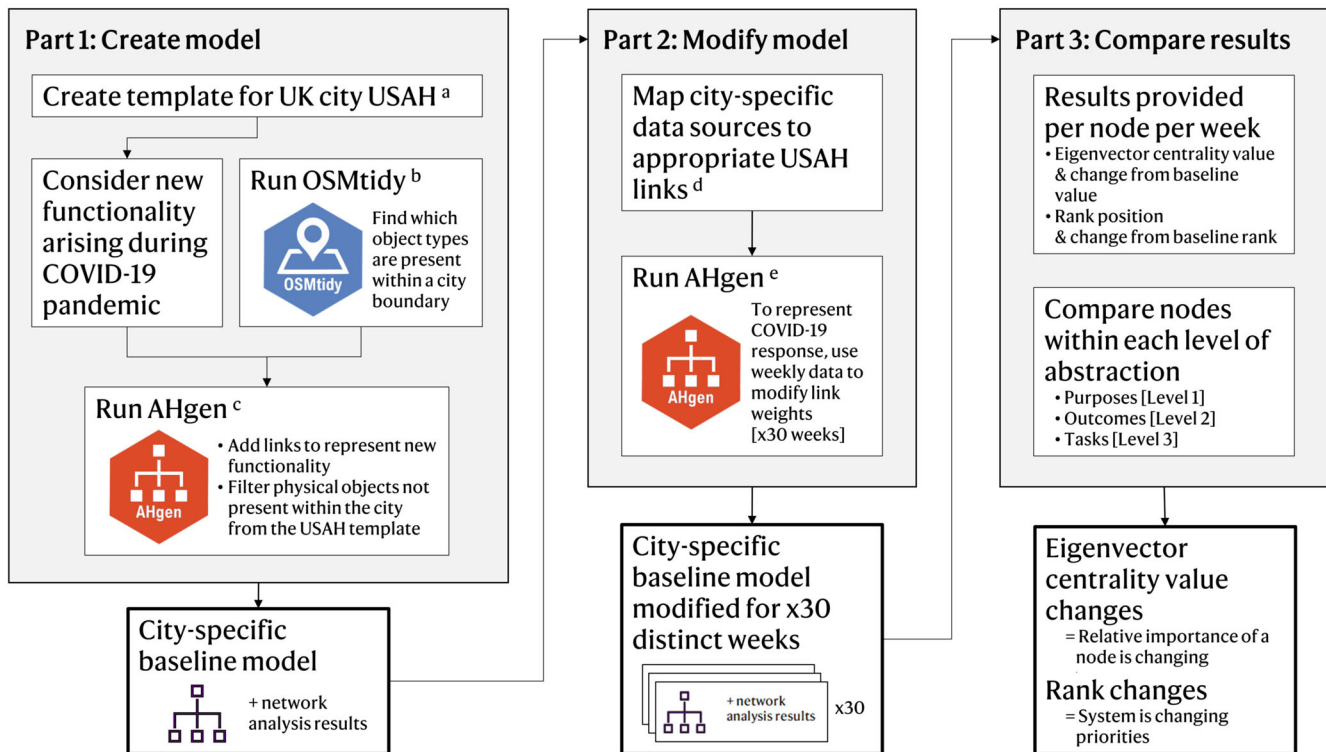
Fig. 2 Methodology overview. [a]see Supplementary Fig. 1 [b]see Supplementary Fig. 2 [c]see Supplementary Fig. 3 [d]see Supplementary Fig. 4 [e]see Supplementary Fig. 5.

Scottish Parliament Building was within the boundary, whereas there were no businesses which manufactured healthcare equipment within the boundary. Using OSMtidy and AHgen, any Resources (and subsequent Processes) that were not present within the Edinburgh City Council boundary were filtered out of the template USAH. For example, the City Resource *Parliamentary buildings* was included in the Edinburgh-specific USAH, whereas the Resource *Manufacturing (healthcare)* and the Process *Manufactures healthcare equipment and supplies* were removed. (See S1 for more detail.)

An administrative boundary was chosen to filter the template to reflect the city of Edinburgh, as this is the spatial scale in which resilient outcomes are monitored in the UK. Additionally, all lockdown mandates were implemented at local council level in Scotland. To encompass urban functional areas that include urban hinterlands, different city limits could be tested by incorporating labour market commuting patterns within the boundary (see Brezzi, 2012[57]. Future work could apply the USAH to a functional urban boundary to explore the impact the pandemic has had on the changing distribution of employment functionality (e.g., less people commuting to urban centers as a result of the working from home recommendation).

To represent Edinburgh-specific system conditions, links between City Resources (Level 5) and Processes (Level 4) were weighted to reflect varying functionality during different time periods (at weekly time steps March to October 2020). National and regional datasets were used to develop 23 quantitative indicators for link weights. For example, the link between *Hospitals* and *Provide general healthcare services* was weighted to reflect numbers of admissions to Intensive Care Units (ICUs) in Edinburgh hospitals using data from Public Health Scotland. Likewise, different types of workplaces and the processes they support were assigned specific indicators, in order to represent whether they were key, online, or closed during different periods of restrictions, and attach a week-specific weighting to reflect this.

For example, *Bars and nightclubs* were identified as a closed workplace. The link between *Bars and nightclubs* and *Act as community meeting space* was assigned to the indicator 'restrictions on gatherings', whereas the link to *Provide employment* was assigned to the indicator 'workforce employment'. All other Processes linked to *Bars and nightclubs* were assigned to the indicator 'workplace closed'.

This approach focused not on individuals' health or disease transmission; rather, the scope of impacts considered were restricted to the urban system (e.g., healthcare and business processes) and the degree to which they are functional as compared to 'normal'. Around 53% of links between Resources and Processes were weighted during the lockdown phase, with a gradual reduction as restrictions eased in Phases 1, 2, and 3. Moreover, three links were added to the generic USAH template to reflect system adaptation during the pandemic. For example, *Airports (major)* had an additional link to *Provide general healthcare services*, reflecting their novel use as COVID-19 test centres.

RESULTS

This section describes the tests applied, as relevant for readability and interpretation of sections Outcomes and Tasks. For a fully detailed description of the methodology please see the Methods section.

Thirty individual networks were created representing Edinburgh (UK) from International Organisation for Standardisation (ISO) weeks 11–40 inclusive, not including the baseline network representing 'normal conditions'. For each network, links between City Resources and Processes were weighted, using real-world data to reflect specific conditions on a weekly time step.

To track change through the system, weighted Eigenvector centrality (EC) is calculated per node to determine its relative influence in each network across the modelled time period. EC can

be interpreted as a node's importance within the network, reflecting system dependency through node neighbours.

To explore possible error around the EC result for each node and each week, a sensitivity analysis was performed on all 30 networks (weeks). Each week's input values (adjusted link weights) were increased by 10% and the network analysis was run to obtain EC values. Then each week's input values were decreased by 10% and the network analysis was run again to obtain EC values. These two sets of sensitivity results each correspond to a specific network structure. Thus error bars connect three distinct scenarios (original inputs, −10% inputs, and +10% inputs).

To explore whether each network (week) was statistically different from 'normal conditions', Mann-Whitney tests were performed. This test compared the set of EC values for Tasks in a given week to Tasks in the baseline, and the set of EC values for Outcomes in a given week to Outcomes in the baseline. Full results can be seen in Supplementary Figs. 6 and 7. Such a test identifies whether a set of EC values differs from its original values as a set; it does not account for changes 'within set'. In other words, there is no statistical test to determine significant differences in situations whereby the relative importance of the two Tasks differs from the baseline, but the EC value set is unchanged.

To understand the relative importance of nodes in more detail, rank changes can be explored. In each network (week) the rank of each node can be compared to its position in the baseline. This is done within-level, i.e., the changing rank of an Outcome node within the Outcomes level can be tracked, or a Tasks node within the Tasks level. To support clarity in visualisations and more detailed discussions, in some cases results for a level are further broken down by a more specific 100RC category: Economy & Society (E&S), Health & Wellbeing (H&W), Infrastructure & Ecosystems (I&E), or Leadership & Strategy (L&S). Rank changes were classified as small (+/− 1 positions), medium (+/− 2 positions), or large (+/− 3 or more positions). To focus on areas of most substantial change, the text below emphasizes rank changes which are medium (two positions) or large (three positions) in magnitude.

Where rank changes occur, this could be viewed as a snapshot of current conditions, providing an indication of possible future regime changes if the short-term context were to continue unimpeded. Regime changes occur when "a system's resilience threshold is crossed and the processes responsible for a system's structure and function change and create new self-organized structures"[39] (p. 584). This analysis touches on how regime changes might occur at the spatial scale of entire urban areas and medium-term temporal scale reaching to months or years, caused by cross-scale interaction (Fig. 1c) from the spatial scale of urban subsystems (e.g., local healthcare systems) and short-term temporal scale of days or weeks. In other words, this highlights how short-term dynamics (Fig. 1b) between Resources (Level 5) and Processes (Level 4) might cause cross-scale changes (Fig. 1c) that lead to regime changes within Tasks (Level 3) or Outcomes (Level 2).

The above sensitivity analysis scenarios were considered to understand if and how possible input error may impact ranks. This investigated in which networks (weeks) it would be possible for either the −10% scenario or the +10% scenario to cause within-level rank changes as compared to the original analysis. This contextualised findings with a confidence rating regarding a node's precise rank within a level; what the magnitude of error for rank may be (one rank position out, or several), and; whether these would have a substantial impact on the directional trends outlined in the discussion. Confidence ratings were assigned on this basis. For a given node in a given week, high confidence was assigned when neither the −10% scenario nor the +10% scenario would cause the node's rank to differ from the original result. Medium confidence was assigned when either the −10% or the +10% scenario would cause a rank change of one magnitude (either +1 or −1). Low confidence was assigned when either the −10% or the +10% scenario would cause a rank change with a magnitude greater than one (e.g., +2). For example, in week 11 *Sustainable economy* was rank 4 and in week 13 this decreased −4 positions to rank 8 (large change). Hypothetically, if the sensitivity analysis identified that varying inputs in week 13 by +10% could cause *Sustainable economy* to move −1 position to rank 5, then uncertainty around model inputs could potentially decrease the magnitude of the rank change. In such a case *Sustainable economy* would be reported as having rank 8 in week 13 (low confidence).

