Bachelor Integration Project

Centrality-based Control Policies for Early Epidemics in Structured Community Networks

Author

C.R. de Bruijn | S3499197

Supervisors

Dr. N. Monshizadeh Naini
Dr. G.K.H. Larsen
V.S.P. Malladi

June 17, 2022

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1 Introduction

New and highly infectious epidemics such as COVID-19 have the ability to cause sudden large-scale societal disruptions, influencing not only the physical health of those infected, but also the dynamics of society as a whole. Global economics, mental health and many other factors are negatively affected, leading to a desire to control these epidemics [21] [8]. One troubling characteristic of new virus strains is the lack of immunity and vaccination availability. In the Netherlands, the COVID-19 vaccination campaign only started in January 2021, while March 2020 marked the first (partial) lockdown of the country [1]. This property of new epidemics calls for intervention policy that reduces the number of contacts between people.

However, isolation comes with a cost. Sudden reductions in work force capacity, detrimental economic effects and psychological ramifications are problematic and can derail normal processes in society [21]. If isolation is seen as a form of control to prevent further spreading, then these economic and societal impacts can be viewed as a control cost [17].

Mathematical modeling of epidemics is commonplace when creating policy recommendations, with the SIS (susceptible-infected-susceptible) compartmental model and its extensions forming the basis for many of these studies [31]. Adding isolation as a third compartment leads to the SIQS (susceptible-infected-quarantined) model, useful for modeling new epidemics as described above [29].

While isolation policy is often defined and applied equally for a population, certain portions of populations are more likely to spread a disease, leading to targeted interventions. For instance, closure of schools due to their densely-connected nature during the COVID-19 pandemic [4]. Given a certain network, more effective isolation policy can thus be created based on the centrality of the nodes contained within.

1.1 Contribution

This research proposes a novel centrality-based isolation policy that aims to control epidemic spreading by isolating only a set percentage of the most central nodes when infected. A discrete-time stochastic SIQS model is used that allows for isolation interventions. Specific contributions are highlighted as follows:

(i) **Network topology versus centrality measures.** Node selection for the proposed isolation policy is centrality-based and dynamic. Therefore, the performance of four commonly-used centrality measures, namely degree-, eigenvector-, closeness-, and betweenness centrality is compared for three different topology types in a dynamic, temporal network. Erdos-Renyi-, nearly-isolated community-, and community-affiliation graphs are considered. The performance of centrality measures is evaluated based on the spectral radius reduction per centrality type, as well as their effect on total costs.

(ii) **Centrality-based intervention policy for early epidemics.** The proposed isolation policy is designed so that only the most central nodes of a given network are to be isolated. Additionally, it is designed to work with limited information, with only infection rate β, recovery rate δ, community membership and basic community density information required. This enables usage in early epidemics where no vaccination strategy is possible. Total costs are minimized by balancing intervention costs and costs of infection, leading to a policy that limits the adverse effects of an epidemic. It is demonstrated that implementation of this targeted implementation strategy leads to similar cost reduction when compared to isolating all nodes, but at a much lower percentage of isolatable nodes.

(iii) **Individual policy recommendations with respect to epidemic severity.** To ensure that policy recommendations stemming from this research are as robust as possible, three epidemic cases of varying degrees of severity are considered. It is demonstrated that different epidemic severities require different policies to effectively control them, resulting in individual policies for each combination of network topology and epidemic case.

2 Problem Analysis

2.1 Problem Description

This research utilizes a controlled SIQS (susceptible-infected-quarantined) model (see figure 1), where γ_i and u_i are controlled using the proposed centrality-based isolation policy. This model considers the effect of epidemic severity, network topology, and choice of centrality measure to formulate a novel dynamic isolation strategy. A complete overview of the mathematics of the model can be found in section 5. A cost-minimization problem is formed that aims to minimize the combined costs related to infection and isolation. The formulation of the cost function and simulated parameters can also be found in section 5, with additional validation in section 9. This section instead focuses on extensive descriptions of the problem at hand, and the system that arises from it.

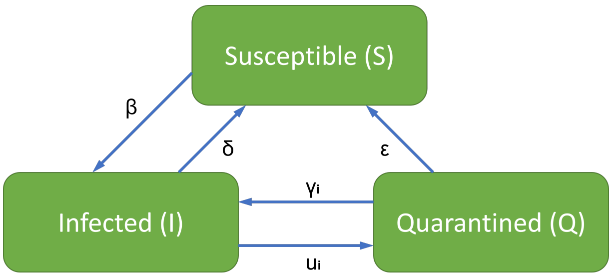


Figure 1: Susceptible-infected-quarantined (SIQS) model. This model consists of three compartments, infected (I), susceptible (S), and quarantined (Q). Parameters $\beta, \delta, \gamma_i, \epsilon_i$ and u_i determine the transitions between compartments, with γ_i, ϵ_i and u_i being controlled using the dynamic intervention strategy.

2.2 Spectral Radius

The most basic way to assess epidemic spread is by using the basic reproduction number R_0, which is the average number of contagions that a single infected person will cause in a susceptible population. In unstructured SIS models, this R_0 is simply defined by infection rate β and recovery rate δ in $\frac{\beta}{\delta}$. A network with $R_0 < 1$ tends to a completely susceptible situation without infected nodes. However, due to the heterogeneous nature of structured network, there is no simple formula that analytically determines this R_0 value [31] [28]. As a result, existing research has used alternative heuristics to asses the potency of epidemics. Chief among them is the spectral radius ρ of a graph, defined as the largest eigenvalue of the adjacency matrix. The smaller the value of ρ, the harder it is for an epidemic to spread, even ensuring sub-linear expected extinction time for epidemics below a certain spectral radius threshold [20] [26]. The mathematical formulation for the spectral radius is as follows:

$$\rho(A) = max\{|\lambda_1|, ..., |\lambda_n|\} \tag{1}$$

Where A is the adjacency matrix of the graph, and λ_k are the eigenvalues of this adjacency matrix. Spectral minimization problems can also be formulated directly but are NP-hard to solve, which is why centrality heuristics are used instead in this research [2].

Key nodes and edges are important to determine in order to create the maximum effectiveness per isolation [11]. To find these driver nodes and edges, centrality heuristics are utilised. These heuristics score each node in a network according to different mathematical criteria, and aim to find the most 'central' nodes. By basing isolation policy on these scores and comparing the resulting reduction in spectral radius, the performance of each individual centrality measure can be determined. Several different measures are considered, as the effectiveness of centrality measures is heavily influenced by the graph topography [6].

2.3 Centrality Types

In order to maximize the effectiveness per intervention, it is paramount to determine which nodes to target for intervention. Despite wide research into the field, centrality type research for dynamic networks is still quite shallow, being mostly focused on how to efficiently calculate centrality scores in dynamic graphs as is the case in [25] and [24]. Currently, systematic research comparing the efficacy of centrality types in dynamic graphs for epidemics has not been have performed [7]. Consequently, this research will analyze four of the most common centrality types and apply them to different network topographies to analyze their efficacy.

2.3.1 Degree Centrality

Degree centrality $C_D(i)$ is the most basic type of centrality, being defined for each node as the number of neighbouring nodes that it shares an edge with. A high-degree node has many direct neighbours and can easily spread a virus locally. However, unless connected to other influential nodes, high-degree nodes do not easily spread epidemics globally [23] [5]. Degree centrality is described mathematically as follows:

$$C_D(i) = \sum_{k=1}^{N} A_{i,j} \tag{2}$$

Where N is the total number of nodes, $A_{ij} = 1$ if and only if node pair A_{ij} of adjacency matrix A has an edge.

2.3.2 Closeness Centrality

Closeness centrality $C_C(i)$ is calculated by the average of the shortest distances between a node and every other node in the network. It is typically compared to the 'convenience' of a node, as information (in this case a virus) tends to travel through the shortest paths possible [23][5]. Closeness centrality is described mathematically as follows:

$$C_C(i) = \frac{1}{\sum_j d(i,j)} \tag{3}$$

Where d(i,j) represents the distance in number of edges between nodes i and j.

2.3.3 Betweenness Centrality

Betweenness centrality $C_B(i)$ concerns how many shortest paths between two nodes cross intermediary node s. If a node is located such that it lies on the shortest path between many nodes, it scores highly on betweenness. A node with a high betweenness centrality score is thus said to play a mediating role on a network, where many popular flows in a network tend to include it. Betweenness centrality is especially interesting for the system at hand due to its higher scoring when connecting disparate parts of a network. Nearly-isolated community graphs and community-affiliation graphs consist of clustered network sections with sparse connections, increasing the importance of identifying these connecting nodes [23][5]. Equation 4 shows the mathematical formulation:

$$C_B(i) = \sum_{i \neq s \neq j \in V} \frac{\sigma_{i,j}(s)}{\sigma_{i,j}} \tag{4}$$

Where $\sigma_{i,j}$ is the number of shortest paths between i and j, and $\sigma_{i,j}(s)$ the number of shortest paths that include intermediary node s.

2.3.4 Eigenvector Centrality

Eigenvector centrality (or eigen centrality) $C_E(i)$ is the final centrality type considered in this research. The score of eigenvector centrality is based both on the number of neighbours, as well as the quality of said neighbour. This quality is determined by the number of neighbours that each neighbour has themselves. Eigenvector-based centrality measures place heavy emphasis on the most central nodes, with large differences in scoring between more and less central nodes. The often-used PageRank and Katz centrality measures are variants of the same basic eigenvector centrality concept [15]. Equation 5 shows the mathematical formulation.

$$\begin{aligned} &C_E(i) = \frac{1}{\lambda} \sum_{b=1}^{n} A_{ij} C_{Ej} \\ &\text{Which can be rewritten as} \\ &\boldsymbol{\lambda x} = \boldsymbol{Ax} \end{aligned} \tag{5}$$

Where λ is the largest eigenvalue of the adjacency matrix, and $\boldsymbol{x}$ is a vector consisting of the values of C_E of all nodes.

2.4 Network Topology Types

Epidemic spreading behaviour in structured networks is heavily dependent on the topology of individual networks. As highlighted before in subsection 2.3, information flows tends to flow according to shortest paths. Topology greatly influences these shortest paths, introducing choke points, hubs and other features that force analysis using different centrality types [13]. The three social network types that are considered in this research consist of Erdos-Renyi-, community-affiliation-, and nearly-isolated community graphs. Erdos-Renyi simulation results serve as a baseline to compare other results to. Nearly-isolated community graphs were chosen due to the fact that any node can belong to one and only one community, with sparse connections between communities. These graphs can be created with limited data regarding which communities nodes belong to. Community-affiliation networks are based on the notion that one node can belong to several communities, and generates a graph with edges based on the shared communities of these nodes [27]. Similarly to nearly-isolated community graphs, these graphs can be constructed with only the knowledge of which nodes belong to which communities.

2.4.1 Erdos-Renyi Graph

Erdos-Renyi graphs are the most basic type of generative graph, and have been studied often in the past. Erdos-Renyi graphs consider the presence and absence of edges, with edge pair $a_{ij} = 1$ generating with probability η and $a_{ij} = 0$ with probability 1 - η [22]. Erdos-Renyi graphs were generated using these dynamics, as well as the nearly-isolated community graphs. The general dynamics are then as follows:

$$P(A|\eta) = \prod_{i,j} \eta^{a_{ij}} (1-\eta)^{(1-a_{ij})} \tag{6}$$

Generally, Erdos-Renyi are considered to have limited accuracy in modeling social network structures due to their low tendency for clustering [19]. Therefore, this research also considers community graphs that tend to cluster.

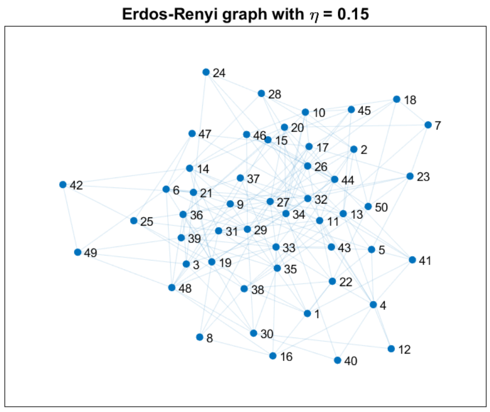


Figure 2: Generated Erdos-Renyi graph. This figure shows an Erdos-Renyi graph that was generated using the generation parameters as described in section 5.4.2.

2.4.2 Nearly-isolated Communities Graph

Nearly-isolated community networks are defined in this research as a variation on the previously described Erdos-Renyi networks. They consist of densely-connected Erdos-Renyi communities with sparse connections between them. This generation structure not only aims to replicate real-world social networks of communities with sparse connections, but additionally aims to highlight the strengths and weaknesses of different centrality types due to the bridge structures that arise in graphs similar to this [3].

Let $\mathcal{C}_k$ be a set of communities consisting of nodes belonging to the total node set $\mathcal{N}$, where $\mathcal{C}_k \cap \mathcal{C}_m = \emptyset$ and $\cup \mathcal{C}_k = \mathcal{N}$. As a result, every node can belong to one and only one community. The generation is described by:

$$P(A|\eta_k, \eta_\epsilon) = \prod_{i,j} f(i,j) \tag{7}$$

$$f(i,j) = \begin{cases} (\eta_k + \eta_\epsilon)^{a_{ij}} (1 - \eta_k - \eta_\epsilon)^{1-a_{ij}}, & i,j \in C_k \\ (\eta_\epsilon)^{a_{ij}} (1-\eta_\epsilon)^{1-a_{i}j}, & i \in \mathcal{C}_k \,\&\, j \in \mathcal{C}_m \,\&\, k \neq m \end{cases} \tag{8}$$

Where η_k is the base generation probability of edge pair a_{ij} within a community, and η_ϵ is the additional cross-community edge pair probability. Each edge pair a_{ij} has a probability of $\eta_k + \eta_\epsilon$ of being formed within a specific community, while outside of the community, the edge generation probability is only η_ϵ. Probability η_k is set to be relatively high, while η_ϵ is set to be very low, introducing densely connected clusters within communities, and sparse connections outside of communities.

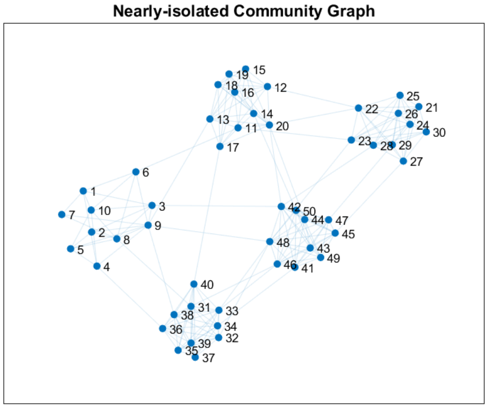
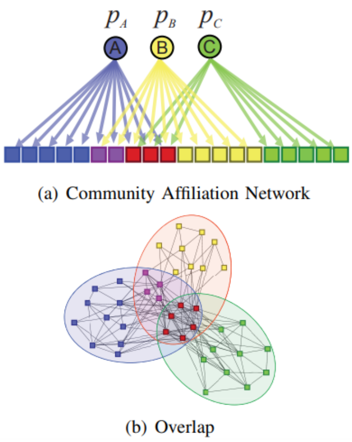


Figure 3: Generated nearly-isolated community graph. This figure shows a nearly-isolated community graph that was generated using the generation parameters as described in section 5.4.2.