Outcomes

Figure 3 illustrates the distribution of EC values in the Outcomes level, for a selection of weeks at the start of each phase of COVID-19 restrictions. This includes error bars produced from a sensitivity analysis of input link weight values, suggesting that EC result values are somewhat sensitive to change, particularly during the
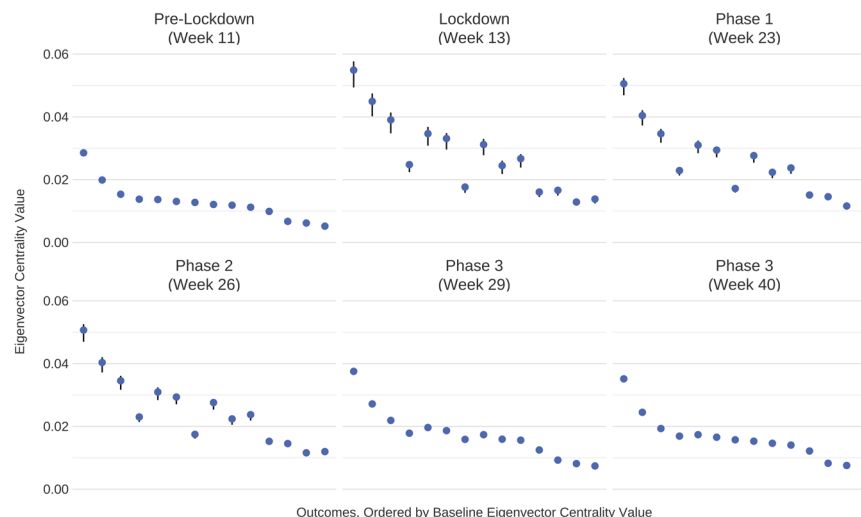
Fig. 3 Distribution of EC values for nodes in the Outcomes level; in descending order of baseline values, with error bars indicating sensitivity – see Methods section. Outcomes in weeks 13, 23, 26, 29, and 40 are all plotted in the same fixed location to demonstrate which Outcomes fall or rise in EC value, throughout the modelled period.
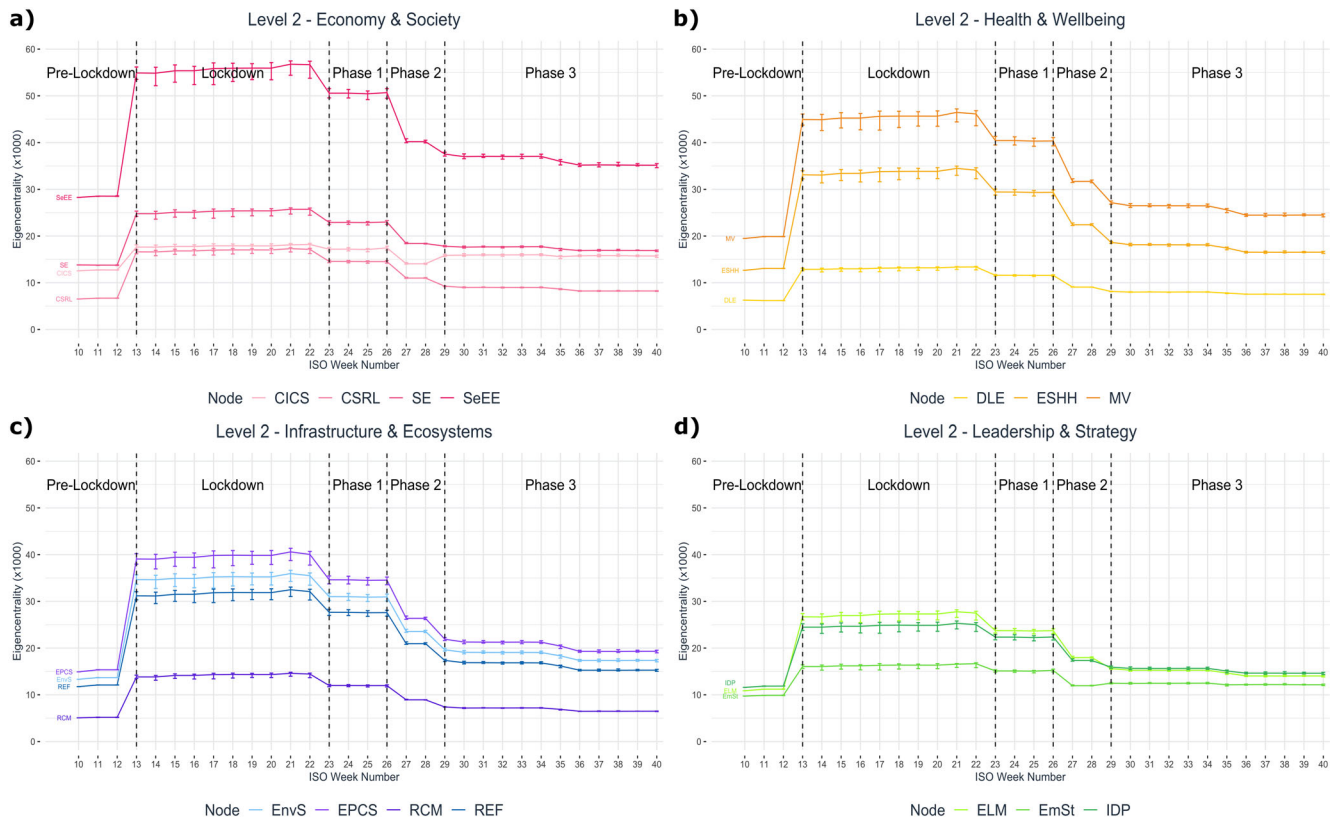
Fig. 4 **Time series of eigenvector centrality (EC) values for nodes (EC confidence included – see "Methods" section) at the outcomes level, throughout the modelled period.** Time series in the **a** economy & society category, **b** health & wellbeing category, **c** infrastructure & ecosystems category, **d** leadership & strategy category (for full node names behind abbreviations see Fig. 5 or Table 8).

lockdown (commencing in Week 13), Phase 1 (Week 23), and Phase 2 (Week 26) modelled periods.

Mann-Whitney statistical testing on the changing values of EC for the set of Outcomes ($n = 14$) shows that the Outcomes were significantly ($p < 0.05$) different from the baseline during lockdown, Phase 1 and Phase 2 of the modelled period (Supplementary Fig. 6). This suggests that the influence of the city Outcomes (when considered together as a set) is significantly different from the baseline, starting in lockdown up to Phase 3.

Figure 4 illustrates in detail how all Outcomes increased in influence, compared to baseline conditions. The most drastic increases from baseline values occurred during the lockdown phase, with the largest change from the baseline being between weeks 20–22 for most nodes. All Outcomes nodes followed the same trend throughout the modelled period; after peaking in the lockdown phase, slowly decreasing in EC value, and approaching but not fully returning to their baseline value around Phase 3. Two Outcomes (*Collective identity and community support* and *Empowered stakeholders*) were minimally closer to their baseline EC value during Phase 2, than in Phase 3.

Though all Outcomes increased in EC, their ranks did not increase consistently. Outcomes which changed in rank can be interpreted as reprioritized system goals. Figures 5 & 6 illustrate the rank (and 100RC category) of each Outcome, showing changes during the modelled period as compared to the baseline.

In the Edinburgh USAH baseline condition reflecting 'normal' everyday conditions, the Outcomes with the top three EC result values (and thus top three ranked) were *Socio-economic equality and equity*, *Minimal vulnerability* and *Effective provision of critical services*. According to the sensitivity analysis there is high confidence in these three highest ranked Outcomes remaining consistent (remaining highly influential to the system) throughout the entire modelled period (Fig. 5). All other Outcomes changed in

rank between ranks 4 and 14 at some point. The changing rank of Outcomes reflects how real-world system dynamics evolve across different phases.

The most rank changes occurred between pre-lockdown and lockdown or between Phase 2 and Phase 3. These were periods of high change, both in terms of the number of rank changes, as well as the magnitude of rank changes. Overall, the sensitivity analysis indicates high confidence in rank results for Outcomes. There were two exceptions where precise ranks were less certain, however these uncertainties did not affect the larger overall trends in Outcomes' rank changes throughout the modelled period.

Outcomes which increased in EC as compared to the baseline (Fig. 4) and also increased in rank as compared to the baseline (Figs. 5 and 6) can be interpreted as areas of relatively greater focus during the pandemic. When rank increases, this indicates system conditions place relatively greater emphasis on these nodes than others. During the modelled period, the Outcomes which increased in rank were *Environmental sustainability*, *Effective safeguards to human health and life*, *Reduced exposure and fragility*, *Effective leadership and management*, *Comprehensive security and rule of law*, and *Reliable communications and mobility*.

Outcomes which decreased in rank (as their increase in EC value was relatively smaller than that of other Outcomes) can be interpreted as what is de-prioritized or traded off by the specific system conditions. In general during the modelled period, Outcomes which decreased in rank were *Sustainable economy*, *Collective identity and community support*, *Empowered stakeholders* and *Diverse livelihoods and employment*.

Within the pre-lockdown phase, no rank changes occurred. However, in both weeks 11 and 12 the precise order of *Sustainable economy* and *Environmental sustainability* (rank positions 4 and 5)
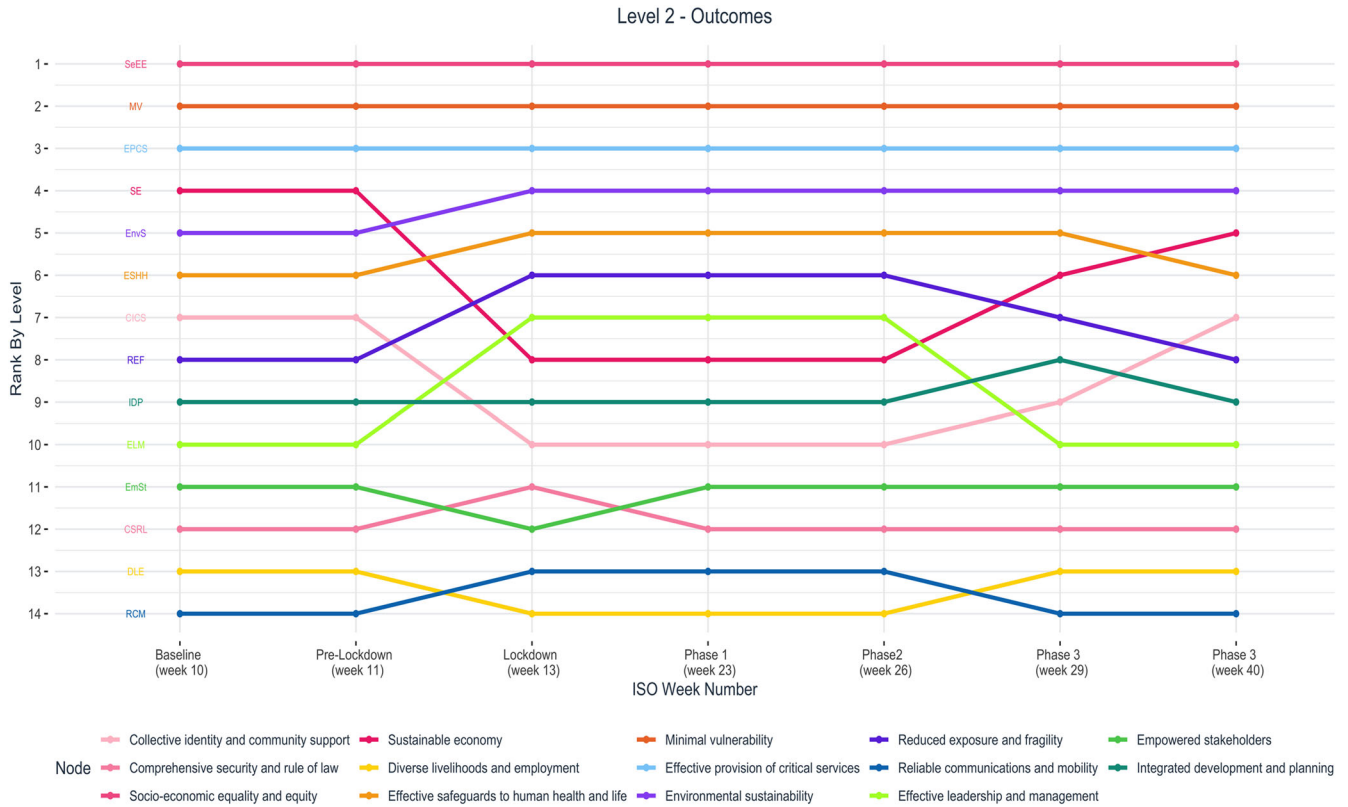
Fig. 5 Rank changes in outcomes (all 100 resilient cities (100RC) categories) at key phase changes throughout the modelled period (rank confidence excluded).
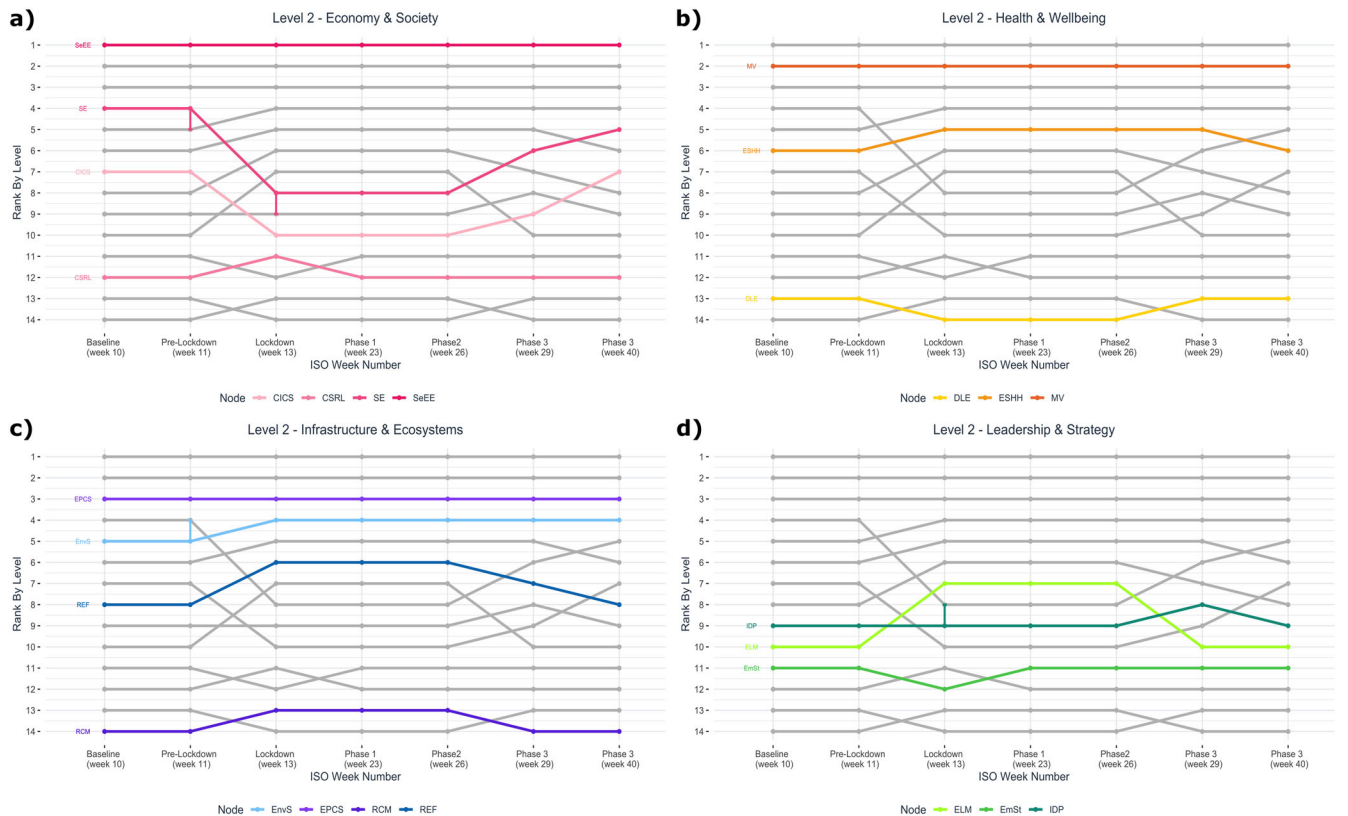
Fig. 6 Rank changes in outcomes at key phases changes throughout the modelled period, by category (rank confidence included – see "Methods" section). Rank changes in the **a** economy & society category, **b** health & wellbeing category, **c** infrastructure & ecosystems category, **d** leadership & strategy category (for full node names behind abbreviations see Fig. 5 or Table 8).
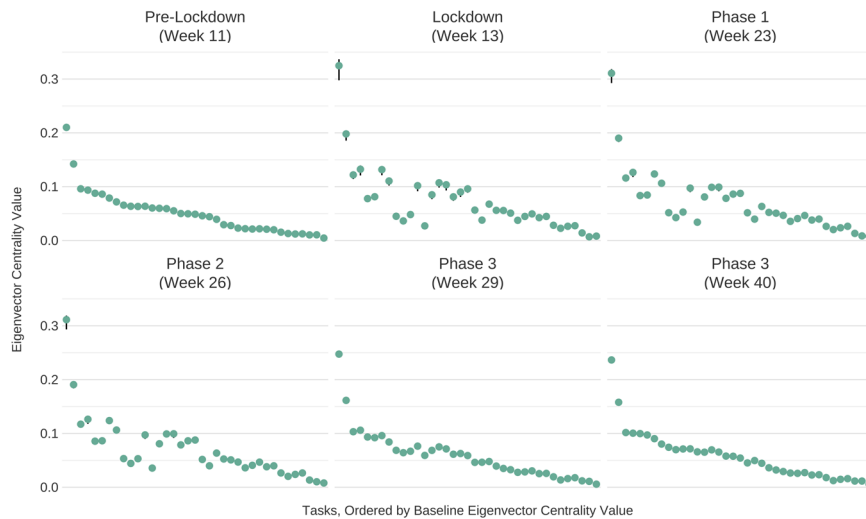
Fig. 7 Distribution of EC values for nodes in the Tasks level; in descending order of baseline values, with error bars indicating sensitivity – see Methods section. Tasks in weeks 13, 23, 26, 29 and 40 are all plotted in the same fixed location to demonstrate which Tasks fall or rise in EC value, throughout the modelled period.

was an area of medium confidence, due to swapping positions in the −10% sensitivity scenario.

Between pre-lockdown and lockdown, changes occurred suddenly between weeks 12 and 13. Six Outcomes (43%) increased in rank whilst four (29%) decreased and four (29%) remained constant. One of these increases was large in magnitude: *Effective leadership and management* increased +3, moving from rank 10 (high confidence) to rank 7 (high confidence). The Outcome *Reduced exposure and fragility* experienced a medium (+2) increase, moving from rank 8 (high confidence) to 6 (high confidence). Of the four decreases at this time, two were large in magnitude. The largest rank change was for *Sustainable economy* decreasing −4, moving from rank 4 (medium confidence) to 8 (medium confidence). In both sensitivity scenarios, the trend in magnitude and direction of rank change for *Sustainable economy* (a large −4 position decrease) between pre-lockdown and lockdown is still likely. *Collective identity and community support* also experienced a large decrease of −3, moving from rank 7 (high confidence) to 10 (high confidence).

Within the lockdown phase, no rank changes occurred. However, in weeks 13–16 and week 21 (50% of lockdown), there was medium confidence in the precise ranks of *Sustainable economy* (rank 8) and *Integrated development and planning* (rank 9) due to swapping positions in the −10% sensitivity scenario.

Between lockdown and Phase 1 (weeks 13–23), one Outcome (7%) increased, one (7%) decreased, and 12 (86%) remained constant (all high confidence findings). Two small rank changes occurred by exchanging positions. Then within Phase 1 (weeks 23–26) no rank changes occurred (all high confidence findings).

Between Phase 2 and Phase 3 (weeks 26–29) there was a period of substantial change in the Outcomes level: four (29%) increased whilst three decreased (21%) and seven (50%) remained constant. In contrast to the more abrupt changes between pre-lockdown week 12 and lockdown week 13, changes unfolded more slowly within Phase 2. The greatest increase was in *Sustainable economy* which experienced a medium increase of +2, moving from rank 8 in week 26 to rank 7 in week 27, and finally to rank 6 in week 29 (all high confidence findings). Of the three Outcomes which decreased in rank, one was large. *Effective leadership and management* experienced a large decrease of −3, from rank 7 in week 26 to rank 8 in week 27, then to rank 10 in week 29 (all high confidence findings).

Within Phase 3, two Outcomes (14%) increased, three (21%) decreased, and nine (64%) remained constant. These were only small exchanges in rank position that occurred in weeks 30 and 36. At the end of the modelled period (week 40) all but two Outcomes had returned to their baseline rank. The exceptions to this were *Sustainable economy* which decreased from rank 4 in week 10 to rank 5 (high confidence), and *Environmental sustainability* which increased from rank 5 in week 10 to rank 4 (high confidence).

Tasks

Figure 7 illustrates the distribution of EC values in the Tasks level, for a selection of weeks at the start of each phase of COVID-19 restrictions. This includes error bars produced from a sensitivity analysis of input link weight values, suggesting that EC result values are somewhat sensitive to error or change, particularly during the lockdown (commencing in Week 13), Phase 1 (Week 23), and Phase 2 (Week 26).

Mann-Whitney statistical testing on the changing values of EC for the set of Tasks ($n = 37$) shows that the Tasks were not significantly different from the baseline during any phase in the modelled period, but did approach the threshold for significance ($p < 0.05$) during lockdown (see Supplementary Fig. 7). This suggests that although the influence of the city Tasks is not significantly different from the baseline when considered together as a set, many individual nodes may be substantially changing within the set, particularly during lockdown. This is due to a mixed EC response (some nodes increase, whilst others decrease) across the Tasks during the modelled period.

Figure 8 illustrates in detail how Tasks changed in influence, compared to baseline conditions. The most drastic changes from baseline values occurred during the lockdown phase, with the largest change from the baseline being between weeks 20–22 for most nodes. Tasks in the H&W and I&E categories all followed the same trend: increasing in EC value in comparison the baseline, peaking in the lockdown phase, and slowly decreasing in EC value to approach but not fully return to their baseline value around Phase 3. Tasks in the E&S and L&S categories had a mixed response, with some experiencing decreases in EC and a gradual increase approaching baseline values in week 40. In the E&S category, this trend of decreasing in EC value was experienced by *Foster social cohesion, Social interaction, Tourism, Historical and cultural value contribution, Recreational activities*, and *Ceremonies*
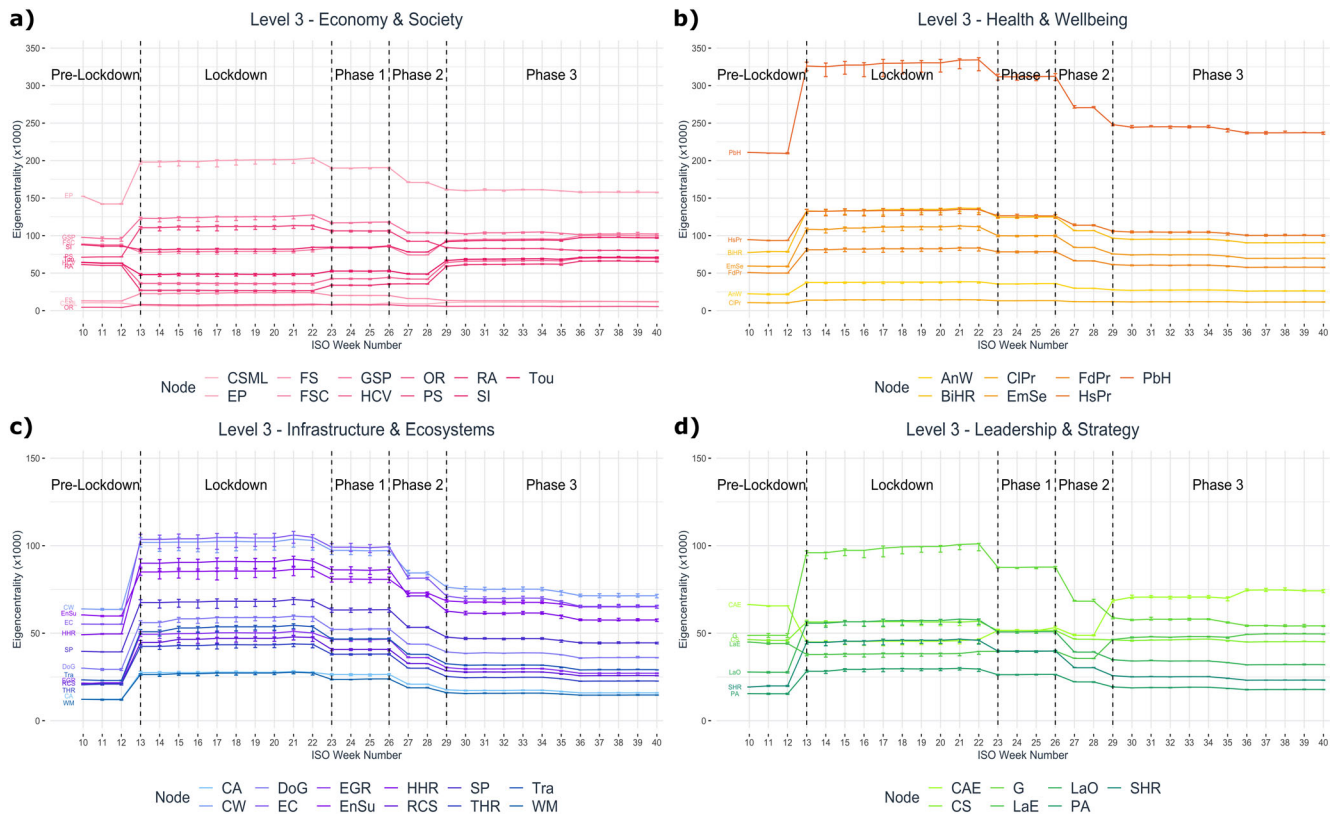
Fig. 8 Time series of eigenvector centrality (EC) values nodes (EC confidence included – see "Methods" section) at the Tasks level, throughout the modelled period. Time series in the **a** economy & society category, **b** health & wellbeing category, **c** infrastructure & ecosystems category, **d** leadership & strategy category (for full node names and abbreviations see Fig. 9 or Table 8).

and services for major life events. In the L&S category, these were *Community activities and engagement* and *Learning and education*. Several of these Tasks experienced a minimal disturbance in this trend during weeks 27-28 (i.e., rather than increasing and approaching their baseline values, these Tasks changed direction and minimally decreased in influence again).

Task ranks changed substantially. Tasks which changed in rank can be interpreted as reprioritised system functions or sectors. Figures 9 and 10 illustrate the rank (and 100RC category) of each Task, showing changes during the modelled period as compared to the baseline. In the baseline condition reflecting 'normal' everyday conditions in Edinburgh, the top two Tasks were *Public health* and *Employment provision*. According to the sensitivity analysis there is high confidence these remained consistent as highly influential to the system throughout the entire modelled period (Fig. 9). All other Tasks changed in rank between ranks 3 and 37 at some point.

The most rank changes occurred between pre-lockdown and lockdown or between Phase 2 and Phase 3. These were periods of high change, both in terms of the number of rank changes, as well as the magnitude of rank changes. Overall, the sensitivity analysis indicated many of the rank findings for Tasks were high confidence. Out of 1110 rank findings during the modelled period (30 non-baseline weeks × 37 positions), just 1.5% (17) were low confidence i.e., had a possible error of 2+ rank positions in either direction. The sensitivity analysis found no instances of >2 rank position error, thus any low confidence findings reported below refer to a possible error of 2 positions. The small number of low confidence rank findings were temporally spread across the modelled period and not concentrated on particular weeks.

When a Task increases in rank this indicates functions or sectors which were prioritised during that phase of the pandemic and can

be used to explore future planning for increasing resilience during similar shocks. Tasks which decreased in rank were de-prioritized or traded off by the system conditions during the pandemic, and are consequences of lockdown-style measures.