2.4.3 Community-affiliation Graph

Community-affiliation networks are generative networks, originating from bipartite graphs that link nodes and communities. The community-affiliation graph model was formulated within the last decade, and is thus a young but promising field. Usage of the model requires very limited information. If membership lists of several partially intersecting communities are known, as well as an estimate regarding the average density of those networks, the community-affiliation graph model provides a state-of-the-art generation algorithm that narrowly approximates real social networks as suggested in [27].

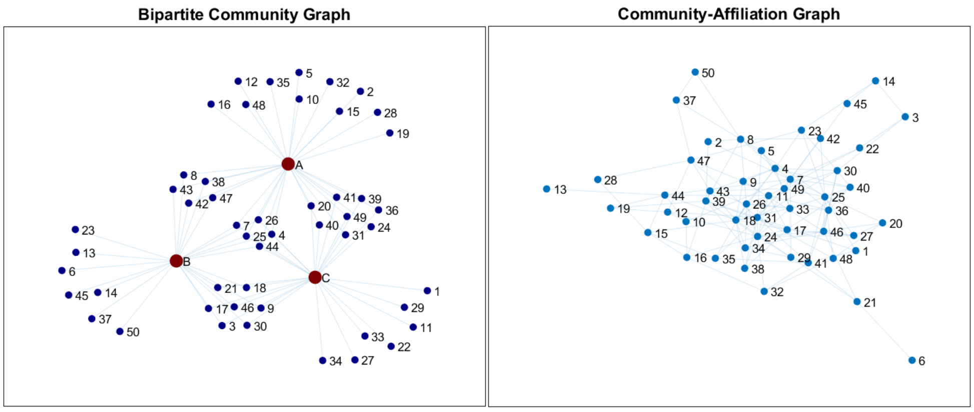
Crucially, nodes can belong to multiple communities, with increased edge pair generation probability for each community that two nodes share. Each community has its own edge generation probability p_c between nodes of that community, reflecting dynamics of real social networks where some communities are more densely connected than others. Finally, all nodes have a very small chance p_ϵ of being connected regardless of their community. This is done by having *all* nodes belonging to a so-called ϵ-community, regardless of their actual community affiliation [27]. Generation probability p_ϵ is set to be very small, mirroring the cross-community probability as seen for nearly-isolated community graphs described in section 2.4.2. Figure 4 shows the described dynamics.



(a) Community Affiliation Network

(b) Overlap

Figure 4: Community-affiliation model. Bipartite community affiliation network networks as visible in (a) are used as the basis for generatively creating a structured community-affiliation graph as seen in (b). Nodes can belong to multiple communities, with each community overlap with another node increasing the probability of edge pair creation.



(a) Bipartite community graph (b) Generated community-affiliation graph

Figure 5: Generated bipartite community- and community-affiliation graphs. This figure shows a bipartite community graph and a community-affiliation graph that were generated using the generation parameters as described in section 5.4.2.

Generation starts with any bipartite network $B(\mathcal{V}, \mathcal{C}, \mathcal{M})$, with $\mathcal{V}$ indicating the set of nodes, $\mathcal{C}$ indicating the set of communities $\mathcal{C} = \{c_k, ..., c_n\}$, and $\mathcal{M}$ indicating an edge set. The community-affiliation graph model then generates graph $G(V, E)$ by the creation of edge (i, j) between nodes $i, j \in \mathcal{V}$ with $p(i, j)$ [27]. The mathematical description of community-affiliation graph generation is as follows:

$$p(i, j) = 1 - \prod_{k \in \mathcal{C}_{ij}} (1 - p_k) \tag{9}$$

Where $\mathcal{C}_{ij} \subset \mathcal{C}$ is a shared community between nodes i, j, and p_k is the community edge generation probability per community.

2.5 Current System State

In the current system state, epidemic spreading is uncontrolled, meaning that no interventions take place to alter the spread. Intervention by way of vaccinations is not an option and limited information is available regarding the epidemic. As a result, substantial costs are incurred by society, not only in terms of physical health, but also socially and economically.

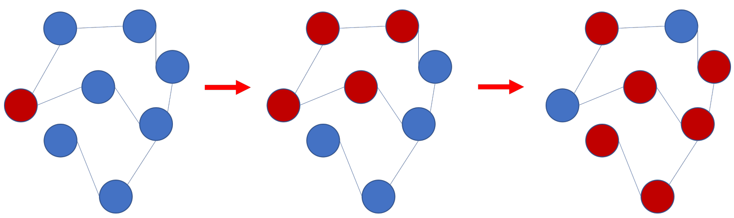


Figure 6: Current system state. Here, the spread of an epidemic in the base model is shown, in red indicating 'infected', and blue indicating 'susceptible'. In the third sub-figure, two nodes are also shown to move from the infected to the susceptible compartment.

2.6 Desired System State

The desired system state consists of a controlled SIQS network, in which nodes can be temporarily isolated via a novel dynamic intervention strategy in order to reduce the spread of the epidemic. The key nodes of these graphs are determined according to the network topology type and the most suitable centrality measure, namely the centrality measure that minimizes the spectral radius and costs of the network once the identified nodes are isolated.

The system is designed to work in an early epidemic, with limited information availability and no developed vaccination strategy. Finally, an individualized policy recommendation is made based on the severity of the epidemic, providing the minimum-cost solution that balances infection costs and isolation costs.

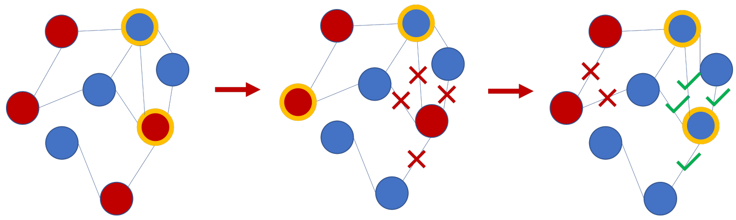


Figure 7: Desired system state. Here, the spread of an epidemic in the desired controlled model is shown, with red indicating the infected state, and blue susceptible. The most central nodes (in this case defined by degree centrality) are highlighted in yellow. Crosses indicate edge removal and check-marks indicate edge reinsertion. Each time-step, the most central nodes are recalculated according to the new post-removal topology. At each time-step, only the most central nodes are isolated if they are infected.

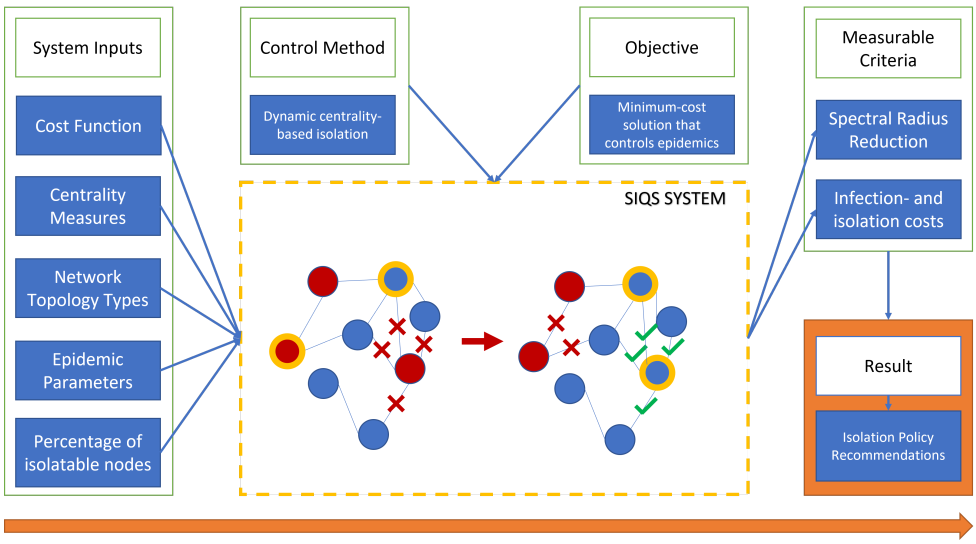


Figure 8: Total system. This figure combines previously determined system inputs, control methods, objectives, and criteria in order to provide a holistic view of the system.

3 Research Objective

The research objective is to find the minimum-cost control solution in SIQS community networks modeled as a discrete-time Markov process. The centrality-based control policy should dynamically detect and isolate the nodes that result in minimized spectral radius in Erdos-Renyi-, nearly-isolated community-, and community-affiliation networks. Three epidemic cases of varying severities are to be considered, leading to individual isolation policy recommendations for each epidemic case.

4 Research Questions

By answering the two central research questions below, the key nodes can be found per network topology type, in turn leading to minimum-cost policy for early epidemic control. This coincides with the research objective stated in section 3.

Central question 1: *Which centrality measure (among degree-, closeness-, betweenness-, and eigen-centrality) most accurately determines the influential nodes in epidemic spreading per network topology type (among Erdos-Renyi, nearly-isolated community-, and community-affiliation graphs?*
Network topology has been proven to have a significant effect on the spread of epidemics [6]. However, this has not been systematically connected to centrality measures for the specific network topologies considered in this research. Determining the most influential nodes is critical in maximizing the effectiveness of each isolation.

Sub question 1.1: *Which centrality measure maximizes spectral radius reduction after isolation of the identified nodes?*
Spectral graph theory states that a minimized spectral radius leads to reduced epidemiological spread and even extermination under a certain epidemic threshold [16] [30]. Answering this question should thus accurately identifies nodes and edges that influence the spread.

Sub question 1.2: *Which centrality measure minimizes the total costs of an epidemic given a quadratic cost function?*
As the final goal of the research is to give a minimum-cost policy recommendation, it is crucial that centrality measures and network topologies are compared to attain this minimum-cost solution.

Sub question 1.3: *What is the influence of epidemic parameters on spectral radius reduction and cost minimization?*
Answering this question validates whether drawn conclusions still hold in case of an ongoing epidemic, as previous research in the field has nearly exclusively operated under the assumption of an infinitesimally small infected starting population [14]. Additionally, the influence of different initial infection- and recovery rates are important to consider when deciding on the ideal isolation policy.

Central question 2: *What is the optimal policy that minimizes total cost for each epidemic case and network topology type?*
Combining the minimum-cost results of central question 1 allows for the formulation of an individualized policy for each epidemic case and network topology type.

5 Methodology

5.1 Controlled SIQS Model

In research regarding epidemic spreading, the stochastic SIS model has traditionally been one of the most often used [17]. The stochastic SIS model consists of two compartments, 'infected' and 'susceptible', with nodes moving between compartments probabilistically at each time-step with infection probability β, and recovery probability δ. The SIS model does not account for immunity, vaccinations, or recovery. Nevertheless, this research concerns epidemics for which little to no immunity has been formed and no vaccinations have been developed [31].

Described mathematically as in [17], the networked SIS model deals with N nodes that form an undirected, connected graph $G = (V, E)$, where $\mathcal{V}$ is the collection of all N nodes and $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ describes the edge set. The adjacency matrix $A \in \mathbb{R}_{\geq 0}^{N \times N}$ has individual components $a_{ij} = 1$ if an edge exists between node i and j, and else $a_{ij} = 0$. Recall that the spectral radius

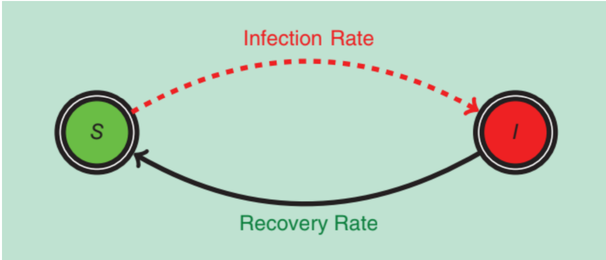


Figure 9: Susceptible-infected-susceptible (SIS) model. This model consists of an 'infected' (I) and a 'susceptible' (S) compartment which contain the nodes of a population. Movement between compartments occurs with infection probability β and recovery probability δ [31]

ρ equals the largest eigenvalue of the adjacency matrix $\lambda_{max(A)}$.

Modeling the spread of an epidemic in graph G is done by formulating the state transitions as a discrete-time Markov process. State variable $X_i(t)$ denotes the state of node i at time t, with $X_i(t) = 1$ denoting 'infected' at time t, and $X_i(t) = 0$ indicating 'susceptible' at time t. Infection can spread to adjacent neighbours with infection probability $\beta > 0$, and infected nodes can recover with recovery probability $\delta > 0$. The state transition dynamics are described thusly:

$$\begin{aligned} \dot{S}(t) &= \delta(I(t) - \beta S(t)I(t) \\ \dot{I}(t) &= \beta S(t)I(t) - \delta I(t) \end{aligned} \tag{10}$$

Which leads to the discrete-time Markov process:

$$\begin{aligned} &X_i : 0 \rightarrow 1 \text{ with probability } \beta\Sigma_{j\in N_i} X_j, \\ &X_i : 1 \rightarrow 0 \text{ with probability } \delta. \end{aligned} \tag{11}$$

Utilizing isolation as the control method introduces a new state Q (quarantined), serving as an extension to the previously described SIS dynamics. With this addition, the system now follows susceptible-infected-quarantined (SIQS) dynamics [29]:

$$\begin{aligned} \dot{S}(t) &= \delta I(t) + \epsilon_i Q(t) - \beta S(t)I(t) \\ \dot{I}(t) &= \beta S(t)I(t) + (\gamma_i - u_i)Q(t) - \delta I(t) \\ \dot{Q}(t) &= u_i I(t) - \gamma_i I(t) - \epsilon_i S(t) \end{aligned} \tag{12}$$

Where γ_i denotes the transition probability from Q to I, u_i is the transition probability from I to Q, and ϵ_i is the transition probability from Q to S. Note that an isolated node can move from to compartment Q to S due to the stochasticity of infection duration. The discrete-time Markov process of the SIQS model is then as follows:

$$\begin{aligned} &X_i : 0 \rightarrow 1 \text{ with probability } \beta\Sigma_{j\in N_i} X_j, \\ &X_i : 1 \rightarrow 0 \text{ with probability } \delta. \\ &X_i : 1 \rightarrow 2 \text{ with probability } u_i. \\ &X_i : 2 \rightarrow 0 \text{ with probability } \epsilon_i. \\ &X_i : 2 \rightarrow 1 \text{ with probability } \gamma_i. \end{aligned} \tag{13}$$

It is important to mention that these dynamics only hold for random transitions u_i, γ_i and ϵ_i. The controlled system (as shown in figure 1) ensures that these transitions are not random, but instead controlled using the centrality-based isolation policy.