Between the baseline (week 10) and lockdown (week 13), no large rank changes occurred. One Task experienced a medium change (Clean water +2, moving from rank 12 to 10) however this was a low confidence finding. The majority of Tasks experienced small changes or remained at their baseline value, and findings were high or medium confidence. Overall, the system experienced relatively minor readjustments at this time.

Between pre-lockdown (week 11) and lockdown (week 13), the system changed substantially. A total of 23 Tasks (62%) increased in rank while 11 (30%) decreased and only three (8%) remained constant. Due to the quantity of changes at this time, Table 2 outlines some of these in detail. Table 2 and the accompanying text includes only those rank changes which were large in magnitude, and only where possible errors identified by the sensitivity analysis do not impact the finding's direction (increase or decrease) or magnitude (i.e., there is no possibility of a medium or small magnitude). For example, *Technological hazard regulation* experienced a large (+3) rank increase; however, the sensitivity analysis identified the possibility that this node moved only +2 positions (possible medium magnitude) thus it was excluded from Table 2.

The 14 Tasks which experienced large increases included seven from the I&E category, four from L&S, and three from H&W. Exploring this further, specific Tasks can be identified which are both important to achieving desired Outcomes (high in rank) and require greater focus compared to 'normal' conditions (large increase in rank). For example these might include *Biological hazard regulation* (+4 to rank 3), *Emergency services* (+8 to rank 7),
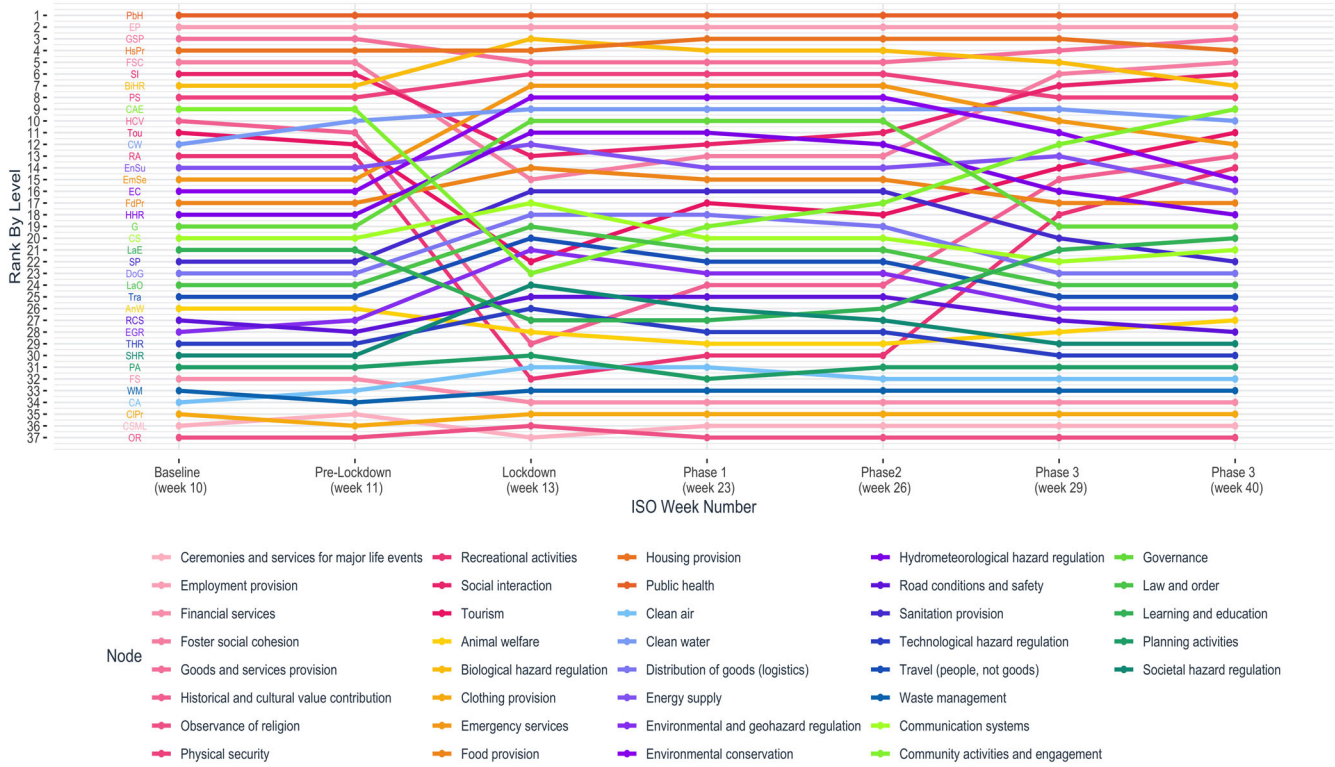
Fig. 9 Rank changes at key phases throughout the modelled period at Tasks level. All 100RC groups (rank confidence excluded).
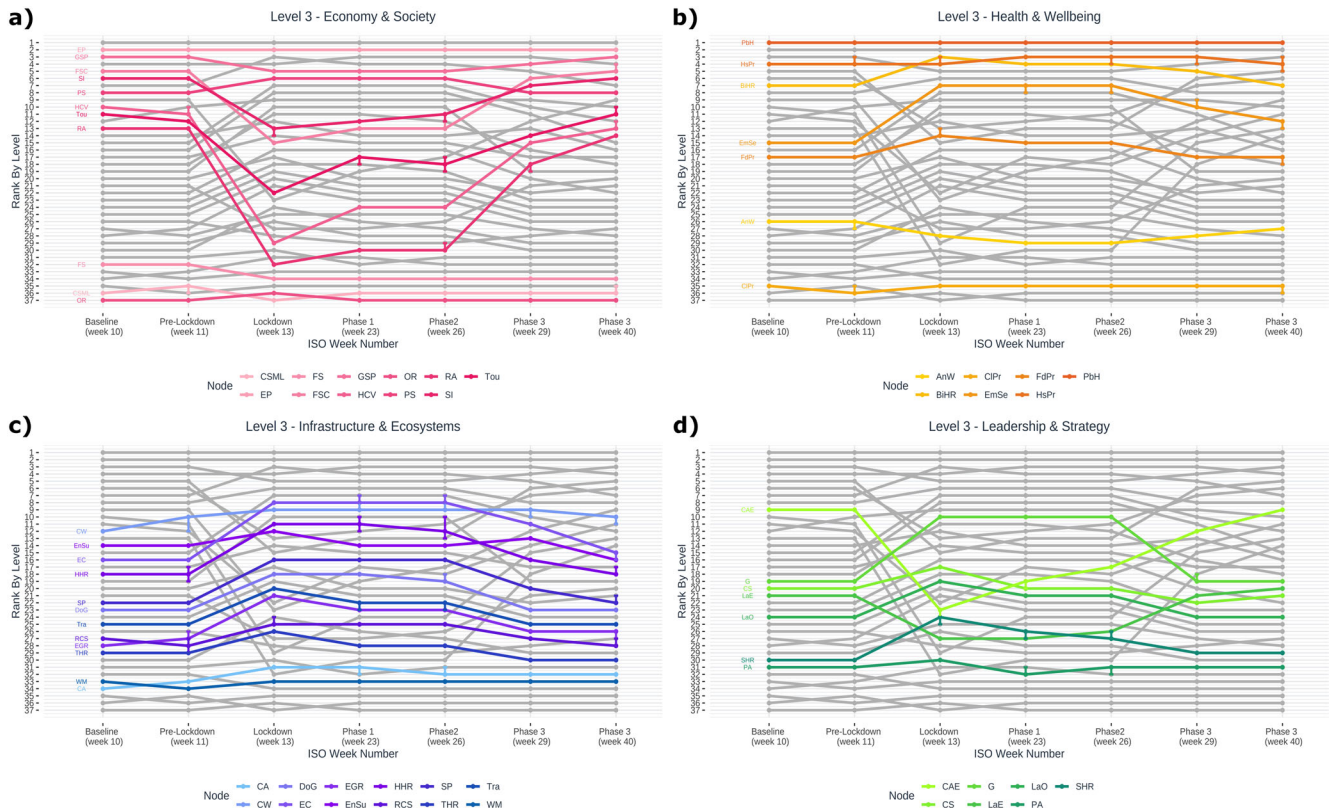
Fig. 10 Rank changes in tasks at key phase changes throughout the modelled period (rank confidence included – see "Methods" section). Rank changes in the **a** economy & society category, **b** health & wellbeing category, **c** infrastructure & ecosystems category, **d** leadership & strategy category (for full node names and abbreviations see Fig. 9 or Table 8).

Table 2. Tasks with large magnitude rank changes which were robust to sensitivity analysis, between pre-lockdown and lockdown phases.

Task	Rank change direction	Rank change magnitude	Pre-lockdown (week 11) rank & confidence	Lockdown (week 13) rank & confidence	100RC category
Governance	Increase	+9	19 (M)	10 (H)	Leadership & Strategy
Emergency services	Increase	+8	15 (H)	7 (H)	Health & Wellbeing
Environmental conservation	Increase	+8	16 (H)	8 (H)	Infrastructure & Ecosystems
Hydrometeorological hazard regulation	Increase	+7	18 (M)	11 (H)	Infrastructure & Ecosystems
Sanitation provision	Increase	+6	22 (H)	16 (H)	Infrastructure & Ecosystems
Environmental and geohazard regulation	Increase	+6	27 (M)	21 (H)	Infrastructure & Ecosystems
Societal hazard regulation	Increase	+6	30 (H)	24 (M)	Leadership & Strategy
Distribution of goods (logistics)	Increase	+5	23 (H)	18 (H)	Infrastructure & Ecosystems
Law and order	Increase	+5	24 (H)	19 (H)	Leadership & Strategy
Travel (people, not goods)	Increase	+5	25 (H)	20 (H)	Infrastructure & Ecosystems
Biological hazard regulation	Increase	+4	7 (H)	3 (M)	Health & Wellbeing
Food provision	Increase	+3	17 (M)	14 (M)	Health & Wellbeing
Communication systems	Increase	+3	20 (H)	17 (H)	Leadership & Strategy
Road conditions and safety	Increase	+3	28 (M)	25 (M)	Infrastructure & Ecosystems
Recreational activities	Decrease	−19	13 (H)	32 (H)	Economy & Society
Historical and cultural value contribution	Decrease	−18	11 (M)	29 (H)	Economy & Society
Community activities and engagement	Decrease	−14	9 (H)	23 (H)	Leadership & Strategy
Foster social cohesion	Decrease	−10	5 (H)	15 ((H)	Economy & Society
Tourism	Decrease	−10	12 (M)	22 (H)	Economy & Society
Social interaction	Decrease	−7	6 (H)	13 (M)	Economy & Society
Learning and education	Decrease	−6	21 (H)	27 (H)	Leadership & Strategy

Confidence reported as high = H, medium = M, low = L.

Environmental conservation (+8 to rank 8), and Governance (+9 to rank 10). Results also highlight the importance of the overall I&E category—"man-made and natural systems that provide critical services, protect and connect urban citizens"[4] (p. 9)—during this type of pandemic lockdown event. Thus I&E Tasks such as Environmental conservation, Hydrometeorological hazard regulation, Sanitation provision, and Environmental and geohazard regulation should be carefully considered in future pandemic resilience planning, as they may not appear influential in 'normal' conditions but they have greater importance during a pandemic lockdown.

The seven Tasks which experienced large decreases included five from the E&S category and two from L&S. Notably, there were half as many largely decreasing Tasks than largely increasing Tasks, and decreases were nearly double the magnitude of the increases. Within this set of decreases, specific nodes can be identified which were important to achieving desired Outcomes in 'normal' conditions (high in rank), but are now being relatively neglected (large decrease in rank). For example these might include Foster social cohesion (−10 from pre-lockdown rank 5), Social interaction (−7 from rank 6), and Community activities and engagement (−14 from rank 9). Results also highlight the overall E&S category—"the social and financial systems that enable urban populations to live peacefully, and act collectively"[4] (p. 9)—as neglected in this phase. If this type of lockdown event continued,

potential feedbacks from the neglected E&S area may cause knock-on impacts to the rest of the system.

Within the lockdown phase, Tasks did not experience any large rank changes. Weeks 13–22 saw a similar activity level to the pre-lockdown phase, where only minor readjustments occurred.

Between lockdown and Phase 1, eight Tasks (22%) increased, 12 (32%) decreased, and 16 (43%) remained consistent. There was a high quantity of change, though there were fewer large magnitude changes and these were less severe and abrupt in comparison to the previous phase change. Only three large rank changes occurred which were robust to the sensitivity analysis and these were all increases from the E&S and L&S categories. Historical and cultural value contribution increased +5, moving from rank 29 (high confidence) to rank 24 (high confidence); Tourism increased +5, moving from rank 22 (high confidence) to rank 17 (medium confidence); and Community activities and engagement increased +4, from rank 23 (high confidence) to rank 19 (medium confidence). In addition four Tasks experienced robust medium rank changes, and these were all decreases in the I&S and E&S categories.

Within Phase 1, weeks 23–26 saw minor readjustments. Overall between Phase 1 and Phase 2, there were no large or even medium rank changes that proved to be robust to the sensitivity analysis.

Between Phase 2 and Phase 3 (weeks 26–29) was another period of substantial change. Ten Tasks (27%) increased in rank

Table 3. Tasks with large magnitude rank changes which were robust to sensitivity analysis, between Phase 2 and Phase 3.

Task	Rank change direction	Rank change magnitude	Pre-lockdown (week 11) rank & confidence	Lockdown (week 13) rank & confidence	100RC category
Recreational activities	Increase	+12	30 (M)	18 (M)	Economy & Society
Historical and cultural value contribution	Increase	+9	24 (H)	15 (H)	Economy & Society
Foster social cohesion	Increase	+7	13 (M)	6 (H)	Economy & Society
Community activities and engagement	Increase	+5	17 (M)	12 (H)	Leadership & Strategy
Learning and education	Increase	+5	26 (M)	21 (H)	Leadership & Strategy
Social interaction	Increase	+4	11 (M)	7 (H)	Economy & Society
Tourism	Increase	+4	18 (M)	14 (H)	Economy & Society
Governance	Decrease	−9	10 (M)	19 (M)	Leadership & Strategy
Hydrometeorological hazard regulation	Decrease	−4	12 (L)	16 (H)	Infrastructure & Ecosystems
Sanitation provision	Decrease	−4	16 (H)	20(H)	Infrastructure & Ecosystems
Distribution of goods (logistics)	Decrease	−4	19 (M)	23 (H)	Infrastructure & Ecosystems
Environmental conservation	Decrease	−3	8 (M)	11 (H)	Infrastructure & Ecosystems
Environmental and geohazard regulation	Decrease	−3	23 (M)	26 (H)	Infrastructure & Ecosystems
Law and order	Decrease	−3	21 (H)	24 (H)	Leadership & Strategy

Confidence reported as high = H, medium = M, low = L.

whilst 16 (43%) decreased and 11 (30%) remained constant. Due to the quantity of changes at this time, Table 3 outlines some of these in detail. As with Table 2, this includes only large magnitude changes which were robust to the sensitivity analysis. The seven Tasks which experienced large increases included five from the E&S category and two from L&S. Approximately half of these (*Foster social cohesion, Learning and education, Social interaction*) increased enough to return to near (within two positions of) their baseline rank, while the other half made substantial progress in this direction. The seven Tasks which experienced large decreases included five from the I&E category and two from the L&S category. With the exception of *Environmental conservation*, these decreased enough to return to near (within 2 positions of) their baseline rank.

Between the start of Phase 3 (week 29) and the end of the modelled period (week 40), 10 Tasks (27%) increased in rank whilst 9 (24%) decreased and 18 (49%) remained constant. Overall, this phase was a period of low to moderate change which unfolded more slowly. Three Tasks experienced large increases in rank which were robust to the sensitivity analysis. *Recreational activities* increased +4, moving from rank 18 (medium confidence) to 14 (high confidence). *Tourism* increased +3, from rank 14 (high confidence) to rank 11 (medium confidence). *Community activities and engagement* increased +3, moving from rank 12 (high confidence) to rank 9 (high confidence). These were in the E&S and L&S categories. One Task experienced a robust large decrease in rank, and this was from the I&E category: *Environmental conservation* decreased −4, moving from rank 11 (high confidence) to rank 15 (medium confidence).

At the end of the modelled period in week 40, 13 Tasks (35%) had returned to their baseline rank with high confidence from the sensitivity analysis. A further 11 Tasks (30%) were found to return to a band of two positions near their baseline rank. For example, *Foster social cohesion* returned to its baseline rank 5, however the sensitivity analysis found this to be of medium confidence, such that in at least one sensitivity scenario *Foster social cohesion* could be rank 4. Only one Task (*Goods and services provision*) returned to its baseline rank 3 with low confidence, such that it could be rank

5. This means that overall, 25 Tasks (68%) returned to 'normal' or 'near-normal' priority. The remaining 12 Tasks (32%) could not have returned to their baseline rank in the original analysis nor the sensitivity scenarios for week 40. These are outlined in Table 4, and indicate specific sectors or functions which have not yet returned to 'normal' priority. All were positioned in rank 10 +, suggesting that the highest priority Tasks (ranks 1–9) stabilized by the end of the modelled period. Of particular interest are Tasks which remain decreased in comparison to their baseline rank, and may require additional support or resources moving forward from week 40.

DISCUSSION

Overall, the sensitivity analysis findings generated insights around the application of the USAH method in general. These suggested that the USAH approach is appropriately sensitive to adjustments in input link weight. The majority of rank findings were high confidence for both the Tasks and Outcomes levels; just 1.5% (Tasks) and 0% (Outcomes) of rank findings were low confidence.

Rank changes did not typically occur within a phase. This indicated that the USAH approach is more sensitive to structural changes between phases (e.g., changing which links in the network are affected) to a greater extent than reflecting fluctuations in real-world week-to-week data (i.e., the extent to which links are affected). Within-phase rank changes for Phase 2 and Phase 3 were likely reflections of the changing USAH structure; in other words a reflection of the gradual easing of restrictions.

The majority of Outcome rank findings were high confidence, being robust to the sensitivity analysis which tested the impact of possible input error. However, the instance of medium confidence around the precise rank order of *Sustainable economy* and *Environmental sustainability* during pre-lockdown is notable because this is the first period where real-world data (from early March 2020) was used to adjust input link weights. Because this precedes any COVID-19 restrictions, this medium confidence rank order indicates the two Outcomes may be close in baseline EC

Table 4. Tasks which did not return to their week 10 (baseline) rank position in week 40.

Task	Rank change direction	Rank change magnitude	Pre-lockdown (week 11) rank & confidence	Lockdown (week 13) rank & confidence	100RC category
Emergency services	Increase	+3	15	12 (M)	Health & Wellbeing
Clean air	Increase	+2	34	32 (H)	Infrastructure & Ecosystems
Clean water	Increase	+2	12	10 (M)	Infrastructure & Ecosystems
Environmental and geohazard regulation	Increase	+2	28	26 (M)	Infrastructure & Ecosystems
Learning and education	Increase	+1	21	20 (H)	Leadership & Strategy
Societal hazard regulation	Increase	+1	30	29 (H)	Leadership & Strategy
Historical and cultural value contribution	Decrease	−3	10	13 (M)	Economy & Society
Financial services	Decrease	−2	32	34 (H)	Economy & Society
Energy supply	Decrease	−2	14	16 (M)	Infrastructure & Ecosystems
Communication systems	Decrease	−1	20	21 (M)	Leadership & Strategy
Recreational activities	Decrease	−1	13	14 (H)	Economy & Society
Technological hazard regulation	Decrease	−1	29	30 (H)	Infrastructure & Ecosystems

Confidence reported as high = H, medium = M, low = L.

Table 5. Trends in changes to Tasks throughout the modelled period, by 100RC category, based on only Tasks with large robust rank changes.

Response	Between pre-lockdown & lockdown	Between lockdown & Phase 1	Between Phase 1 & Phase 2	Between Phase 2 & Phase 3	Between Phase 3 & end
Increased in rank	Infrastructure & Ecosystems; Health & Wellbeing	Leadership & Strategy	--	Economy & Society	Economy & Society; Leadership & Strategy
Mixed response	Leadership & Strategy	Economy & Society	--	Leadership & Strategy	--
Decreased in rank	Economy & Society	Infrastructure & Ecosystems	--	Infrastructure & Ecosystems	Infrastructure & Ecosystems
Did not experience large robust rank changes / remained relatively constant	--	Health & Wellbeing	Economy & Society; Health & Wellbeing; Infrastructure & Ecosystems; Leadership & Strategy	Health & Wellbeing	Health & Wellbeing

value (i.e., similar levels of importance in 'normal' conditions), which can be confirmed in Fig. 4a and c. On the other hand, this medium confidence rank order may also indicate that real-world health and workforce data from March 2020 differed enough from baseline data from the previous year to cause a minor fluctuation in rankings, i.e., reflected that conditions on the ground were quickly beginning to have an impact on the Outcomes *Sustainable economy* and *Environmental sustainability* when COVID-19 transmission was left unchecked by any restrictions. Both aspects could be true: the two Outcomes are held with similar structural importance (EC values) in the baseline USAH, but given that two other Outcomes with similarly close baseline values in pre-lockdown did not have medium confidence rank findings (e.g., *Effective safeguards to human health and life* and *Collective identity and community support*), it is still possible that the March 2020 data had an additional effect that increased uncertainty and potentially reprioritized Outcomes. Similar minor disturbances and readjustments were identified in week 11 for the Tasks level. These findings suggest the USAH approach is capable of capturing week-to-week fluctuations in real-world conditions, i.e., more subtle contextual variation.

Examining similar medium confidence rank findings for *Sustainable economy* and *Integrated development and planning* in weeks 13–22 further supports that the USAH approach is able to capture week-to-week fluctuations in real-world conditions. In part, the absence of rank changes within lockdown could also be explained by the effectiveness of lockdown measures, i.e., it is possible that lockdown measures were effective enough in containing the spread of COVID-19 to dampen the severity of changes to other input link weights (e.g., reduced workforce capability due to illness).

Thus, overall the USAH approach is sensitive enough to capture weekly fluctuations in data, yet robust enough to deliver findings with a good level of accuracy (i.e., typically identifying precise rank positions with no error, or rank findings with a possible error of one position).

Moving from broad methodological insights to practical findings, this paper tracked Edinburgh's specific response to the COVID-19 pandemic. During the modelled period, the system changed substantially at several points. Although EC values (representing nodes' influence) within the Tasks level in the modelled weeks were not statistically significantly different from the baseline due to the set of values consistently residing in a common range, there are clear patterns in how individual Tasks changed value and position within this range. By focusing on large rank changes (3 + positions) that were robust to the sensitivity analysis, high-level trends in the importance of different Task types were identified. Table 5

summarises these by 100RC category to illustrate trade-offs between different sectors.

Broadly, H&W was prioritized in lockdown, and through minor readjustments in the rest of the system throughout the modelled period, eventually returned to 'near-normal' (with the exception of *Emergency services*, which continued to be a higher priority than in 'normal' conditions). E&S Tasks were abruptly de-prioritized in lockdown, in contrast to other Tasks predominantly from the I&E category (see Table 2). In the absence of the USAH analysis, it would be no surprise that restricting the public's ability to mix households would have a detrimental impact on the economy and society; however, the USAH approach identified the specific E&S aspects and determined the extent to which they have been affected in the context of the wider urban system (e.g., *Recreational activities* and *Historical and cultural value contribution* were heavily impacted). In this type of lockdown event, potential feedbacks from these neglected E&S Tasks may cause knock-on impacts to the rest of the system. Further to this, increased I&E Tasks should be carefully considered in future pandemic resilience planning, as they may not appear as influential in 'normal' conditions, but have greater importance during a pandemic lockdown (e.g., *Environmental conservation*, *Hydrometeorological hazard regulation*, *Sanitation provision*, and *Environmental and geohazard regulation*).

Due to further easing of restrictions, the E&S and I&E categories reversed during Phase 2, and further re-stabilized in Phase 3. At the end of the modelled period, 12 Tasks spread across all 100RC categories had not returned to their 'normal' rank (see Table 4). This identified Tasks which remained deprioritized (e.g., *Historical and cultural value contribution* at −3 below its baseline rank), indicating that they may require additional support or resources to recover in the future.

These changes in tangible system conditions cascaded into re-prioritized system Outcomes. Mann-Whitney tests showed that as a result of cross-scale interactions, Outcomes increased in influence, such that they were statistically significantly different from 'normal' conditions from lockdown through Phase 2. This aligns with the timing of restrictions easing at week 27 (in Phase 2) and week 29 (the start of Phase 3), causing substantial rank changes in the Tasks level. Alongside the Mann-Whitney results for Outcomes, this suggests that the quantity and magnitude of Task rank changes at this time (see Table 3) contributed greatly to the system's 'return to normal'. The phased easing of restrictions over the modelled period was intended to enable this, and contributed to Outcomes' EC values and ranks indeed returning to (or closely approaching) baseline conditions.

The timeline of rank changes for Outcomes mirrored that for Tasks. This included a sudden increased emphasis on *Environmental sustainability*, *Effective safeguards to human health and life*, *Reduced exposure and fragility*, *Effective leadership and management*, *Comprehensive security and rule of law*, and *Reliable communications and mobility* during lockdown. At the same time, the Outcomes *Sustainable economy*, *Collective identity and community support*, *Empowered stakeholders*, and *Diverse livelihoods and employment* were deprioritized or traded off. These are specific high-level resilience goals which were affected by the tangible conditions during lockdown. In particular, the deprioritized Outcomes are the specific yet indirect ways in which the system's "resilience threshold" would be tested, if not fully crossed, should the same conditions continue unimpeded over the long-term. All Outcomes returned to 'near-normal' order of priority by the end of the modelled period.