5.2 Cost Function

To model the costs that arise from infections and isolations during an isolation, a quadratic cost function was chosen. This is due to its ability to closely estimate non-linear effects that emerge due to strict isolation policy on the one hand, and a large infected population on the other [10]. The cost function is formulated as follows:

$$J(u, a) = \sum_{t=0}^{T} \frac{1}{2}u_t^2 + \theta\frac{1}{2}a_t^2 \tag{14}$$

Where $J(u, a)$ is defined the total cost over the course of epidemic, t is the time instance, T is the total time in days until epidemic extinction, u_t are intervention costs, θ is a cost coefficient, and I_t denotes infection costs. Intervention costs u_t are proportional to the square of the node degree, as the intervention in this model deals only with isolation. Infection costs a_t are proportional to the square of the infected population. Low values of θ correspond to relatively higher intervention costs, incentivizing fewer isolations and thus a milder intervention strategy. Inversely, higher values of θ place more emphasis on infection costs, stimulating stricter intervention strategy [10]. The value θ=60 used throughout this research was determined heuristically by running simulations, ensuring that isolation costs and infection costs were given approximately equal weight, as shown in 21.

5.3 Intervention Strategies

This research mainly utilizes dynamic node removal in order to control the spread of the epidemic. As a supplementary tool, static removal is used to analyze the effect of increased isolation on spectral radius radius reduction. In this section, both intervention strategies and their implementation are discussed.

5.3.1 Dynamic Removal

The dynamic removal strategy that is proposed in this research is predicated on the goal of decreasing the necessary number of isolations while still maintaining effectiveness in reducing spectral radius and total system costs. To achieve this, the centrality of each node in graph G is calculated at each time-instance. Subsequently, a selection of the most central nodes is made, based on the chosen centrality measure and the percentage of 'isolatable' nodes. That is to say, a set maximum percentage of nodes that can be isolated at each time-instance. This set of isolatable nodes $\mathcal{H} \subset \mathcal{V}$ is then cross-referenced with state X. If a node is both (a) isolatable and (b) infected at a certain time-instance, then the node is moved to the quarantined compartment Q of the formulated SIQS model (see 5.1), with a certain isolation duration. The remaining duration of each node isolation is stored at each iteration. When this duration becomes 0 for any node, this node then moves to either the infected compartment I or the susceptible compartment S depending on whether the node recovered from its infection during its isolation. Note that isolation always occurs with a single time-instance delay due to the formulation of the Markov process, where state $X(t + 1)$ depends only on state $X(t)$ [17]. An infected node thus always has a single time-instance opportunity to infect its neighbours. This delay mirrors epidemic dynamics where a node either is unaware of its infection or gets tested. The complete flowchart of this removal strategy can be found in figure 10. Additionally, figure 11 shows one time-instance of the model where the centrality of each node is calculated.

Finally, all simulations involving dynamic removal compared not only the performance of the four centrality measures considered in this research, but also random removal as a baseline. To model random removal, isolatable node set $\mathcal{H}$ was populated with random nodes at each time-instance. However, the size of set $\mathcal{H}$ remains consistent with its counterpart in centrality-based removal simulations.

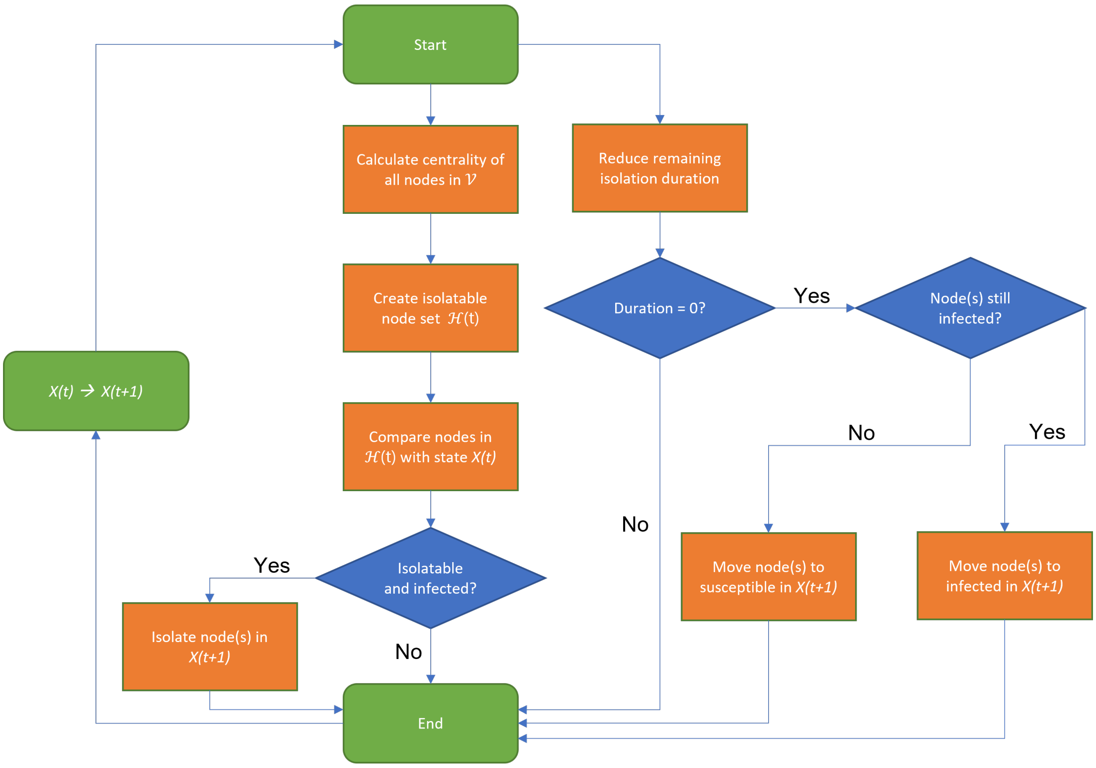
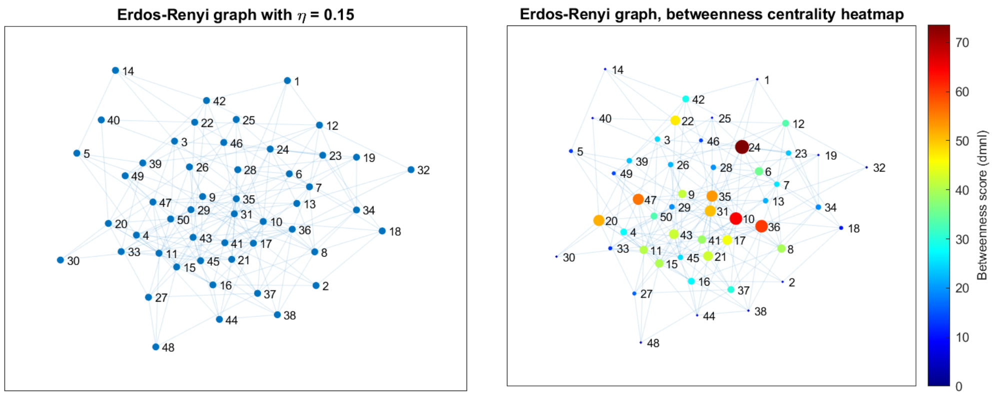


Figure 10: Flowchart for dynamic removal. This flowchart graphically displays the steps described in 5.3.2 that lead to the total dynamic removal strategy used. Isolatable node set $\mathcal{H}$ is compared with their respective states. If a node is both isolatable and infected, it is isolated starting at the next system iteration. Furthermore, each iteration reduces the remaining isolation duration for all isolated nodes, sending them to the appropriate compartment S or I depending on their infection status.



(a) Erdos-Renyi base graph

(b) Erdos-Renyi graph, centrality heatmap

Figure 11: Erdos-Renyi graph with centrality heatmap. This figure shows the base Erdos-Renyi graph in (a) and the heatmap version that is used as the basis for isolation in (b).

5.3.2 Static Removal

As the main proposed removal strategy is dynamic, it is difficult to draw independent conclusions regarding the effect of centrality measure choice on spectral radius reduction. Different isolations are performed for each simulation due to stochasticity. Therefore, a simple static removal strategy was formulated. Rather than recalculating node centrality scores at each time instance during the epidemic simulation, isolations are performed before epidemic simulations begins. Instead of an 'isolatable' node percentage, the number of isolations in the static case is directly determined by the isolation percentage ζ and total node number N. At each iteration preceding the epidemic simulation, centrality scores for all nodes in the network are calculated, after which the node with the largest centrality score is (preemptively) put into indefinite isolation. This is repeated for the number of nodes that are to be removed, isolating the new most central node each iteration. The steps of this static removal algorithm are displayed in figure 12.

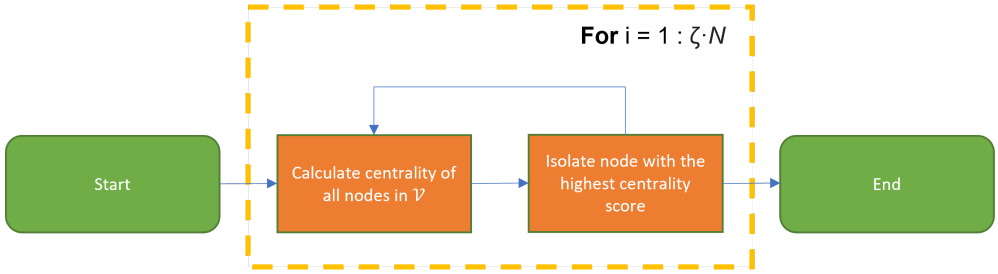


Figure 12: Flowchart for static removal. This flowchart graphically displays the steps described in 5.3.2 that lead to the total static removal strategy used. The centrality of each node in $\mathcal{V}$ is calculated, after which the node with the highest centrality score is isolated. This is repeated until the number of iterations equals the product of isolation percentage ζ and total node number N.

5.4 Simulated Parameters

5.4.1 Epidemic Parameters

Three different simulated epidemic parameter sets were used for different purposes throughout this research. The first set named "COVID-19" is based on δ as found in [18] and β as found in [12]. This is the most aggressive case. Important to note is that during the real COVID-19 epidemic, very strict control measures were taken to control the epidemic. Isolation was used in addition to β-lowering measures such as social distancing, face masks, and group size restrictions [9]. The second parameter set named "epidemic" simulates an epidemic that is approximately twice as weak as COVID-19, and the final parameter set "weak epidemic" is set to be four times as weak as COVID-19. Setting the parameters in this fashion effectively simulates harsh, middling, and mild epidemics, for which individual policy recommendations can be made.

Table 1: Simulated parameters for the three considered epidemic cases. COVID-19 is the most aggressive epidemic, with δ determined via [18] and β via [12]. 'Epidemic' is the middle case and 'Weak epidemic' is the mildest case.

	COVID-19	**Epidemic**	**Weak epidemic**
β	0.22 [12]	0.1	0.05
δ	0.1 [18]	0.1	0.1

5.4.2 Graph Parameters

In order to make the results of the proposed model as generally applicable as possible, every simulation was run using newly generated graphs. Therefore, this section does not include the exact networks used, but rather their generation parameters. Early simulation results showed that lower edge generation probabilities lead to larger differences between centrality type performances, ostensibly due to the reduced homogeneity within network structure. Erdos-Renyi generation probability was thus set to η=0.15 in line with findings as shown in appendix 10.1. Furthermore, the number of nodes per simulation N was set to 50 in order to keep simulation

Table 2: Graph generation parameters. In this table, the parameters used for the generation of Erdos-Renyi-, community-affiliation-, and nearly-isolation community graphs are denoted, including justification where necessary.

General	
Parameter	**Value**
N	50
Erdos-Renyi	
Parameter	**Value**
η	0.15 (see section 10.1)
Community-affiliation	
Parameter	**Value**
Communities	3
p_c	[0.1 0.1 0.2]
p_ϵ	0.002 [27]
Nearly-isolated community	
Parameter	**Value**
Communities	5
Community size	10
η_k	0.5
η_ϵ	0.02

times manageable while still having the ability to generate distinct communities of adequate size. Nearly-isolated community graphs in which nodes belong to one and only one community were set to have 5 communities of 10 nodes each, with a dense η_k=0.5 edge generation probability within communities, and a sparse η_ϵ=0.02 inter-community edge generation probability. Finally, community-affiliation graphs where nodes potentially belong to multiple communities were set slightly lower to have 3 communities, with edge generation probability per community $p_c = [0.1\ 0.1\ 0.2]$ and ϵ-community probability of p_ϵ=0.002.

6 Results

In this section, simulation results are detailed pertaining to the model described in section 5.

First, the centrality-based static removal method from section 5.3.2 was used to compare the spectral radius reduction performance of degree-, eigen-, closeness-, and betweenness centrality, as well as random removal, for Erdos-Renyi-, nearly-isolated community-, and community affiliation networks. These results pertain solely to reduction in spectral radius, without considering epidemic spreading (see 6.1). The effect of Erdos-Renyi generation probability η was investigated before running final simulations and can be found in appendix 10.1.

Secondly, the dynamic centrality-based and random removal algorithms described in section 5.3.1 are applied to epidemic simulations, once again comparing spectral radius reduction performance of the four previously mentioned centrality measures and random dynamic removal (see 6.2). Harsh, middling, and mild epidemic cases are considered, named "COVID-19", "Epidemic", and "Weak Epidemic", respectively, as described in section 5.4.1.

Thirdly, these same dynamic simulation settings are then utilized to measure centrality measure performance in reducing simulated extinction time (see 6.3), and subsequently employed in combination with the cost function (14) in order to calculate the total costs per epidemic case and topology type (see 6.4). Exhaustive tables regarding cost outputs can be found in section 10.3, Section 10.2 contains graphs concerning the ratio of isolation- and infection costs for each simulation.

Finally, results from cost simulations are merged into two tables, containing the near-minimum-cost solutions related to 102% and 105% of minimum-cost. These tables contain individual intervention strategies per case and topology type (see 6.4.1).

6.1 Spectral Radius Reduction utilizing Static Removal

From fig. 13, the following can be concluded:

(i) For all three topology types, static isolation based on betweenness- and degree centrality tends to provide the largest spectral radius reduction at each removal percentage, closeness centrality generally performs worse, and eigen-centrality tends to yield the lowest spectral radius reduction. There are two notable exceptions to these observations. First, betweenness centrality loses efficacy at higher removal percentages in nearly-isolated community graphs, being overtaken by closeness centrality and eigen centrality at 76% and 84% removal, respectively. Secondly, despite betweenness centrality performing the best out of all four centrality measures after 42% removal in community-affiliation graphs, it is outperformed by degree-, eigen-, and closeness centrality before 30% removal.

(ii) Random removal leads to roughly linear spectral radius reduction for all three network topology types, performing worse at all isolation percentages for Erdos-Renyi and community-affiliation graphs. For nearly-isolated community graphs, random removal performs better than closeness- and eigen centrality for nearly all isolation percentage values, as well as outperforming betweenness centrality after 58% removal.

(iii) Differences between the spectral radius reduction values for the best- and worst performing centrality measures vary greatly between topology types. For Erdos-Renyi graphs, all centrality measures perform relatively similarly throughout, with the maximum difference between the best- and worst performing centrality measures amounting to roughly 10% of the starting spectral radius ρ. For nearly-isolated community graphs, the maximum difference is roughly 25% of the starting ρ, and for community-affiliation graphs this difference is approximately 20%.

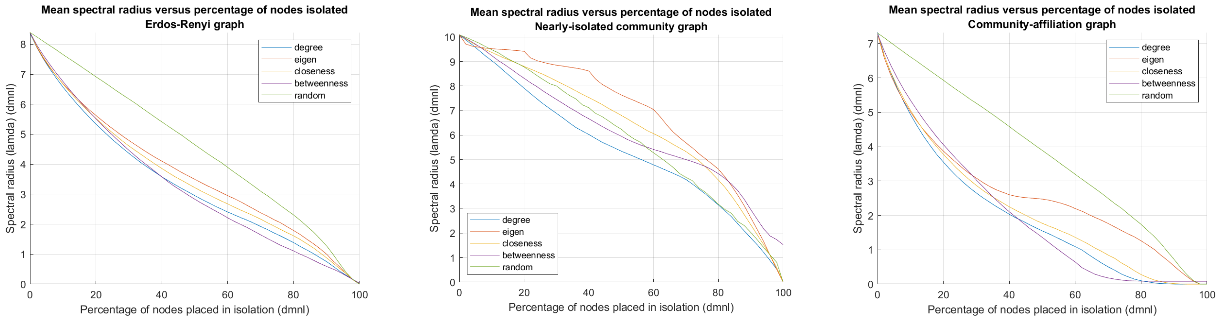


Figure 13: Mean spectral radius versus the percentage of isolated nodes for static removal. Static removal (as described in 5.3.2) was used to remove a set percentage of the most central nodes before calculating the spectral radius. This percentage ranged from 2% to 100% of nodes removed in 2% intervals. Centrality-based isolation was performed using degree-, eigen-, closeness-, and betweenness- centralities, as well as randomly-selected removal. Simulations were performed for Erdos-Renyi graphs (a), nearly-isolated community graphs (b) and community-affiliation graphs (c).

6.2 Spectral Radius Reduction utilizing Dynamic Removal

From fig. 14, the following can be concluded:

(i) For all network topology types, the severity of the epidemic has three notable influences. First, the amplitude of spectral radius reduction is increased proportionally to the epidemic severity. Second, lower epidemic severity causes the system to move towards an asymptotic value more quickly. Finally, the differences between spectral radius reduction performance of centrality measures are larger for more severe epidemics.

(ii) In general, random removal results in higher spectral radius values for low removal percentages (approximately 0-25%), but results in lower spectral radius values for higher removal percentages.

(iii) Generally speaking, centrality measures that performed well in static spectral radius reduction cause a lower minimum spectral radius for low removal percentages, but a higher mean spectral radius at higher removal percentages. Nevertheless, note that performance amongst the four chosen centrality measures is more homogeneous than in the case of static removal.

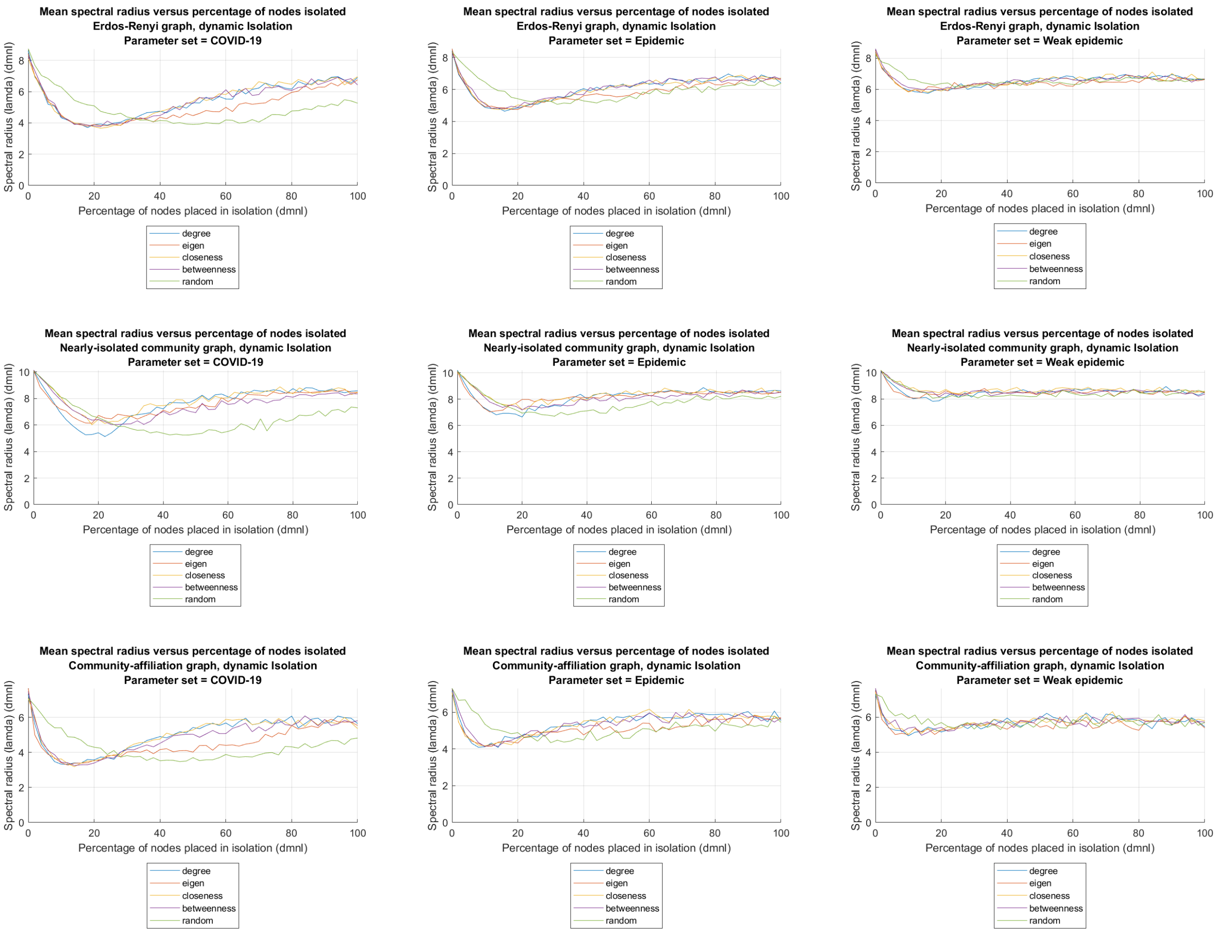


Figure 14: Mean spectral radius versus the percentage of isolatable nodes utilizing dynamic isolation for Erdos-Renyi- (row 1), nearly-isolated community (row 2), and community-affiliation (row 3) graphs with generation parameters according to 5.4.2. Centrality-based dynamic isolation and randomly-selected dynamic removal were both utilized (as described in 5.3.1) for isolatable node percentage ranging from 2% to 100% of nodes, removed in 2% intervals. Centrality-based isolation was performed using degree-, eigen-, closeness-, and betweenness-centralities. Simulations were performed for three parameter sets (detailed in 5.4.1), "COVID-19" (a), "Epidemic" (b) and "Weak Epidemic" (c).

6.3 Extinction Time

From fig. 15, the following can be concluded:

(i) Epidemic severity has three main influences on extinction time across all network topologies. First, higher epidemic severity generally leads to longer extinction times. As a consequence, the more severe the epidemic, the higher the isolation percentage required to observe epidemic extinction. Secondly, similar to findings in 6.1 and 14, increased epidemic severity amplifies the differences between the performance of centrality measures. Finally, the efficacy of random removal is directly tied to epidemic severity. The more severe the epidemic, the worse random removal performs. However, in the weak epidemic set, it performs similarly to centrality-based removal, even outperforming all centrality types for nearly-isolated community graphs.

(ii) Betweenness- and degree centrality provide the best performance in terms of extinction time reduction for Erdos-Renyi-, and community-affiliation graphs, while eigen-centrality performs the worst in for all network topology types. A notable exception is betweenness centrality in Erdos-Renyi graphs when simulating COVID-19 parameters. Here, similarly to findings in figure 13, closeness- and eigen centrality surpass betweenness centrality at 70% and 84%, respectively.

(iii) All simulations tend towards an asymptotic extinction time of 40 days.

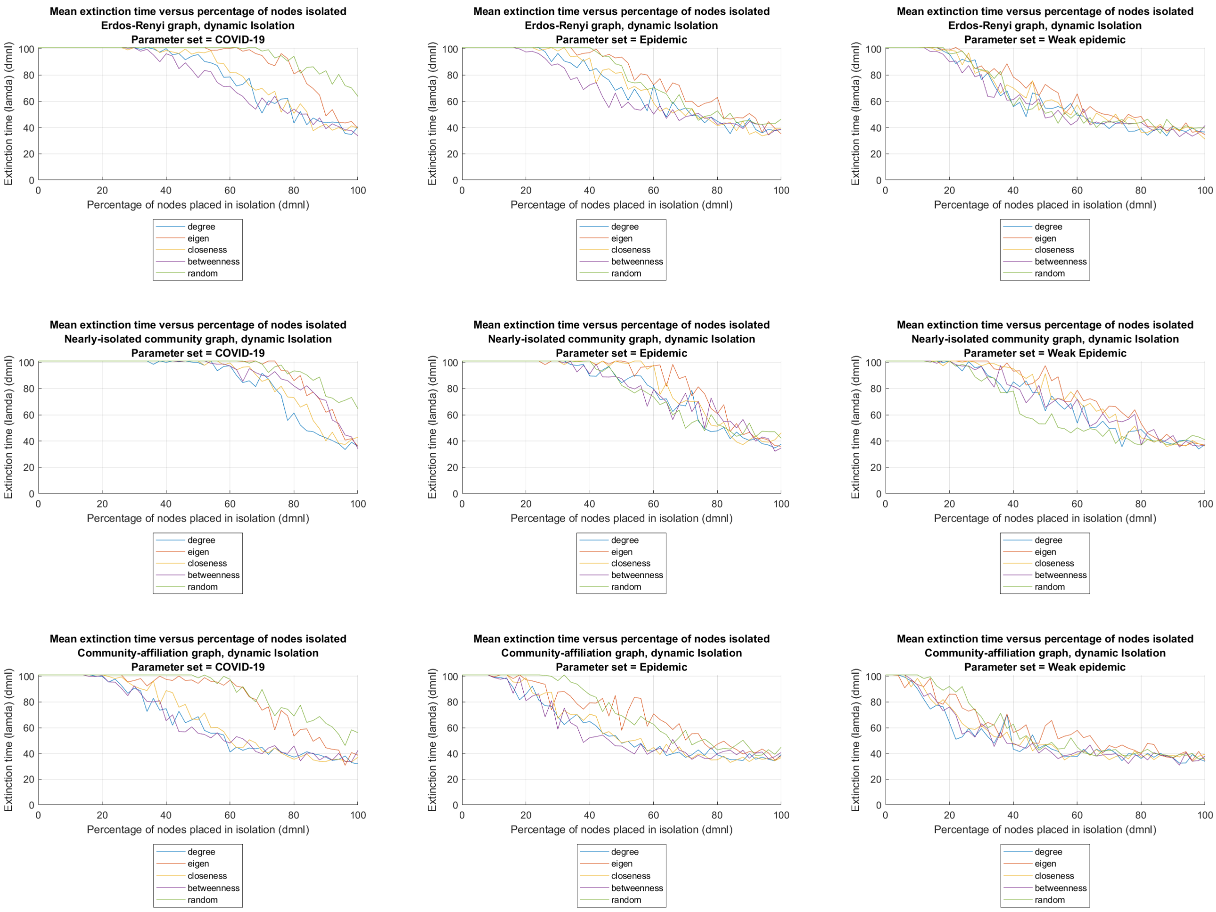


Figure 15: Mean simulated extinction time versus the percentage of isolatable nodes utilizing dynamic isolation for Erdos-Renyi- (row 1), nearly-isolated community (row 2), and community-affiliation (row 3) graphs with generation parameters according to 5.4.2. Centrality-based dynamic isolation and randomly-selected dynamic removal were both utilized (as described in 5.3.1) for isolatable node percentage ranging from 2% to 100% of nodes, removed in 2% intervals. Centrality-based isolation was performed using degree-, eigen-, closeness-, and betweenness- centralities. Simulations were performed for three parameter sets (detailed in 5.4.1), "COVID-19" (a), "Epidemic" (b) and "Weak Epidemic" (c).

6.4 Total Costs

From fig. 16, the following can be concluded:

(i) Similar to previous results, betweenness- and degree centrality provide the lowest costs across the board, with eigen centrality performing worst. Random removal leads to highest costs, with an exception of outperforming eigen-centrality for the middling and mild epidemic cases in Erdos-Renyi graphs.

(ii) For the COVID-19 parameter set, low isolation percentages lead to higher costs than those incurred by the uncontrolled system.

(iii) An asymptotic cost value is observed, corresponding to a situation of approximately equal isolation- and infection costs as observable in 10.2. Important to note is that the minimum-cost solution is thus always reached when the isolatable node percentage equals 100%, $\mathcal{H} = \mathcal{V}$.

Fig. 17 shows the results of simulations with the same parameters as fig. 16 (row 2, column 3), but with N=200 instead of N=50. Here, it is observable that betweenness centrality performs better, and degree centrality performs worse relative to the base N=50 case.