The trend of all Outcomes increasing in EC, particularly from lockdown through Phase 2, suggests an increased importance of maintaining focus on all high-level goals during periods of higher uncertainty. In other words, when deeper impacts or restructuring at the tangible City Resources level occurs (as represented through adjusted link weights in the lockdown phase), the system emphasises the importance of fulfilling goals, to a greater degree than focusing on specifically how these are achieved. In such situations, approaching the more tangible levels of the hierarchy with flexibility, and understanding different options as to 'how' goals can be achieved, is key. More specifically, understanding diversity and redundancy in the urban system would support decision-making approaches that promote responsive or proactive resilience.

These findings be interpreted for future adaptation. With highly influential Outcomes identified, the USAH can explore how the system could be strengthened to similar events by tracing those Outcomes down the hierarchy, illustrating how they are achieved. For example, *Effective leadership and management* jumps three ranks [from rank 10 to 7] during lockdown, then returns to its baseline rank in Phase 2. *Effective leadership and management* is described as follows: "This is enabled by trusted individuals, multi-stakeholder consultation, evidence-based decision-making and disaster risk reduction activities"[4] (p. 25). This Outcome is achieved through the Tasks *Biological hazard regulation*, *Societal hazard regulation*, *Technological hazard regulation*, *Governance, Law and order*, *Emergency services* and *Communications systems* (for further detail see Supplementary Fig. 8). These Tasks can be traced back to explore the Processes and City Resources which enable them. For example, to build future resilience to this specific type of pandemic shock in Edinburgh, strengthening the communications systems through improvement of the ICT network, or supporting and improving the waste, water and wastewater infrastructure which provides biological hazard regulation would prove beneficial. Results are due to combined effects across the USAH at a specific time, such that a single root cause cannot be determined; however, some plausible reasons for this include a general move from physical meeting spaces to online interaction, as well as working-from-home increases. This approach allows the interconnected nature of the system to be explored, recognizing dependencies which deliver the desired outcomes, as well as tradeoffs of possible intervention approaches.

If a return to 'normal', everyday baseline conditions is desired, Outcomes which have fallen in rank require prioritization during pandemic recovery. This is where governments and communities should look to build support during the short- to medium-term recovery phases. Similar to the Outcomes which increase in rank, the USAH can be used to trace back through the hierarchy to understand how these outcomes are achieved and thus consider how recovery support may usefully be designed. For example, *Sustainable economy* is described as follows: "This is observed in sound management of city finances, diverse revenue streams, and the ability to attract business investment, allocate capital, and build emergency funds"[4] (p. 21). This is achieved through the Tasks *Distribution of goods*, *Employment provision*, *Financial services*, *Goods and services provision*, *Tourism*, *Travel*, *Recreational activities* and *Social interaction* (for further detail see Supplementary Fig. 9). Pandemic recovery could be supported by tracing these Tasks back to the Processes and City Resources which achieve them. One example would be to focus on supporting *Goods and services provision* e.g., ensuring investment in sustainable transport networks and manufacturing infrastructure. Many of these insights are not bounded by the city limits; the USAH provides a starting point for further discussion amongst stakeholders on a wider spatial scale.

To understand how best to strengthen Tasks related to Infrastructure and Ecosystems, they can be traced down through the hierarchy to explore how they are delivered, and thus enable a conversation on the design of future interventions including which City Resources should be prioritized and protected. For example tracing *Governance* (at local, regional or national levels) down through the network demonstrates the important and multi-faceted role that *Council offices* play, but also highlights the role of *Community centres*, *Citizen Advice Bureaus* and *Charity*

Table 6. Number of nodes that the Task *Governance* is connected to across each level of the USAH in comparison to the Task *Recreational activities*.

Task (Level 3)	Purposes (Level 1)	Outcomes (Level 2)	Processes (Level 4)	Resources (Level 5)
Governance	8	13	39	88
Recreational activities	8	2	10	128

organisations (for further detail see Supplementary Fig. 10). These City Resources are unique in the sets of Processes they contribute to in the system, but they also have overlapping redundancies. This mix of diversity and redundancy supports future long-term resilience and can also be utilised within short-term emergency plans. For example, short-term response to a shock wherein some City Resource types are shut down could be supported with flexible policies and plans that allow other City Resources to deliver a greater-than-usual range of services. This would ensure essential Processes, Tasks and Outcomes are protected in the short-term.

As with the city Outcomes, Tasks can be traced back in order to understand how to move forward in the recovery phase. For example, *Recreational activities* (covering processes that enable recreational and leisure activities) are delivered by a diverse spread of Processes including creative, cultural, recreational and leisure aspects (for further detail see Supplementary Fig. 11). The Process *Act as a community meeting* space was no longer functional during lockdown. Most of the City Resources linked to *Act as community meeting space* were closed thus removing their ability to deliver recreation. This underscores the importance of green and blue spaces in the urban environment[20], as despite restrictions on meeting spaces, the natural environment remained 'open' to *Facilitate leisure or recreation* to some degree. Whilst these contributed to *Recreational activities*, this was weaker than otherwise would have been during 'unrestricted' conditions, i.e., green and blue spaces alone do not deliver the necessary and desired level of recreational diversity within a city system.

Diversity and redundancy can be explored across the intangible and tangible levels of the USAH. Whilst the Tasks of *Governance* and *Recreational activities* (Supplementary Figs 10 and 11) both contribute to all eight Functional Purposes within city systems (Table 6), *Governance* contributes to more resilient Outcomes (13), but does not enable *Collective identity and community support* which is fulfilled by *Recreational activities*. When considering how these Tasks can be achieved, *Recreational activities* can be achieved by more City Resources (Table 6), suggesting there is more redundancy in the urban system to achieve this Task.

At a more tangible level, where *Parks* and *Museums and art galleries* both contribute to *Facilitate leisure and recreation*, they had different responses to the pandemic. *Parks* were restricted but remained opened whilst *Museums and art galleries* were closed. The impact of this can be traced further up the hierarchy to Tasks such as *Recreational activities* and *Social interaction* and Outcomes such as *Collective identity and community support*, and allows the role of response diversity[45] in urban systems to be explored.

Wider research on urban resilience lends support to these results. The USAH approach found that *Socio-economic equality and equity*, *Minimal vulnerability*, and *Effective safeguards to human health and life* remained the most influential Outcomes for Edinburgh throughout all phases of the modelled period. The pandemic has exacerbated existing inequalities[58] and these will widen over the long-term[35]. The World Bank predicts an increase in 'new urban poor' driven by COVID-19[38]. This is emphasized by Marmot et al.[59] who state that "the unequal conditions into which COVID-19 arrived contributed to the high and unequal death toll from COVID-19 in England" (p. 7). Large-scale shocks have produced similar effects throughout history[26]. According to Marmot et al., "reducing health inequalities requires long-term strategic policies with equity as the focus"[59] (p. 7). Both our results and wider literature affirm these Outcomes must remain 'influential' in future government plans.

The Outcomes *Sustainable economy, Collective identity and community support, Empowered stakeholders* and *Diverse livelihoods and employment* were de-prioritized during lockdown. These were traded off with *Effective leadership and management* which was found to have increased importance. Strong governance and leadership[28,29] are critical to stop outbreaks and deliver support to communities. Only top-down government measures toward these aims could be included in this analysis. In reality, other actors e.g., community groups may have filled this gap and been key to urban resilience[33,35], however, no data for these more informal responses was readily available. Whilst top-down measures restricted in-person gatherings, thus de-activating Processes like *Act as a community meeting space* and de-prioritizing the fulfilment of the *Collective identity and community support* Outcome, bottom-up actors adapted to what they saw as gaps in other essential Processes e.g., *Provide social support* or *Act as access point for food*. Without a physical space available for meeting and making logistical plans, such groups relied less on City Resources like *Community centres* and moved to interacting in a primarily online- or phone-based space only captured by the importance of nodes like *ICT cables* and *Personal devices*.

Pandemic resilience plans must include supporting E&S Tasks which decreased in importance—both to dampen the impacts of lockdown events, and fully recover from impacts persisting in week 40. In particular Tasks from Table 5 aimed at recovering *Sustainable economy* (e.g., *Financial services*) and re-building *Collective identity and community support* (e.g., *Historical and cultural value contribution)* should be given attention within pandemic resilience plans. Expanding the conceptualization of *Collective identity and community support* to multiple scales may also support this i.e., working between cities and strengthening institutional arrangements across regions[35]. Mapping responses from different actors to the USAH, and addressing gaps and overlaps in future resilience planning, presents opportunities for deeper collaboration and transformational change, thus supporting responsive or proactive resilience.

Overall, the USAH approach confirms that the relationships between aesthetics, well-being, and infrastructure provide multi-faceted benefits which support urban resilience[60]. The importance of greenspace in cities is evident[20] particularly around supporting positive health outcomes. As greenspace nodes often contribute not just to health-related Outcomes, but to all 14, it has co-benefits for other long-term needs like tackling the climate emergency. Functional paths to a 'green recovery' are illustrated in the USAH, and show how changes to urban planning and the way we live in cities can achieve resilience Outcomes[35,38].

Chester et al.[60] highlight the role resilience theory can have in supporting managers to navigate the increasing complex landscape of future urban infrastructure. Understanding immediate demand changes during a pandemic (e.g., a surge in household water use, or slump in public transport need) informs reactive resilience. However, understanding these in combination with longer-term impacts (e.g., eventual degradation of the environment due to lapsed or postponed quality checks) is key to responsive resilience.

By the end of the modelled period many nodes (at both Outcomes and Tasks levels) approached their original rank. This suggests that the approach taken by Scottish Government to manage effects on public health, economy, and society during the pandemic were successful in returning Edinburgh to a 'near-normal-baseline', at least from an urban systems perspective.

Beyond developing more specific practical recommendations for Edinburgh from the application of this methodology, the above 'snapshots' of the system and the tracking of rank changes also demonstrates that this approach may work in other locations and for a range of hazard types (known or hypothetical). This contributes a place-based approach to understanding cross-scale interactions, i.e., how short-term dynamics on a scale of hours or days or weeks may lead to regime changes on a scale of months or years, if the system remains in the short-term state. In the case of Edinburgh during the initial months of the COVID-19 pandemic, it was demonstrated that emergent system behaviour (within-phase fluctuations in data) and more obvious structural changes (between-phase policy changes) both opened the door to possible rank changes. Through the USAH approach, it is possible to track rank change as a signal of possible future regime changes, in order to avert, influence, or respond to them. The information available from undertaking this analysis can feed future policies which can directly support reactive and responsive resilience, and consider actions for proactive resilience.

The research reported here demonstrates the USAH as a means to analytically prototype different scenarios, taking an approach that can incorporate real-world data to understand ongoing scenarios, but does not necessarily rely on such data to test hypothetical scenarios and understand conditions before we are living in them. In future, the USAH could be tested as a foundational step in understanding the impacts of a range of known (and imagined) hazards in Edinburgh, and other cities.

The aims of this paper were to demonstrate how the USAH approach (1) acknowledges cross-sectoral interdependencies; (2) models how short-term shocks translate into long-term impacts; (3) builds in local, contextual variation; and (4) recognises a wide set of priorities (e.g., including wellbeing alongside economic outcomes). The USAH approach explicitly captures cross-sectoral interactions, and the results of the analysis clearly show different Task categories changing priority in relation to each other throughout modelled period. These changing Task categories clearly impact Outcomes, thus showing the propagation of the short-term shocks through to potential long-term impacts, across a wide range of priorities. This approach was applied to the city of Edinburgh, reflecting country-specific restrictions and local health and workforce data, showing that the model is sensitive to structural changes (i.e., as restrictions change) as well as contextual fluctuations in the week-to-week data.

In this paper the USAH was used to analyse real-world pandemic shocks in Edinburgh (UK), demonstrating a modelling approach that frames cities as complex systems, considers a range of timescales and contexts, and includes a wide set of outcomes. Thus, this paper makes both methodological contributions (in the form of testing a new complex systems approach) and practical contributions (in the form of city-specific results) to urban science.

City Resources and Processes created higher-level system conditions at the Outcomes level that were significantly different from a 'normal' pre-pandemic baseline. Findings for Edinburgh indicate that Outcomes were re-prioritized during the modelled period, with a near return to 'normal' conditions as the city unlocked in a phased manner over the summer of 2020. Tracking these changes enabled identification of which system parts were emphasized (I&E nodes), and traded off (E&S nodes), and when these hints at system reorganization occurred over time. Overall this analysis suggests that cities should look beyond economic stimulus to ensure a holistic recovery towards a diverse set of city Outcomes, and provides a way to determine the relative importance of, and interdependencies between, society, governance, health, infrastructure and the environment. The USAH has been demonstrated as a potential tool to support integrated reactive and response resilience planning, as well as to inform discussions of more radical strategies for proactive resilience.