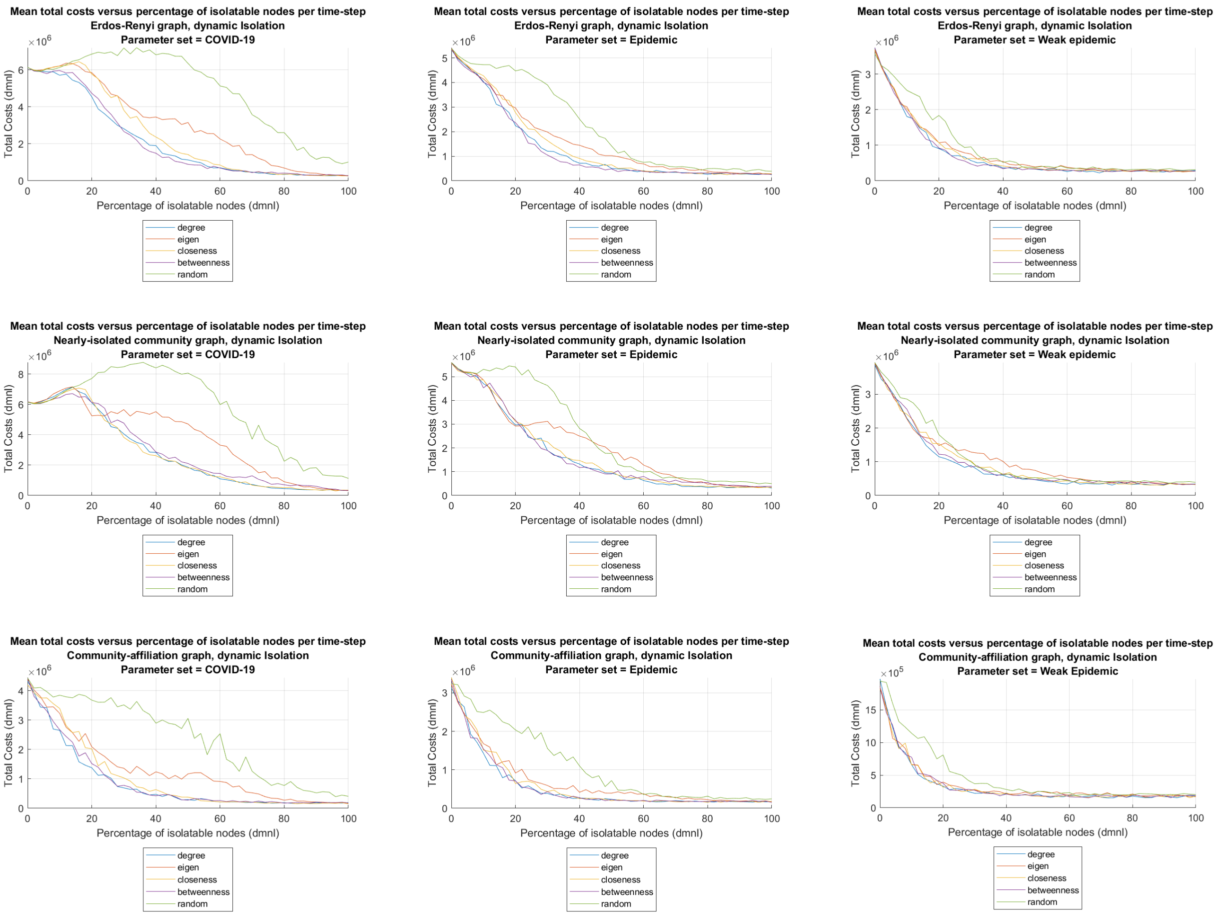


Figure 16: Mean total costs versus the percentage of isolatable nodes utilizing dynamic isolation for Erdos-Renyi- (row 1), nearly-isolated community (row 2), and community-affiliation (row 3) graphs with generation parameters according to 5.4.2. Costs are calculated using cost function 14. Centrality-based dynamic isolation and randomly-selected dynamic removal were both utilized (as described in 5.3.1) for isolatable node percentage ranging from 2% to 100% of nodes, removed in 2% intervals. Centrality-based isolation was performed using degree-, eigen-, closeness-, and betweenness- centralities. Simulations were performed for three parameter sets (detailed in 5.4.1), "COVID-19" (a), "Epidemic" (b) and "Weak Epidemic" (c).

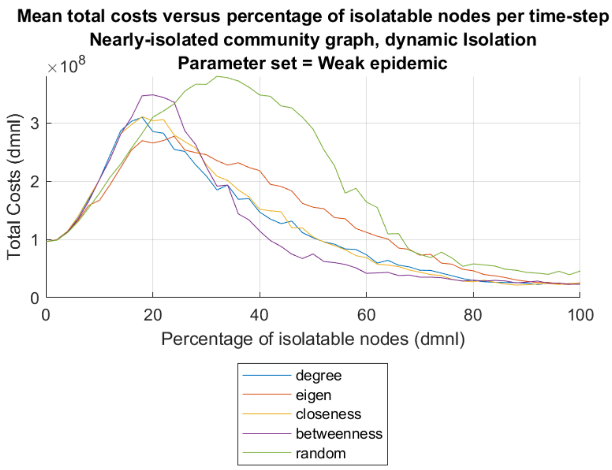


Figure 17: Mean total costs versus the percentage of isolatable nodes for an N=200 nearly-isolated community graph, using the "Weak Epidemic" parameter set.

6.4.1 Policy Recommendations

As shown in 16, the minimum-cost solution is always reached when the isolatable node percentage equals 100%, $\mathcal{H} = \mathcal{V}$. At this percentage, all non-random removal strategies approach the asymptotic minimum-cost solution. When every node is subject to intervention, the strategy is no longer targeted. Therefore, this section describes which strategies lead to the 102%- and 105% of minimum-cost solutions with the lowest percentage of isolatable nodes. These strategies approach the minimum-cost solution but reduce the required intervention severity.

It follows from tables 3 and 4 that epidemic severity plays a large role in the recommended policy. For the "COVID-19" parameter set, nearly all nodes still need to be isolatable in order to approach the minimum-cost solution. This is especially the case for the simulated Erdos-Renyi-, and nearly-isolated community networks. However, the required percentage of isolatable nodes to approach the minimum-cost decreases significantly when considering less severe epidemics. This is demonstrated best by the "Weak Epidemic" parameter set, where only 60%, 68%, and 48% of nodes have to be isolatable in order to achieve 105% of the minimum-cost solution for Erdos-Renyi-, Nearly-isolated community-, and community-affiliation graphs, respectively. It should be noted that with one exception, dynamic removal based on degree- and closeness centralities constitute the best-performing strategy for all topology types and epidemic cases.

Table 3: Sub-102% of minimum-cost solution intervention strategies with the lowest isolatable percentage. This table compares Erdos-Renyi-, Nearly-isolated community-, and community-affiliation networks using parameter sets "COVID-19", "Epidemic", and "Weak Epidemic".

	COVID-19	**Epidemic**	**Weak Epidemic**
Erdos-Renyi	Closeness, 0.92	Degree, 0.8	Degree, 0.64
Nearly-isolated community	Closeness, 0.92	Degree, 0.8	Degree, 0.68
Community-affiliation	Degree, 0.76	Betweenness, 0.62	Closeness, 0.5

Table 4: Sub-105% of minimum-cost solution intervention strategies with the lowest isolatable percentage. This table compares Erdos-Renyi-, Nearly-isolated community-, and community-affiliation networks using parameter sets "COVID-19", "Epidemic", and "Weak Epidemic".

	COVID-19	**Epidemic**	**Weak Epidemic**
Erdos-Renyi	Degree, 0.88	Closeness, 0.78	Degree, 0.6
Nearly-isolated community	Closeness, 0.92	Degree, 0.8	Degree, 0.68
Community-affiliation	Closeness, 0.74	Degree, 0.56	Closeness 0.48

7 Discussion

It follows from the presented results that spectral radius reduction is indeed an accurate performance measurement when aiming to control the spread of epidemics. Results from sections 5.3.2, 14, 6.3, and 6.4 consistently show that two centrality measures which performed best in static spectral radius reduction overall, degree- and betweenness centrality, also showed the best performance in extinction time and cost minimization. Additionally, closeness centrality performs very similarly to, if not better, than betweenness centrality at high isolatable node percentages, as reflected in the final results of 6.4.1.

As shown in figure 17, the excellent performance of degree centrality may be a product of of the low node number used in simulations. This figure suggests that betweenness centrality performs better than degree- and closeness centrality in a medium isolatable node percentage range (34-80%) for higher node numbers. At higher isolatable node percentage values, however, closeness centrality still approaches the minimum-cost solution more quickly. These findings are in line with [23] and [5], where it is described that degree centrality is very effective for minimizing local spreading, but less effective at global spreading reduction. However, the effect of network size would have to be more systematically analyzed to draw substantiated conclusions from.

Results suggest that the ideal policy for controlling epidemics is one where the size of the infected population is reduced rapidly using aggressive isolation policy, after which small infected population remains that does not greatly increase costs due to the low number of infections and required isolations. In keeping with this conclusion, low isolation percentages are shown to increase total costs, rather than decrease them. Results regarding the ratio between infection costs and isolation costs, combined with those concerning the extinction time (fig. 21 and 15) suggest that this is due to the fact that isolation costs are high, while intervention efforts are not enough to drive the system to extinction. Therefore, large isolation costs are incurred throughout, while infection costs are never lowered to approach the asymptotic value.

Finally, two of the most impactful limitations of the used model will be discussed. First, despite the wide-spread usage of SIQS models, current research often considers models that introduce additional states which model phenomena that are essential to epidemic spreading, including recovery, vaccination, detection, and deaths [17]. Results obtained from this research might thus be generalized and not robust enough to support actionable policy. Secondly, this research assumes that network centrality is measured at every time-step, and that the isolation strategy adapts accordingly. However, realistically only a limited number of policy changes are possible within a given time frame. This is further explored in [10].

8 Conclusion

This research aimed to determine which centrality measure (among degree-, closeness-, betweenness-, and eigen centrality) most accurately determines the influential nodes in epidemic spreading per topology type (among Erdos-Renyi, nearly-isolated community-, and community-affiliation graphs), keeping in mind the influence of epidemic severity. Then, policy recommendations were to be given for the control of early epidemics with no developed vaccination strategy and limited information regarding the involved communities and the epidemic itself.

A novel dynamic centrality-based isolation strategy was proposed, in which only a set percentage of the most central nodes is isolatable at each time-instance. It was shown that spectral radius reduction is an effective performance indicator for centrality-based intervention strategies, with cost minimization and simulated extinction time mirroring the results found for spectral radius reduction utilizing static- and dynamic removal. Isolation based on betweenness-, and degree centrality were demonstrated to lead to the greatest reductions in spectral radius, extinction time, and costs overall, with closeness centrality performing well for high isolatable node percentages.

Finally, policy recommendations for minimum-cost solutions were given, as well as recommendations for policy allowing more node freedom, while only being 2-5% more costly than the minimum-cost solution. For these policy recommendations, three epidemic cases were considered, one simulating COVID-19 epidemic parameters, one with 50% of COVID-19's infection strength, and finally one with 25% of its infection strength. In the end, individual policies were provided for Erdos-Renyi-, nearly-isolated community-, and community-affiliation networks pertaining to each epidemic case.

9 Validation

In order to validate the research at hand, justifications for chosen equations and parameters were given throughout, most prevalent in sections 5.4.2 and 5.4.1. Obtained results are internally consistent, and are in line with theory regarding centrality and epidemic spreading that were used throughout, most notably [17] and [31]. Finally, the lower-bound condition for SIS models was tested to further validate model outputs.

For the SIS model, a threshold condition has been determined in [6] that leads to a sufficient condition for sub-linear expected extinction time by utilising infection strength $\tau = \frac{\beta}{\delta}$. This lower-bound was tested for parameters satisfying the condition, with an output example visible in fig. 18.

$$\begin{aligned}&\text{if:}\\&\tau < \frac{1}{\lambda_{max}(A)}\\&\text{then:}\\&E[T] \leq \frac{logN+1}{\delta - \beta\lambda_{max}(A)}\\&\text{for any initial condition X(0).}\end{aligned} \tag{15}$$

Where τ is the infection strength, $\lambda_{max}(A)$ is the spectral radius, and $E[T]$ is the lower-bound for expected extinction time.

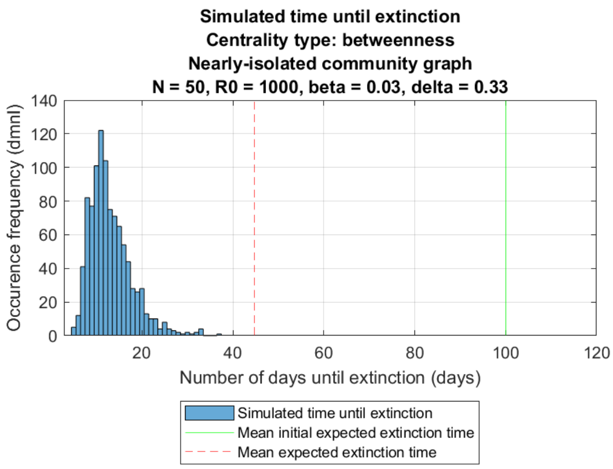


Figure 18: Sub-linear expected extinction time model test. A nearly-isolated community graph was tested with β=0.03 and δ=0.33. The initial bound for expected extinction time is shown in green, and the average bound keeping in mind dynamic removal is indicated in red.

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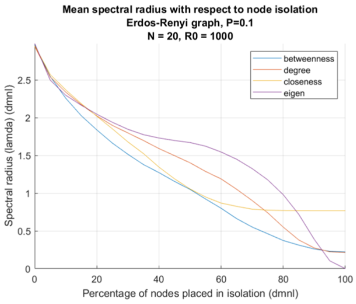
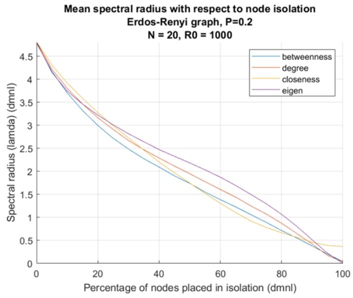
10 Appendix

10.1 Effect of Erdos-Renyi η-value on Centrality Performance

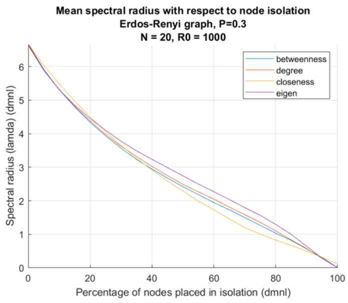


(a) Erdos-Renyi η=0.1

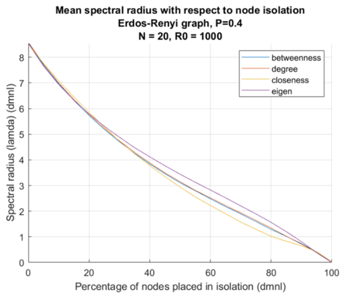


(b) Erdos-Renyi η = 0.2

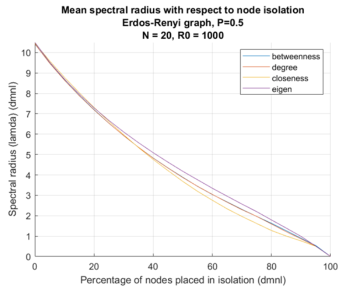
Figure 19: Effect of Erdos-Renyi η-value on centrality performance for spectral radius reduction. Erdos-Renyi, η=0.1 and η=0.2



(a) Erdos-Renyi η=0.3



(b) Erdos-Renyi η = 0.4



(c) Erdos-Renyi η = 0.5

Figure 20: Effect of Erdos-Renyi η-value on centrality performance for spectral radius reduction. Erdos-Renyi, η=0.3, η=0.4 and η=0.5.