The USAH is a living framework to be adapted for different scales, locations, and scenarios. This work provides a glimpse of what is possible when applying real-world data to such a holistic systems method. Future applications could contribute to building effective response, recovery, and resilience strategies not only for COVID-19 but all future urban challenges.

METHODS
The overall approach can be seen in Fig. 2 above. This is further detailed in Supplementary Methods and Supplementary Figs. 1–5. Broadly this involved creation of a city-specific Edinburgh model; modifying that model 30 times to reflect distinct weeks during the COVID-19 pandemic; and comparing network analysis results to the pre-pandemic Edinburgh scenario, to track changes.

Part 1: Create the model
First the UK city USAH template was created. The USAH template[7,41] is a functional approach to understanding how different conditions can impact different aspects of cities. A summary flowchart overviewing the creation of the generic USAH template can be seen in S1 Figure 17. A pilot USAH was created by Beevers et al.[43], modified and tested by McClymont et al. (2021)[45]. This was then robustly validated by subject-matter experts in McClymont et al. (2022)[41]. Validation included input from experts from diverse disciplines (both academia and public sector) to determine which nodes should be included or excluded, via a Delphi questionnaire. This was followed by over 50 h of discussion and consensus building to construct appropriate links between nodes. To explore a full, interactive model with definitions for each node, see Visser-Quinn et al.[46].

Then new functionality arising during the COVID-19 pandemic was considered, to determine if new links must be added to template USAH. The USAH template was developed to reflect 'normal' urban functionality. The authors considered the possibility of new functionality arising during the COVID-19 pandemic, either under emergency government powers or emergent industry responses. Three links were added to the generic USAH template to reflect system adaptation during the pandemic:

- *Airports (major)* was linked to *Provide general healthcare services*, reflecting their novel use as COVID-19 test centres.
- *Manufacturing (consumer staples)* was linked to *Manufacture healthcare equipment and supplies* to reflect that breweries and distilleries temporarily manufactured sanitizer.
- *Offices (other)* was linked to *Provide public communications service* to reflect contractors performing COVID-19 contact tracing services.

Then OSMtidy was run to detect physical object types present in Edinburgh. The USAH template can be made more location-specific by applying geospatial data, using OSMtidy, as seen in S1 Figure 18. OSMtidy is an open source software written in R[55] to capture large messy OpenStreetMap (OSM) data and tidy this into a streamlined dataset with a simple naming convention. By applying a shapefile of a city boundary—in this case Edinburgh City Council – to extract OSM data, OSMtidy detects which City Resources (Level 5 - Physical Objects) from the USAH template are actually present in that location. The contribution of the Edinburgh OSMtidy output in this study is to identify which object types are present or are not present in Edinburgh, in a binary sense. The number of different object types in Edinburgh, and more granular information in the OSMtidy output such as the area or length of objects, were not used in this study.

Finally, AHgen was run to create the Edinburgh baseline USAH. Using a relational key, the data in any OSMtidy output can be matched to the template USAH City Resources (Level 5 - Physical Objects) using AHgen[56]. For example, in the relational key OSMtidy object types *Attractions; Paintball* and *Attractions; Water and theme parks* both match to the broader umbrella of the USAH Physical Object *Attractions*.

The workflow for generating city-specific USAHs by using OSMtidy outputs in AHgen can be seen in S1 Figure 19. The key detects which descriptive terms were present in the OSMtidy output, and sets some object types to be included regardless which were not present but are never excluded due to known data gaps. For example, critical infrastructure is not well-represented in OSM data, such that the Physical Object *ICT cables* is never removed from the USAH, as it is assumed to be

ubiquitous in the urban environment even if no data with the descriptor *Telecommunications; Cable* is found in the OSMtidy output.

For example, the Edinburgh OSMtidy output did not contain any data with the descriptors *Attractions; Aquarium* and *Food production and horticulture; Aquaculture*, therefore the City Resources *Aquariums* and *Aquaculture* were removed from the Edinburgh baseline USAH.

Part 2: Modify the model

Next the model was modified, by mapping city-specific data sources to appropriate USAH links. For hazards that are spatially-explicit across urban areas, such as floods, OSMtidy outputs can be used to compare the count of object types in a baseline (corresponding to a shapefile for an entire city boundary) to a count of object types in a hazard scenario (corresponding to a shapefile for a flood extent within the city). Based on the proportion of each object type that has been affected (e.g., 6/10 *Places of worship* have been flooded) link weightings can be modified (e.g., all link weightings from *Places of worship* to connected Processes would be modified from 1 in the baseline to 0.4 in the flood scenario)[45]. Hazards of all kinds can be introduced to the USAH through adjusting link weightings in this way.

Though COVID-19 disease transmission is localised and spatially-explicit, the USAH does not address this aspect of the pandemic. Rather than the spatial aspects of person-to-person transmission, the USAH focuses on the scale of an entire urban area, and on the functioning of Resources and city services (Tasks). Therefore to modify link weightings and reflect distinct weeks of the COVID-19 pandemic in Edinburgh, OSMtidy outputs or other spatially-explicit data were not used.

To reflect the real-world context of the COVID-19 pandemic during each week of the modelled period, three indicator groups were developed from the Oxford Coronavirus Government Response Tracker:[30] *Economic Response, Healthcare Systems*, and *Containment and Closure*.

Within these categories, quantitative data was gathered covering March-October 2020, to represent weekly time increments. This data supported a total of 23 indicators also broken down in weekly time increments. In general, these indicators were developed by establishing a baseline value (some period of time on or before ISO week 10 beginning March 2nd 2020) fixed at a link weight of 1, calculating the percentage change of the new value at each subsequent ISO week, and normalising on a scale of 0–2 where values below 1 represent reduced capacity, values above 1 represent increased capacity, and 1 represents baseline conditions. For further detail see Supplementary Methods for a summary of data gathered, and detailed method statements of assumptions and processing steps behind each indicator. Indicators in categories *Economic Response* and *Healthcare Systems* were calculated from routinely published datasets, as described above, and in Supplementary Methods e.g., Office of National Statistics Business Impact of COVID-19 Survey[61].

However, the nature of *Containment and Closure* responses such as "Restrictions on gathering size" were binary in nature and did not require published quantitative data. Thus when *Containment and Closure* measures were applicable in a given week, some links were "not functional" and this was represented by a proxy link weight of zero.

To convert the above data and indicators to adjusted link weightings, edge guides were used for different phases of the pandemic across the modelled period. Each pandemic phase within the modelled period was considered, spanning a range of conditions between pre-pandemic ('normal') and lockdown (most severe). Across six phases, 12 edge guides were developed.

Each edge guide identified which measures were in place, how these measures would affect links between City Resources (Level 5 – Physical Objects) and Processes (Level 4 - Object-Related Processes), and which quantitative indicator would reflect the functionality of these links, such that an indicator name could call an associated link weighting for a specific week within that phase. The six-step, two-stage process for this is outlined in S1 Figure 20. The first stage involved preparing the baseline, while stage two modelled the COVID-19 response.

Stage 1: Prepare the baseline: **Step 1: Node selection**. All Resources in Level 5 that were linked to either *Provide employment*, *Act as community meeting space*, *Advise on community activities*, or *Facilitate cultural events* were selected. This helped identify all Resources that might be impacted by lockdown restrictions.

Step 2: Node categorization. These Resources were then assigned to one of 19 mutually-exclusive UK Standard Industry Classification (SIC) categories[62] to help input workforce data across different sectors (note

that not all Resources connected to *Act as community meeting space* have a SIC category as they may not be employment-based e.g., *Parks*).

Step 3: Workplace categorization. Resources that had a SIC category were then categorised as key, online, shut, or hybrid workplaces during lockdown.

Stage 2: Model the COVID-19 response: **Step 4: COVID-19 response aspects**. Moving to Stage 2, the COVID-19 response was modelled. Five COVID-19 response aspects were used:

1. *Contain A; restrictions on gatherings* which focuses on the restrictions imposed on social gatherings;
2. *Contain B; workplace* which focuses on the imposed lockdown on different industry sectors;
3. *Economic* which focuses on the Government's economic response to the workplace restrictions;
4. *Hazard* which focuses on the impact of COVID-19 to the healthcare system to reflect a change in capacity to afford particular processes; and
5. *Healthcare* which focuses on the public health response to COVID-19.

Each of the selected Resources were assigned to one or more response aspects based on the Processes they afford (e.g., *National government buildings* was assigned Contain B; workplace, Economic and Healthcare response aspects).

Step 5: Indicators. Indicators were assigned to the different links for each Resource based on these response aspects. Indicators were broken down by SIC category where relevant.

Step 6: Link weighting. The final step involved translating the indicator into a link weighting. This was done based on the capacity of a Resource to afford Processes compared to baseline conditions. Whilst the data and thus the weight assigned to each indicator might fluctuate within a phase, more substantial structural changes were reflected by a new guide (i.e., moving into a new phase). The Scottish Government Route Map[63] and the SPICe timeline of coronavirus[64] informed the guides. The guides then implemented link weightings in the USAH on a week-by-week basis. See the GitHub repository *USAH-outputs/2022-xx – Nature Urban Sustainability*[65] to download and view the details of all edge guides used, covering thousands of possible links to be adjusted. For example, Table 7 shows a simplified sample of five links (edges) in the edge guide for the lockdown phase. First, specific nodes are named (e.g., *Provide employment* and *Supermarkets*). The next columns record the response aspect and the workplace category in Scottish Government terminology, to make transparent the justification for why this specific link should be adjusted. The indicator name describes how weekly data (held elsewhere in a protected database) should be combined, and the indicator ID and the SIC column (e.g., Wholesale And Retail Trade) calls this combination for a pre-specified week. At the end of the process, a specific link weight is attached to each row, and by matching the Process-Resource link from the edge guide to the overall USAH edgelist, the new weight is inserted.

Edge guides covered the following phases as follows:

- *Baseline (ISO week 10):* A baseline representing everyday pre-pandemic conditions in Edinburgh did not require a guide, as all links were weighted as 1.
- *Pre-lockdown (ISO weeks 11–12):* This phase had one guide, and reflected Edinburgh in the 'ramp-up' to any formal government measures. It included some Hazard and Healthcare response aspects (e.g., the link from *Hospitals* to *Administrate healthcare services* weighted by the indicator 'planned admissions') and some workplace aspects (e.g., the link from *Higher education* to *Administrate educational facilities* was weighted by the indicator 'workforce functionality').
- *Lockdown (ISO weeks 13–22):* This phase had one guide, and included all five COVID response aspects. All Resources (Level 5) that were linked to *Provide employment* were weighted by the indicator 'workforce employment' to reflect the indirect impact of the furlough scheme. For key workplaces, all workforce-related links were weighted by the indicator 'workforce functionality'. For online workplaces, all links that could be afforded by working from home were weighted by that indicator, and all links that required physical access to the building were 'removed'. For shut workplaces, all links were 'removed' except *Provide employment*. Hybrid workplaces were those that did not follow a standard set of rules, thus link weightings were decided on a node-by-node basis. For example, some *Eateries* adapted to take-away services which was reflected by the indicator 'working as normal'.
- *Phase 1 (ISO weeks 23–25):* This phase had one guide and included the same aspects as lockdown, with a cautious re-opening of some aspects

Table 7. Simplified sample of an edge guide.

Process	Resource	Response aspect	Indicator name	Indicator ID	Workplace category	Accommodation And Food Service Activities	Wholesale And Retail Trade
Facilitate cultural events	Bars and nightclubs	Contain; workplace	Workplace closed	ind20_1	Shut	TRUE	FALSE
Act as community meeting space	Bars and nightclubs	Contain; restrictions on gatherings	Restrictions on gatherings	ind21_1	Shut	TRUE	FALSE
Provide staple goods	Supermarkets	Contain; workplace	Workforce functionality	ind10_15	Key	FALSE	TRUE
Provide working environment	Supermarkets	Contain; workplace	Working as normal	ind17_15	Key	FALSE	TRUE
Provide employment	Supermarkets	Contain; workplace	Workforce employment	ind09_15	Key	FALSE	TRUE

as per the Scottish Government Route Map[62] (e.g., Getting around; Schools; Working and running a business; Shopping, eating and drinking out; Sport, culture and leisure activities; Community and public services; Gatherings and occasions; Health and social care)[64]. If a Resource from one of these categories could re-open, its links were weighted by 'workforce functionality'.

- *Phase 2 (ISO weeks 26–28):* This phase had two guides. The first reflected easing of restrictions on gatherings by reintroduction of the Process *Act as community meeting space*. The second followed re-opening of further Resources or re-introduction of further Processes, as per the Scottish Government Route Map[64] categories from Phase 1.
- *Phase 3 (ISO weeks 29–40):* This phase had seven guides, following the same structure as phases 1 and 2, and reflecting the gradual reopening of the economy.

This generated 31 separate USAH networks. These scenarios represented urban system conditions in Edinburgh for one baseline condition, and 'snapshots' of conditions across 30 individual ISO weeks between March–October 2020.