10.2 Cost Divisions

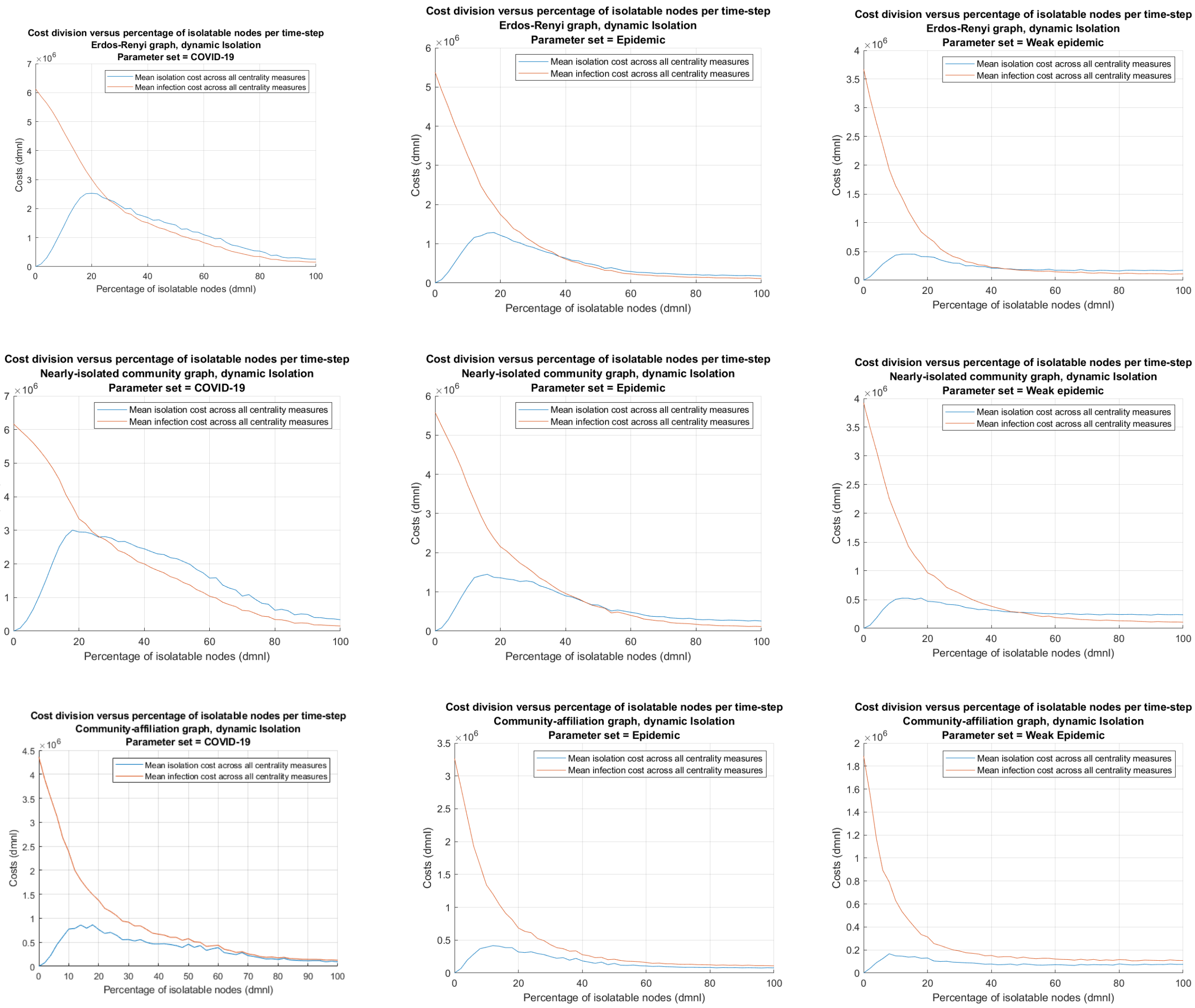


Figure 21: Mean division of total costs versus isolatable nodes. In this figure, the division between mean isolation costs and mean infection costs is visualised for all simulations. Centrality-based dynamic isolation and randomly-selected dynamic removal were both utilized (as described in 5.3.1) for isolatable node percentage ranging from 2% to 100% of nodes, removed in 2% intervals. Centrality-based isolation was performed using degree-, eigen-, closeness-, and betweenness-centralities. Simulations were performed for three parameter sets (detailed in 5.4.1), "COVID-19" (a), "Epidemic" (b) and "Weak Epidemic" (c).

10.3 Output Tables

Table 5: Mean spectral radius ρ versus isolation percentage, static removal, Erdos-Renyi. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random removal.

iso%	Degree	Eigen	Close	Between	Random
0.00	7.50	7.49	7.50	7.50	7.52
0.02	7.22	7.21	7.22	7.22	7.37
0.04	6.97	6.96	6.97	6.98	7.23
0.06	6.73	6.73	6.74	6.74	7.08
0.08	6.49	6.51	6.52	6.52	6.93
0.10	6.27	6.31	6.31	6.30	6.79
0.12	6.06	6.11	6.10	6.08	6.66
0.14	5.86	5.92	5.90	5.88	6.53
0.16	5.66	5.74	5.70	5.67	6.39
0.18	5.46	5.56	5.51	5.48	6.26
0.20	5.26	5.39	5.33	5.28	6.15
0.22	5.07	5.22	5.15	5.09	6.03
0.24	4.89	5.05	4.97	4.90	5.90
0.26	4.72	4.89	4.80	4.72	5.78
0.28	4.53	4.73	4.64	4.53	5.66
0.30	4.36	4.57	4.47	4.35	5.56
0.32	4.19	4.42	4.31	4.17	5.44
0.34	4.01	4.27	4.15	3.99	5.34
0.36	3.85	4.12	4.00	3.82	5.24
0.38	3.68	3.97	3.84	3.64	5.11
0.40	3.52	3.83	3.69	3.48	5.03
0.42	3.36	3.69	3.54	3.31	4.93
0.44	3.21	3.54	3.39	3.16	4.84
0.46	3.07	3.39	3.25	2.99	4.71
0.48	2.92	3.26	3.10	2.84	4.64
0.50	2.77	3.12	2.96	2.69	4.53
0.52	2.63	2.98	2.81	2.54	4.42
0.54	2.49	2.85	2.67	2.40	4.36
0.56	2.36	2.72	2.53	2.25	4.27
0.58	2.23	2.58	2.40	2.09	4.16
0.60	2.08	2.44	2.26	1.94	4.08
0.62	1.95	2.31	2.13	1.80	4.04
0.64	1.81	2.17	2.01	1.65	3.92
0.66	1.69	2.04	1.87	1.52	3.87
0.68	1.56	1.90	1.75	1.40	3.77
0.70	1.43	1.77	1.61	1.28	3.73
0.72	1.32	1.64	1.50	1.18	3.63
0.74	1.23	1.53	1.37	1.09	3.54
0.76	1.15	1.40	1.26	1.01	3.47
0.78	1.06	1.28	1.17	0.95	3.42
0.80	0.98	1.19	1.07	0.89	3.36
0.82	0.91	1.08	0.97	0.83	3.30
0.84	0.83	0.99	0.89	0.77	3.24
0.86	0.76	0.88	0.81	0.72	3.14
0.88	0.68	0.77	0.72	0.63	3.09
0.90	0.59	0.67	0.61	0.57	3.02
0.92	0.50	0.55	0.51	0.49	2.97
0.94	0.39	0.44	0.41	0.40	2.90
0.96	0.28	0.32	0.28	0.30	2.82
0.98	0.16	0.15	0.14	0.17	2.79
1.00	0.00	0.00	0.00	0.04	2.71

Table 6: Mean spectral radius ρ versus isolation percentage, static removal, community-affiliation. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	7.26	7.26	7.31	7.32	7.35
0.02	6.62	6.57	6.69	6.81	7.21
0.04	6.09	6.06	6.20	6.39	7.07
0.06	5.64	5.65	5.78	6.02	6.95
0.08	5.24	5.31	5.42	5.69	6.82
0.10	4.89	5.00	5.09	5.37	6.71
0.12	4.55	4.71	4.79	5.08	6.57
0.14	4.26	4.46	4.50	4.80	6.44
0.16	3.98	4.25	4.25	4.54	6.34
0.18	3.74	4.05	4.01	4.30	6.19
0.20	3.51	3.85	3.78	4.06	6.13
0.22	3.30	3.67	3.57	3.84	5.99
0.24	3.12	3.51	3.38	3.64	5.87
0.26	2.94	3.37	3.21	3.45	5.77
0.28	2.79	3.22	3.03	3.25	5.69
0.30	2.63	3.08	2.88	3.05	5.57
0.32	2.50	2.96	2.74	2.86	5.49
0.34	2.37	2.84	2.62	2.66	5.40
0.36	2.26	2.74	2.51	2.47	5.26
0.38	2.14	2.65	2.40	2.29	5.19
0.40	2.03	2.58	2.28	2.11	5.10
0.42	1.93	2.54	2.18	1.96	4.94
0.44	1.83	2.52	2.06	1.80	4.85
0.46	1.73	2.50	1.97	1.66	4.81
0.48	1.63	2.48	1.89	1.51	4.71
0.50	1.55	2.46	1.81	1.36	4.63
0.52	1.46	2.43	1.72	1.21	4.52
0.54	1.37	2.39	1.64	1.08	4.48
0.56	1.26	2.34	1.55	0.94	4.43
0.58	1.18	2.27	1.47	0.79	4.28
0.60	1.07	2.19	1.38	0.66	4.24
0.62	0.97	2.10	1.30	0.53	4.14
0.64	0.86	2.01	1.20	0.42	4.06
0.66	0.75	1.92	1.11	0.33	4.02
0.68	0.63	1.82	1.00	0.24	3.94
0.70	0.52	1.73	0.89	0.18	3.89
0.72	0.41	1.64	0.77	0.14	3.81
0.74	0.31	1.54	0.63	0.12	3.73
0.76	0.22	1.44	0.51	0.10	3.67
0.78	0.15	1.35	0.40	0.10	3.68
0.80	0.09	1.25	0.30	0.09	3.53
0.82	0.05	1.13	0.21	0.09	3.49
0.84	0.03	1.00	0.14	0.09	3.40
0.86	0.02	0.85	0.08	0.09	3.38
0.88	0.01	0.70	0.04	0.09	3.29
0.90	0.00	0.52	0.02	0.09	3.23
0.92	0.00	0.37	0.01	0.09	3.21
0.94	0.00	0.22	0.00	0.09	3.15
0.96	0.00	0.08	0.00	0.09	3.15
0.98	0.00	0.00	0.00	0.09	3.04
1.00	0.00	0.00	0.00	0.09	2.96

Table 7: Mean spectral radius ρ versus isolation percentage, static removal, Nearly-isolated community. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	10.09	10.12	10.09	10.08	10.11
0.02	9.88	9.73	9.90	9.94	10.00
0.04	9.68	9.64	9.74	9.79	9.89
0.06	9.45	9.59	9.61	9.64	9.79
0.08	9.24	9.56	9.49	9.46	9.65
0.10	9.05	9.53	9.37	9.27	9.52
0.12	8.83	9.52	9.26	9.08	9.39
0.14	8.59	9.50	9.14	8.89	9.27
0.16	8.36	9.48	9.02	8.71	9.16
0.18	8.11	9.45	8.91	8.52	9.04
0.20	7.91	9.42	8.80	8.34	8.90
0.22	7.69	9.17	8.69	8.15	8.75
0.24	7.46	9.06	8.58	7.99	8.64
0.26	7.24	8.98	8.46	7.83	8.54
0.28	7.03	8.91	8.35	7.68	8.41
0.30	6.83	8.85	8.22	7.50	8.31
0.32	6.62	8.81	8.10	7.33	8.13
0.34	6.47	8.77	7.95	7.16	8.03
0.36	6.31	8.73	7.82	6.99	7.93
0.38	6.15	8.68	7.68	6.82	7.80
0.40	6.00	8.60	7.52	6.67	7.75
0.42	5.87	8.29	7.36	6.52	7.59
0.44	5.75	8.08	7.22	6.38	7.48
0.46	5.63	7.94	7.08	6.21	7.37
0.48	5.50	7.82	6.91	6.08	7.24
0.50	5.38	7.68	6.76	5.97	7.17
0.52	5.28	7.56	6.61	5.83	7.05
0.54	5.16	7.45	6.47	5.73	7.00
0.56	5.06	7.33	6.33	5.61	6.81
0.58	4.95	7.23	6.19	5.52	6.74
0.60	4.84	7.10	6.04	5.45	6.66
0.62	4.73	6.79	5.91	5.38	6.54
0.64	4.61	6.46	5.75	5.29	6.49
0.66	4.47	6.16	5.62	5.21	6.37
0.68	4.33	5.92	5.46	5.13	6.27
0.70	4.19	5.69	5.30	5.04	6.23
0.72	4.00	5.48	5.12	4.95	6.05
0.74	3.83	5.27	4.92	4.84	6.00
0.76	3.62	5.07	4.71	4.72	5.88
0.78	3.39	4.85	4.48	4.58	5.79
0.80	3.17	4.63	4.20	4.42	5.74
0.82	2.93	4.32	3.89	4.24	5.65
0.84	2.64	3.95	3.53	4.03	5.57
0.86	2.38	3.55	3.15	3.76	5.51
0.88	2.10	3.13	2.74	3.40	5.41
0.90	1.78	2.65	2.37	3.00	5.32
0.92	1.48	2.16	1.98	2.57	5.28
0.94	1.17	1.65	1.57	2.17	5.18
0.96	0.84	1.11	1.14	1.87	5.06
0.98	0.51	0.50	0.61	1.71	5.04
1.00	0.00	0.00	0.01	1.50	4.97

Table 8: Mean spectral radius ρ versus isolation percentage, dynamic removal, Erdos-Renyi, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	8.61	8.42	8.12	8.26	8.75
0.02	6.95	7.02	6.99	7.34	7.70
0.04	6.27	6.37	6.15	6.37	7.04
0.06	5.20	5.35	5.48	5.52	6.85
0.08	5.08	5.12	4.75	5.25	6.47
0.10	4.33	4.50	4.45	4.39	6.30
0.12	4.18	4.18	4.22	4.22	5.88
0.14	3.95	3.94	4.01	3.90	5.45
0.16	3.89	3.88	3.95	3.94	5.29
0.18	3.71	3.79	3.87	3.86	5.16
0.20	3.90	3.91	3.76	3.81	5.10
0.22	3.93	3.83	3.66	3.77	4.74
0.24	3.86	3.83	3.71	4.12	4.63
0.26	4.00	3.94	3.85	3.91	4.54
0.28	4.05	3.84	3.86	3.99	4.63
0.30	4.24	4.11	4.15	4.02	4.38
0.32	4.28	4.17	4.33	4.29	4.29
0.34	4.48	4.33	4.23	4.29	4.18
0.36	4.66	4.22	4.36	4.28	4.19
0.38	4.70	4.07	4.61	4.45	4.09
0.40	4.75	4.36	4.73	4.48	4.16
0.42	4.65	4.27	4.85	4.70	4.14
0.44	4.90	4.51	5.02	5.06	3.97
0.46	5.09	4.34	4.98	4.84	4.02
0.48	4.95	4.61	5.22	5.29	3.93
0.50	5.30	4.47	5.38	5.25	3.91
0.52	5.28	4.61	5.65	5.62	3.93
0.54	5.65	4.80	5.43	5.59	4.01
0.56	5.45	4.73	5.57	5.60	3.97
0.58	5.69	4.71	5.86	5.72	3.95
0.60	5.53	5.00	5.82	6.12	4.19
0.62	5.52	4.73	6.10	5.67	4.17
0.64	6.16	5.19	6.02	5.92	3.99
0.66	5.85	5.29	6.20	6.22	4.04
0.68	6.15	5.20	6.20	5.76	4.21
0.70	6.23	5.25	6.64	5.82	4.05
0.72	6.55	5.28	6.53	6.26	4.28
0.74	6.39	5.54	6.23	6.26	4.54
0.76	6.39	5.47	6.64	6.34	4.53
0.78	6.23	5.75	6.54	6.15	4.47
0.80	6.17	5.96	6.48	6.08	4.77
0.82	6.65	6.04	6.78	6.27	4.78
0.84	6.48	6.39	6.63	6.31	4.91
0.86	6.49	6.13	6.42	6.83	4.86
0.88	6.78	6.29	6.71	6.45	5.10
0.90	6.66	6.30	6.65	6.59	5.04
0.92	6.92	6.56	6.89	6.74	5.22
0.94	6.97	6.37	6.91	6.92	5.11
0.96	6.74	6.67	6.44	6.73	5.49
0.98	6.55	6.47	6.70	6.84	5.41
1.00	6.91	6.77	6.96	6.44	5.27

Table 9: Mean spectral radius ρ versus isolation percentage, dynamic removal, Erdos-Renyi, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	8.39	8.54	8.35	8.31	8.34
0.02	6.93	6.99	7.10	7.24	7.86
0.04	6.28	6.31	6.54	6.38	7.45
0.06	5.62	5.70	5.71	6.05	7.08
0.08	5.20	5.20	5.25	5.42	6.70
0.10	4.88	4.93	5.17	5.09	6.46
0.12	4.80	4.95	4.80	4.82	6.14
0.14	4.83	4.85	4.75	4.83	5.92
0.16	4.64	4.85	4.77	4.80	5.88
0.18	4.76	4.75	4.81	4.95	5.51
0.20	4.84	4.75	5.03	4.88	5.42
0.22	4.94	4.95	4.97	5.20	5.31
0.24	5.07	4.89	5.10	5.06	5.24
0.26	5.08	5.24	5.15	5.32	5.29
0.28	5.30	5.19	5.38	5.43	5.25
0.30	5.26	5.43	5.24	5.49	5.26
0.32	5.55	5.41	5.38	5.52	5.07
0.34	5.51	5.45	5.48	5.49	5.15
0.36	5.60	5.40	5.56	5.86	5.12
0.38	5.89	5.34	5.78	5.68	5.40
0.40	6.05	5.61	5.96	5.68	5.28
0.42	5.91	5.67	5.80	6.12	5.23
0.44	6.14	5.73	5.98	5.92	5.15
0.46	5.94	5.64	5.98	6.19	5.31
0.48	6.26	5.62	6.15	6.23	5.35
0.50	6.19	5.54	6.22	6.09	5.21
0.52	6.34	5.57	6.30	6.23	5.41
0.54	6.11	5.64	6.23	6.16	5.59
0.56	6.31	5.81	6.22	6.33	5.42
0.58	6.48	5.68	6.36	6.40	5.84
0.60	6.32	5.94	6.37	6.58	5.72
0.62	6.38	6.04	6.59	6.35	6.02
0.64	6.24	5.98	6.35	6.41	5.76
0.66	6.70	5.88	6.37	6.70	5.72
0.68	6.64	6.13	6.45	6.60	6.17
0.70	6.53	6.30	6.36	6.58	5.97
0.72	6.46	6.06	6.61	6.34	6.08
0.74	6.66	6.30	6.56	6.66	6.18
0.76	6.46	6.36	6.34	6.71	5.80
0.78	6.55	6.47	6.62	6.67	6.18
0.80	6.56	6.29	6.73	6.79	5.96
0.82	6.74	6.29	6.55	6.45	6.18
0.84	6.97	6.43	6.80	6.59	6.24
0.86	6.78	6.29	6.81	6.59	6.27
0.88	6.79	6.61	6.90	6.55	6.42
0.90	6.58	6.53	6.68	6.64	6.25
0.92	6.44	6.68	6.60	6.85	6.26
0.94	6.91	6.72	6.82	6.49	6.56
0.96	6.76	6.61	6.76	6.66	6.30
0.98	6.72	6.73	6.63	6.79	6.21
1.00	6.40	6.58	6.71	6.65	6.38

Table 10: Mean spectral radius ρ versus isolation percentage, dynamic removal, Erdos-Renyi, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	8.35	8.46	8.32	8.59	8.20
0.02	7.39	7.31	7.40	7.59	7.74
0.04	6.86	6.88	7.09	6.93	7.62
0.06	6.45	6.45	6.38	6.65	7.31
0.08	6.11	6.12	6.10	6.31	7.07
0.10	5.96	5.86	5.83	6.11	6.64
0.12	5.84	5.98	5.97	6.06	6.61
0.14	5.81	5.80	5.94	5.99	6.43
0.16	5.75	6.17	5.80	6.00	6.36
0.18	5.93	6.16	5.98	5.98	6.27
0.20	5.98	6.05	5.89	5.98	6.37
0.22	5.91	5.90	6.06	6.14	6.41
0.24	6.10	6.44	6.06	6.03	6.16
0.26	6.36	6.12	6.11	6.09	6.23
0.28	5.99	6.27	6.12	6.21	6.23
0.30	6.14	6.28	6.39	6.38	6.19
0.32	6.12	6.40	6.27	6.34	6.28
0.34	6.33	6.37	6.48	6.47	6.34
0.36	6.19	6.04	6.25	6.35	6.30
0.38	6.27	6.29	6.27	6.32	6.45
0.40	6.54	6.33	6.25	6.45	6.44
0.42	6.35	6.38	6.46	6.62	6.41
0.44	6.57	6.37	6.54	6.58	6.23
0.46	6.50	6.25	6.29	6.35	6.56
0.48	6.66	6.43	6.34	6.57	6.38
0.50	6.72	6.45	6.71	6.50	6.51
0.52	6.61	6.41	6.62	6.68	6.54
0.54	6.73	6.20	6.82	6.52	6.40
0.56	6.73	6.38	6.70	6.70	6.45
0.58	6.86	6.22	6.70	6.72	6.36
0.60	6.81	6.19	6.62	6.60	6.31
0.62	6.53	6.54	6.80	6.58	6.33
0.64	6.63	6.39	6.65	6.57	6.55
0.66	6.74	6.59	6.58	6.59	6.73
0.68	6.80	6.42	6.64	6.75	6.46
0.70	6.67	6.47	6.96	6.63	6.54
0.72	6.67	6.45	6.97	6.76	6.66
0.74	6.87	6.47	6.67	6.67	6.54
0.76	6.95	6.45	6.90	6.93	6.75
0.78	6.70	6.57	6.83	6.87	6.73
0.80	6.88	6.43	6.82	6.72	6.68
0.82	6.69	6.69	6.67	6.87	6.75
0.84	6.80	6.72	7.11	6.60	6.72
0.86	6.88	6.60	6.68	6.68	6.50
0.88	6.80	6.53	6.55	6.86	6.56
0.90	6.94	6.55	7.02	6.72	6.51
0.92	6.84	6.76	6.72	6.55	6.62
0.94	6.68	6.66	6.66	6.77	6.49
0.96	6.66	6.58	6.97	6.46	6.60
0.98	6.62	6.55	6.66	6.65	6.68
1.00	6.64	6.62	6.66	6.66	6.63

Table 11: Mean spectral radius ρ versus isolation percentage, dynamic removal, nearly-isolated community, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	10.12	10.12	10.08	10.13	10.07
0.02	9.24	8.85	9.60	9.59	9.64
0.04	8.48	8.27	9.10	9.10	9.17
0.06	7.77	7.63	8.70	8.47	8.74
0.08	7.00	7.22	8.22	7.98	8.14
0.10	6.41	7.05	7.57	7.53	7.94
0.12	5.95	6.62	7.12	7.13	7.48
0.14	5.57	6.35	6.86	6.87	7.31
0.16	5.26	6.15	6.66	6.57	7.01
0.18	5.28	6.13	6.01	6.37	6.68
0.20	5.41	6.72	6.43	6.41	6.54
0.22	5.13	6.52	6.11	6.26	6.34
0.24	5.40	6.46	6.27	6.02	6.12
0.26	5.81	6.80	6.26	6.03	5.89
0.28	6.19	6.71	6.55	6.07	5.88
0.30	6.70	6.66	6.64	6.09	5.72
0.32	6.77	6.44	6.81	6.31	5.60
0.34	6.84	6.65	7.44	6.04	5.62
0.36	6.92	6.85	7.60	6.27	5.40
0.38	7.34	6.70	7.44	6.75	5.49
0.40	7.21	7.11	7.46	7.02	5.37
0.42	7.69	6.92	7.52	6.76	5.25
0.44	7.68	7.26	7.91	6.91	5.31
0.46	7.65	7.24	7.88	7.21	5.24
0.48	7.68	7.35	7.46	7.03	5.24
0.50	7.91	7.25	7.74	6.93	5.31
0.52	8.24	7.55	8.17	7.63	5.37
0.54	7.89	7.40	7.76	7.15	5.64
0.56	8.27	7.36	8.16	7.18	5.60
0.58	8.33	8.05	8.01	7.82	5.41
0.60	8.12	7.75	8.05	7.55	5.52
0.62	7.95	8.06	8.46	7.60	5.68
0.64	8.48	7.91	8.35	7.95	6.09
0.66	8.36	8.30	8.51	7.63	5.92
0.68	8.61	8.27	8.39	7.95	5.62
0.70	8.54	8.25	8.40	7.87	6.46
0.72	8.53	8.18	8.58	7.66	5.55
0.74	8.65	8.48	8.51	7.85	6.20
0.76	8.57	8.36	8.87	7.88	6.46
0.78	8.38	8.42	8.53	8.17	6.26
0.80	8.73	8.40	8.35	8.09	6.39
0.82	8.47	8.47	8.79	8.28	6.74
0.84	8.81	8.42	8.57	8.28	6.70
0.86	8.78	8.45	8.37	8.17	6.75
0.88	8.58	8.50	8.44	8.32	7.06
0.90	8.56	8.50	8.55	8.32	6.66
0.92	8.71	8.57	8.64	8.39	7.09
0.94	8.52	8.53	8.80	8.42	7.17
0.96	8.43	8.65	8.70	8.20	6.94
0.98	8.54	8.44	8.29	8.35	7.35
1.00	8.57	8.46	8.45	8.34	7.29

Table 12: Mean spectral radius ρ versus isolation percentage, dynamic removal, nearly-isolated community, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	10.20	10.12	9.98	10.12	10.13
0.02	9.31	8.99	9.70	9.62	9.60
0.04	8.48	8.27	9.09	9.17	9.16
0.06	7.84	7.89	8.71	8.74	8.85
0.08	7.39	7.35	8.29	8.23	8.39
0.10	7.10	7.03	8.16	7.78	8.08
0.12	6.81	7.11	7.75	7.58	7.79
0.14	6.92	7.16	7.60	7.37	7.57
0.16	6.92	7.50	7.53	7.54	7.39
0.18	6.86	7.66	7.66	7.46	7.20
0.20	6.64	7.98	7.21	7.19	6.94
0.22	7.32	7.98	7.31	7.47	7.02
0.24	7.12	7.80	7.84	7.45	6.99
0.26	7.57	8.02	7.98	7.33	6.83
0.28	7.38	7.89	7.58	7.43	6.78
0.30	7.52	7.94	7.96	7.59	6.71
0.32	7.47	7.98	8.00	7.56	6.99
0.34	7.84	8.11	8.12	7.49	6.81
0.36	8.14	8.19	7.83	7.56	6.92
0.38	8.37	8.12	8.05	8.02	7.07
0.40	8.04	8.13	7.94	7.87	7.11
0.42	8.28	8.12	8.34	8.12	7.19
0.44	8.43	8.08	8.41	7.87	6.95
0.46	8.44	8.32	8.48	7.91	6.93
0.48	8.30	8.23	8.20	8.23	7.46
0.50	8.45	8.30	8.36	7.85	7.13
0.52	8.44	8.26	8.63	8.05	7.37
0.54	8.36	8.15	8.39	8.06	7.37
0.56	8.29	8.33	8.62	8.09	7.52
0.58	8.43	8.39	8.40	8.25	7.64
0.60	8.51	8.23	8.51	8.28	7.85
0.62	8.54	8.60	8.45	8.18	7.52
0.64	8.58	8.52	8.84	8.06	7.75
0.66	8.65	8.63	8.68	8.29	7.70
0.68	8.63	8.52	8.59	8.22	7.93
0.70	8.55	8.39	8.55	8.39	7.73
0.72	8.44	8.48	8.38	8.32	7.94
0.74	8.54	8.49	8.58	8.37	8.27
0.76	8.87	8.40	8.55	8.12	7.99
0.78	8.58	8.40	8.76	8.55	7.92
0.80	8.57	8.59	8.60	8.42	8.25
0.82	8.51	8.52	8.47	8.35	8.03
0.84	8.41	8.51	8.66	8.19	8.03
0.86	8.60	8.41	8.47	8.44	8.15
0.88	8.47	8.62	8.51	8.70	8.25
0.90	8.64	8.60	8.47	8.56	8.18
0.92	8.57	8.52	8.63	8.40	8.07
0.94	8.54	8.39	8.85	8.62	8.05
0.96	8.62	8.42	8.35	8.49	8.23
0.98	8.67	8.45	8.67	8.45	8.08
1.00	8.64	8.56	8.49	8.52	8.22