Finally, AHgen was run to modify the Edinburgh baseline USAH for x30 COVID-19 weeks. In the baseline Edinburgh model, all links were weighted as 1 to represent fully 'normal' urban functionality pre-pandemic. To introduce the COVID-19 response into the system weights were introduced to links between Resources (Level 5) and Processes (Level 4) in the USAH network. This process followed a structured approach similar to the AHgen workflow for applying OSMtidy outputs, as shown in S1 Figure 21.

Examples of link weighting
Three examples are provided below to demonstrate how links were weighted for a (1) key, (2) online and (3) closed workplace.

Supermarkets were identified as a key workplace and were assigned to the Wholesale and retail SIC category (Steps 1–3). This SIC category had workforce data available. Two response aspects were identified for this Resource: Contain; restrictions on gatherings and Contain; workplace (Step 4). For Contain; Restrictions on gatherings, the link to *Advise on community activities* was assigned to the indicator 'restrictions on gatherings'. For Contain; workplace, the link to *Provide employment* was assigned to the indicator 'workforce employment', *Provide other discretionary goods* was assigned to the indicator 'workplace restricted' and *Provide working environment* was assigned to the indicator 'working as normal'. All other processes were assigned to 'workforce functionality', with the exception of Processes that were related to the physical building (e.g., *Act as access point for electricity*) as the capacity to afford these would not be impacted by the availability of the workforce (Step 5). These indicators were then translated into a link weight (Step 6). As an example of how this would be done, if 10% of the workforce from the Wholesale and retail sector were made redundant, then the link weight from *Supermarkets* (Level 5) to *Provide employment* (Level 4) would reduce from 1 to 0.9.

National government buildings were identified as an online workplace and were assigned to the Public administration and defence SIC category (Steps 1–3). The response aspects for this Resource were Contain; workplace, Economic response, and Healthcare response (Step 4). For contain; workplace, all Processes that were related to the physical building were assigned to the indicator 'workplace closed' (e.g., *Provide temporary shelter*) with the exception of *Act as access point for telecommunications* to account for online working. For Economic response, the link to *Support access to employment* was assigned to the indicator 'furlough (all industries)', *Administrate welfare benefits* was assigned to the indicator 'Universal credit (Housing entitlement)' and *Administrate business support* to indicator 'business support grants'. For Healthcare response, the link to *Provide public communication services* was assigned to the indicator 'public information campaigns' (Step 5). As this category did not have workforce data available, all other links to Processes that could be afforded from home remained fully functional. As an example of how the indicators are translated to a link weight, if 20% of the workforce were on furlough, then the link weight from *National government buildings* (level 5) to *Support access to employment* (Level 4) would increase from 1 to 1.2 (Step 6).

Bars and nightclubs were identified as a closed workplace and assigned to Accommodation and food service activities (Steps 1–3). The two response aspects for this Resource include Contain; Restrictions on gatherings and Contain; Workforce. For Contain; restrictions on gatherings the link to *Act as community meeting space* and *Advise on community activities* were assigned to the indicator 'restrictions on gatherings'. For Contain; workplace, the link to *Provide employment* was assigned to the indicator 'workforce employment'. All other Processes linked to *Bars and nightclubs* were assigned to the indicator 'workplace closed'.

Metrics
The USAH is an undirected, hierarchical graph, representing a complex topology of 481 nodes and 4463 links. Network metrics can be used to identify and navigate its highly interdependent parts, both in the baseline, and in scenarios representing other conditions e.g., a flood or pandemic. Here the network metric (weighted) eigenvector centrality (EC) has been used to determine each node's relative influence based upon the influence of its neighbours, and explore the importance of a node within the USAH.

For a graph $G:=(V,E,W)$ with $|V|$ vertices and $|E|$ edges and $|W|$ weights, the adjacency matrix **A** defines the weighting between nodes. The EC of a node x is then defined as

$$C_e(x) = \frac{1}{\lambda}\sum_j A_{ij}C_e(x_j) \tag{1}$$

This can be rewritten in matrix form as the eigenvector equation:

$$\lambda \mathbf{C}_e = \mathbf{A}\mathbf{C}_e \tag{2}$$

where $\mathbf{C}_e = [C_e(x_1), \ldots, C_e(x_n)]^T$ is the eigenvector of $G(V,E,W)$[66]. Then, by the Perron-Frobenius theorem, the eigenvector corresponding to the maximal eigenvalue, λ, contains only positive values. This ensures that $\mathbf{C}_e$ is the normalised dominant eigenvector of **A** with every EC bounded by 1 for each node in the graph.

EC provides a stable, continuous centrality measure, which is critical to ensure that system noise has little effect on the centrality result. This allows exploration of small permutations within link weightings (equivalent to variations in an adjacency matrix) which do not result in discontinuities, as seen in betweenness centrality[66].

To ensure comparability when applying network analysis to (31) different scenarios, the same number of nodes and links were required. This means that 'removal' of any link or node in the USAH is represented by a proxy for zero (weight of $1E^{-9}$). For each scenario (or network), different conditions are reflected through link weightings, and EC returns

Table 8. Outcomes and Tasks mapped to 100RC categories with abbreviations.

Level	100RC Category	Abbreviation	Node Name
Outcomes (Level 2)	Economy & Society (E&S)	CICS	Collective identity and community support
		CSRL	Comprehensive security and rule of law
		SeEE	Socio-economic equality and equity
		SE	Sustainable economy
	Health & Wellbeing (H&W)	DLE	Diverse livelihoods and employment
		ESHH	Effective safeguards to human health and life
		MV	Minimal vulnerability
	Infrastructure & Ecosystems (I&E)	EPCS	Effective provision of critical services
		EnvS	Environmental sustainablility
		REF	Reduced exposure and fragility
		RCM	Reliable communications and mobility
	Leadership & Strategy (L&S)	ELM	Effective leadership and management
		EmSt	Empowered stakeholders
		IDP	Integrated development and planning
Tasks (Level 3)	Economy & Society (E&S)	CSML	Ceremonies and services for major life events
		EP	Employment provision
		FS	Financial services
		FSC	Foster social cohesion
		GSP	Goods and services provision
		HCV	Historical and cultural value contribution
		OR	Observance of religion
		PS	Physical security
		RA	Recreational activities
		SI	Social interaction
		Tou	Tourism
	Health & Wellbeing (H&W)	Anw	Animal welfare
		BiHR	Biological hazard regulation
		ClPr	Clothing provision
		EmSe	Emergency services
		FdPr	Food provision
		HsPr	Housing provision
		PbH	Public health
	Infrastructure & Ecosystems (I&E)	CA	Clean air
		CW	Clean water
		DoG	Distribution of goods (logistics)
		EnSu	Energy supply
		EGR	Environmental and geohazard regulation
		EC	Environmental conservation
		HHR	Hydrometeorological hazard regulation
		RCS	Road conditions and safety
		SP	Sanitation provision
		THR	Technological hazard regulation
		Tra	Travel (people, not goods)
		WM	Waste management
	Leadership & Strategy (L&S)	CS	Communication systems
		CS	Community activities and engagement
		G	Governance
		LaO	Law and order
		LaE	Learning and education
		PA	Planning activities
		SHR	Societal hazard regulation

results for each individual node. When exploring a single scenario, comparisons are made only between nodes within a level (e.g., Level 3 City Tasks to City Tasks) rather than across the whole graph (e.g., Level 5 City Resources, to Level 3 City Tasks) due to the imposed hierarchical nature of the USAH network, where certain levels are at a mathematical disadvantage for central connectivity. Where nodes experience within-level rank changes over time, this indicates underlying conditions have reprioritized parts of the system.

Analysis and comparison of both the raw EC values from each node in the 31 (weekly) networks, as well as the rank change in importance of nodes (as defined by the raw EC value at each week) was undertaken. High EC values suggest that some nodes are highly influential to the overall network, so much so that their dominance may mask the relative change in other nodes. This highlights the importance of understanding the distribution of EC in baseline conditions (Figs. 3 and 7) and identifying changes through rank, rather than changes in absolute EC value. Given the typical distribution of nodes' EC values within a level, this also suggests that rank results for nodes at the upper end of the EC distribution within a level (e.g., in the Tasks level a $+4$ change from rank 6 to rank 2, vs. a $+4$ change from rank 37 to rank 33) may be less subject to sensitivity in input error i.e., are potentially higher confidence.

In each network (week) the rank of each node can be compared to its position in the baseline. This is done within-level, i.e., the changing rank of an Outcome node within the Outcomes level can be tracked, or a Tasks node within the Tasks level. Rank changes were classified as small ($\pm$ one positions), medium ($\pm$ two positions), or large ($\pm$ three or more positions). To support clarity in visualisations and more detailed discussions, in some cases results for a level are further broken down by a more specific 100RC category: Economy & Society (E&S), Health & Wellbeing (H&W), Infrastructure & Ecosystems (I&E), or Leadership & Strategy (L&S).

To explore possible error around the EC result for each node and each week, a sensitivity analysis was performed on all 30 networks (weeks). Firstly, each week's input values (adjusted link weights) were increased by 10% and the network analysis was run to obtain EC values. Then each week's input values were decreased by 10% and the network analysis was run again to obtain EC values. These two sets of sensitivity results each correspond to a specific network structure. Secondly, two distributions (uniform and Gaussian) were used to vary the adjusted link weights, in a similar manner, but with a degree of independence between links. Using a sampling distribution to select the increase (or decrease) in link weights correspond to a further four network structures. Combining the results allows the error bars to be added to Figs. 3, 4a–d, 7, and 8a–d. Thus error bars connect seven distinct scenarios (original inputs, −10% inputs, +10% inputs, + Gaussian from 0–10% inputs, - Gaussian from 0–10% inputs, + uniform from 0–10% inputs and - uniform from 0–10% inputs), rather than representing a full error range. Adding further scenarios to the sensitivity analysis could investigate this further, however a more sophisticated approach is not feasible. This is due to the high number of inputs which would need to be varied: a maximum of up to 1875/3554 (53%) of links between the Resources and Processes levels had adjusted values at some point in the modelled period (minimum $=$ 736 links; mean $=$ 1383 links; median $=$ 1308 links). This means independently varying the total number of possible permutations (1875! (factorial)) is computationally unfeasible.

The above sensitivity analysis scenarios were considered to understand if and how possible input error may impact ranks. Possible impacts are represented by error bars on node ranks in Figs. 6a–d and 10a–d. This investigated in which networks (weeks) it would be possible for either the −10% scenario or the +10% scenario to cause within-level rank changes as compared to the original analysis. This contextualised findings with a confidence rating regarding a node's precise rank within a level; what the magnitude of error for rank may be (one rank position out, or several); and whether these would have a substantial impact on the directional trends outlined in the discussion. Confidence ratings were assigned on this basis. For a given node in a given week, high confidence was assigned when neither the −10% scenario nor the +10% scenario would cause the node's rank to differ from the original result. Medium confidence was assigned when either the −10% or the +10% scenario would cause a rank change of one magnitude (either $+1$ or -1). Low confidence was assigned when either the −10% or the +10% scenario would cause a rank change with a magnitude greater than one (e.g., +2). For example, in week 11 *Sustainable economy* was rank 4 and in week 13 this decreased −4 positions to rank 8. Hypothetically, if the sensitivity analysis identified that varying inputs in week 13 by +10% could cause *Sustainable economy* to move −1 position to rank 5, then uncertainty around model inputs could potentially decrease

the magnitude of the rank change. In such a case *Sustainable economy* would be reported as having rank 8 in week 13 (low confidence).

To test the difference in EC distribution for each week a non-parametric Mann-Whitney U test was performed for the EC results per level. This test compared the set of EC values for Tasks in a given week to Tasks in the baseline, and the set of EC values for Outcomes in a given week to Outcomes in the baseline. Therefore this tested the hypothesis that the network (and therefore potential regime changes and cross-scale interactions) in each week changed significantly from the baseline (week 10). Results can be seen in Supplementary Figs. 6 and 7. Such a test identifies whether a set of EC values differs from its original values as a set; it does not account for changes 'within set'. In other words, there is no statistical test to determine significant differences in situations whereby e.g., the EC result values for two Tasks have swapped, such that the relative importance of the two Tasks differs, but the EC value set is unchanged.

Scope & interpretation
The purpose of this analysis was to demonstrate a new systems method and explore how tangible COVID-19 conditions (at Level 5 City Resources and Level 4 Processes) affect intangible Tasks (37 Generalised Functions) and Outcomes (14 Values and Priority Measures) needed for city resilience. Changes in the network were analysed through a point-in-time analysis (a single week) and a time-series analysis (trends across weeks). To categorise and interpret the results, nodes at the targeted levels were grouped into 100RC categories: Economy & Society (E&S), Health & Wellbeing (H&W), Infrastructure & Ecosystems (I&E), or Leadership & Strategy (L&S) (see Table 8). A full list of USAH nodes and definitions can be found at Bedinger et al.[66].

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