Table 13: Mean spectral radius ρ versus isolation percentage, dynamic removal, nearly-isolated community, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	**Degree**	**Eigen**	**Closeness**	**Betweenness**	**Random**
0.00	10.07	10.17	10.16	10.10	10.17
0.02	9.44	9.26	9.75	9.80	9.64
0.04	9.02	8.56	9.27	9.28	9.39
0.06	8.62	8.44	9.33	9.02	9.10
0.08	8.25	8.16	8.75	8.79	8.94
0.10	8.01	8.07	8.85	8.60	8.64
0.12	8.07	8.07	8.58	8.56	8.51
0.14	8.10	8.38	8.62	8.48	8.46
0.16	7.81	8.34	8.56	8.51	8.05
0.18	7.85	8.32	8.47	8.15	8.13
0.20	8.15	8.61	8.72	8.45	8.08
0.22	8.42	8.42	8.46	8.32	8.25
0.24	8.12	8.34	8.39	8.28	8.12
0.26	8.46	8.38	8.57	8.29	8.24
0.28	8.14	8.43	8.43	8.57	8.24
0.30	8.48	8.57	8.56	8.63	8.07
0.32	8.53	8.78	8.61	8.60	8.28
0.34	8.47	8.42	8.72	8.23	8.17
0.36	8.59	8.50	8.77	8.33	8.20
0.38	8.43	8.43	8.54	8.44	8.22
0.40	8.51	8.50	8.72	8.40	8.30
0.42	8.57	8.53	8.87	8.49	8.23
0.44	8.69	8.45	8.53	8.44	8.22
0.46	8.50	8.45	8.51	8.56	8.17
0.48	8.51	8.34	8.51	8.36	8.18
0.50	8.43	8.45	8.69	8.60	8.50
0.52	8.65	8.33	8.54	8.50	8.38
0.54	8.47	8.46	8.79	8.55	8.15
0.56	8.63	8.62	8.85	8.68	8.65
0.58	8.52	8.61	8.80	8.73	8.48
0.60	8.76	8.44	8.76	8.59	8.35
0.62	8.63	8.45	8.70	8.43	8.26
0.64	8.77	8.48	8.88	8.36	8.29
0.66	8.67	8.67	8.62	8.46	8.36
0.68	8.62	8.63	8.76	8.56	8.18
0.70	8.66	8.55	8.72	8.60	8.41
0.72	8.55	8.20	8.67	8.65	8.18
0.74	8.58	8.45	8.82	8.54	8.51
0.76	8.56	8.58	8.56	8.57	8.41
0.78	8.71	8.66	8.70	8.70	8.73
0.80	8.49	8.54	8.43	8.64	8.45
0.82	8.51	8.38	8.71	8.56	8.39
0.84	8.59	8.34	8.58	8.56	8.43
0.86	8.58	8.57	8.87	8.54	8.65
0.88	8.93	8.46	8.55	8.60	8.25
0.90	8.55	8.60	8.54	8.59	8.39
0.92	8.71	8.47	8.64	8.48	8.42
0.94	8.44	8.36	8.68	8.36	8.69
0.96	8.43	8.62	8.42	8.45	8.53
0.98	8.28	8.55	8.53	8.20	8.65
1.00	8.49	8.47	8.58	8.36	8.50

Table 14: Mean spectral radius ρ versus isolation percentage, dynamic removal, community-affiliation, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	7.31	7.67	7.08	7.48	7.10
0.02	5.62	5.00	6.03	5.92	6.67
0.04	4.47	4.29	4.57	4.71	6.20
0.06	3.96	3.90	4.16	4.11	5.70
0.08	3.48	3.69	3.64	3.87	5.41
0.10	3.33	3.41	3.63	3.44	5.41
0.12	3.33	3.28	3.37	3.41	4.90
0.14	3.40	3.39	3.18	3.26	4.87
0.16	3.39	3.39	3.39	3.30	4.71
0.18	3.60	3.42	3.50	3.30	4.40
0.20	3.58	3.54	3.52	3.40	4.30
0.22	3.74	3.55	3.61	3.57	4.24
0.24	3.71	3.83	3.77	3.70	3.89
0.26	3.61	3.83	3.87	3.68	4.11
0.28	4.02	3.76	3.88	4.03	3.74
0.30	4.22	4.02	4.26	4.16	3.82
0.32	4.34	4.06	4.47	4.15	3.75
0.34	4.45	4.02	4.57	4.30	3.77
0.36	4.68	4.15	4.58	4.43	3.55
0.38	4.79	3.93	4.72	4.33	3.70
0.40	4.91	4.17	4.76	4.52	3.53
0.42	4.84	4.22	5.11	4.73	3.56
0.44	5.01	4.04	4.99	4.96	3.55
0.46	5.18	4.10	5.12	5.00	3.48
0.48	5.12	4.11	5.20	5.04	3.51
0.50	5.43	4.02	5.28	5.05	3.71
0.52	5.36	4.40	5.49	4.87	3.54
0.54	5.54	4.40	5.66	5.06	3.58
0.56	5.67	4.13	5.64	5.26	3.58
0.58	5.54	4.45	5.60	5.08	3.70
0.60	5.68	4.41	5.90	5.08	3.89
0.62	5.46	4.43	5.84	5.38	3.78
0.64	5.76	4.36	5.89	5.50	3.74
0.66	5.96	4.48	5.88	5.68	3.77
0.68	5.59	4.53	5.59	5.18	3.75
0.70	5.65	4.64	5.66	5.46	3.87
0.72	5.88	5.04	5.78	5.23	3.97
0.74	5.66	4.88	5.62	5.46	4.00
0.76	5.70	5.12	5.94	5.87	3.86
0.78	5.83	5.02	5.74	5.59	4.35
0.80	6.08	5.54	5.52	5.54	4.32
0.82	5.41	5.34	5.85	5.72	4.25
0.84	5.64	5.41	5.48	6.09	4.51
0.86	5.90	5.51	5.84	5.84	4.28
0.88	5.96	5.42	5.57	5.52	4.39
0.90	5.66	5.74	5.88	5.89	4.57
0.92	5.75	5.90	5.71	5.54	4.68
0.94	6.08	5.75	5.64	5.63	4.68
0.96	5.99	5.74	6.00	5.83	4.46
0.98	5.96	5.75	5.71	5.72	4.77
1.00	5.65	5.54	5.37	5.82	4.83

Table 15: Mean spectral radius ρ versus isolation percentage, dynamic removal, community-affiliation, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	7.15	7.08	7.05	7.28	7.30
0.02	5.78	5.45	5.47	6.13	6.65
0.04	4.82	4.81	4.68	5.22	6.67
0.06	4.31	4.43	4.50	4.79	6.11
0.08	4.09	4.30	4.20	4.36	5.88
0.10	4.12	4.16	4.17	4.13	5.34
0.12	4.32	4.13	4.25	4.23	5.09
0.14	4.08	4.37	4.34	4.14	5.04
0.16	4.68	4.41	4.31	4.41	4.94
0.18	4.60	4.38	4.23	4.46	4.83
0.20	4.59	4.32	4.50	4.65	4.89
0.22	4.81	4.65	4.77	4.76	4.61
0.24	4.69	4.69	4.77	4.99	4.66
0.26	4.65	4.93	4.75	5.00	4.43
0.28	4.94	4.88	4.97	4.69	4.77
0.30	5.19	4.92	4.96	4.94	4.34
0.32	5.20	4.91	5.19	4.98	4.48
0.34	5.23	4.99	5.28	5.39	4.37
0.36	5.24	5.09	5.29	5.37	4.42
0.38	5.36	5.08	5.20	5.47	4.58
0.40	5.33	4.76	5.52	5.17	4.49
0.42	5.58	4.99	5.55	5.29	5.00
0.44	5.57	5.43	5.47	5.25	4.46
0.46	5.74	5.06	5.48	5.51	4.64
0.48	5.43	5.22	5.74	5.46	4.76
0.50	5.75	4.90	5.44	5.27	5.01
0.52	5.71	4.94	5.53	5.61	4.58
0.54	5.80	5.03	5.77	5.47	4.58
0.56	5.53	5.16	5.85	5.78	4.89
0.58	5.70	5.41	6.03	5.73	5.11
0.60	5.95	5.39	6.16	5.96	5.08
0.62	5.76	4.92	5.86	5.75	4.94
0.64	5.69	5.20	5.66	5.46	5.15
0.66	5.71	5.04	5.46	5.41	5.08
0.68	5.67	5.18	5.80	5.98	5.47
0.70	5.68	5.24	5.67	5.73	5.17
0.72	5.74	5.24	6.15	5.97	5.24
0.74	5.93	5.66	5.85	5.72	5.31
0.76	5.92	5.24	5.75	5.89	5.22
0.78	5.86	5.53	5.59	5.44	5.29
0.80	5.87	5.62	5.62	5.75	4.96
0.82	5.89	5.60	5.85	5.40	5.39
0.84	5.89	5.63	5.41	5.65	5.31
0.86	5.75	5.67	5.92	5.77	5.26
0.88	5.93	5.65	5.78	5.93	5.17
0.90	6.03	5.28	5.66	5.72	5.33
0.92	5.70	5.80	5.84	5.80	5.22
0.94	5.69	5.74	5.75	5.53	5.30
0.96	5.48	5.58	5.79	5.66	5.20
0.98	6.06	5.66	5.78	5.46	5.79
1.00	5.55	5.70	5.62	5.68	5.44

Table 16: Mean spectral radius ρ versus isolation percentage, dynamic removal, community-affiliation, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0.00	7.27	7.48	7.40	7.64	7.31
0.02	6.22	5.85	6.10	6.25	7.13
0.04	5.38	5.42	5.77	5.60	6.40
0.06	5.25	5.01	5.35	5.84	6.07
0.08	5.23	5.07	5.34	5.15	6.19
0.10	4.93	5.01	5.02	5.37	5.90
0.12	5.14	5.35	5.33	5.43	6.12
0.14	5.19	5.15	5.07	4.96	5.59
0.16	5.43	5.32	5.38	5.13	5.91
0.18	5.30	5.01	5.18	5.33	5.52
0.20	5.15	5.26	5.27	5.41	5.69
0.22	5.26	5.25	5.45	5.20	5.46
0.24	5.37	5.36	5.32	5.24	5.39
0.26	5.55	5.55	5.39	5.56	5.54
0.28	5.34	5.63	5.62	5.53	5.69
0.30	5.59	5.57	5.68	5.61	5.31
0.32	5.32	5.48	5.50	5.60	5.67
0.34	5.47	5.63	5.57	5.72	5.41
0.36	5.86	5.61	5.88	5.52	5.58
0.38	5.66	5.43	5.80	5.77	5.28
0.40	5.95	5.31	5.65	5.69	5.77
0.42	5.66	5.55	5.78	5.40	5.58
0.44	5.46	5.81	5.67	5.77	5.39
0.46	5.63	5.78	5.70	5.73	5.66
0.48	5.82	5.67	5.94	5.67	5.42
0.50	5.94	5.42	5.85	6.05	5.73
0.52	6.21	5.52	5.69	5.89	5.96
0.54	5.98	5.32	5.88	5.86	5.65
0.56	5.88	6.01	5.77	5.67	5.40
0.58	5.70	5.50	5.70	6.07	5.37
0.60	5.64	5.57	5.62	5.58	5.85
0.62	5.86	5.85	6.02	5.64	5.72
0.64	6.24	5.76	6.16	5.45	6.01
0.66	5.93	5.35	5.61	6.00	5.63
0.68	5.62	5.43	5.66	5.85	5.46
0.70	6.17	5.91	6.01	5.64	5.68
0.72	6.12	5.62	6.31	5.97	5.91
0.74	5.88	5.82	5.70	5.88	6.09
0.76	5.83	5.53	5.84	5.90	5.74
0.78	5.87	5.34	5.75	5.92	5.77
0.80	5.81	5.25	5.83	5.94	5.53
0.82	5.60	5.75	5.83	5.74	5.60
0.84	5.34	5.79	5.75	5.76	5.75
0.86	5.85	5.75	5.77	5.77	6.13
0.88	5.96	5.88	5.71	5.76	5.61
0.90	5.55	5.60	5.94	5.71	5.53
0.92	5.75	5.66	5.79	5.70	5.87
0.94	5.74	6.06	6.02	6.14	5.45
0.96	5.96	5.80	5.73	5.61	5.93
0.98	5.75	5.70	5.88	5.76	5.53
1.00	5.44	5.38	5.78	5.71	5.69

Table 17: Mean extinction time versus isolation percentage, dynamic removal, Erdos-Renyi, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	**Degree**	**Eigen**	**Closeness**	**Betweenness**	**Random**
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	101
0.16	101	101	101	101	101
0.18	101	101	101	101	101
0.2	101	101	101	101	101
0.22	101	101	101	101	101
0.24	101	101	101	101	101
0.26	101	101	101	101	101
0.28	101	101	99.2	100.5	101
0.3	101	101	101	100.85	101
0.32	99.55	101	101	98.15	101
0.34	101	101	101	99.65	101
0.36	99.95	101	101	95.4	101
0.38	97.5	101	97.15	90.1	101
0.4	100.2	101	98.7	96.25	101
0.42	95.45	101	97.6	94.45	101
0.44	96.45	101	96.45	84.85	101
0.46	91.65	101	99.85	89.4	101
0.48	94.4	101	95.95	84.05	101
0.5	95.7	101	97.45	78	101
0.52	90.4	101	97	83.55	101
0.54	89.35	98.9	98.6	82.5	101
0.56	87.3	99	89.25	74.35	101
0.58	78.3	100.1	88.7	71.25	101
0.6	78.55	100.45	81.8	71.45	101
0.62	71.7	101	81.7	66.65	101
0.64	73	98.2	79	63.75	100.1
0.66	77.65	99.35	72.2	58	101
0.68	60.15	96.4	68.5	54	101
0.7	51.1	94.95	69.85	62.7	98.3
0.72	60.3	88.9	64.9	57.05	99.3
0.74	58.35	87.1	67.6	64.05	93
0.76	61.7	96.4	51.7	54.55	94.8
0.78	62.25	92.55	60.75	50.65	90.65
0.8	43.45	80.85	50.8	54.15	94.35
0.82	52.25	83.85	58.2	50.2	81.45
0.84	42.1	73.4	52.15	50.35	85.75
0.86	47.3	69.75	37.6	42.15	86.3
0.88	44.75	64.75	40.6	47.4	80.7
0.9	43.6	48.9	42.65	39.1	83.35
0.92	44.2	53.75	37.95	42.85	72.95
0.94	43.75	44.15	40	40.7	80.55
0.96	35.55	43.5	37.45	38.35	71.95
0.98	34.7	44.65	41.3	37.65	70.25
1	40.65	39.45	39.55	33.7	63.8

Table 18: Mean extinction time versus isolation percentage, dynamic removal, Erdos-Renyi, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	101
0.16	101	101	101	101	101
0.18	101	101	101	99.9	101
0.2	101	101	101	97.6	101
0.22	101	101	101	98.1	101
0.24	100.85	101	98.8	96.35	101
0.26	97.85	101	99.65	92.7	101
0.28	90.2	101	101	87.45	101
0.3	96.5	98.3	98.3	88.55	101
0.32	90.75	101	101	85.45	101
0.34	89.2	101	93.9	76.5	101
0.36	85.55	95.15	94.5	78.15	101
0.38	91.85	96.55	90.6	68.95	101
0.4	83.15	97.1	93.05	72.55	101
0.42	85.05	99.9	73.85	74.3	97.85
0.44	79.4	94.05	83.7	63.55	94.5
0.46	76.15	95.8	84.8	55.15	94.25
0.48	68.35	93.1	81.4	66.35	88.6
0.5	70.8	93.65	81.95	55.15	87.15
0.52	60.85	89.2	69.1	59.4	75.15
0.54	69.45	75.9	71.4	54.15	74.05
0.56	62.05	81	68.3	53.25	74.3
0.58	52.65	80.05	69.3	57.75	69.05
0.6	72.65	72.55	58.8	50.2	70.35
0.62	56.5	77.35	52.45	56.7	67.9
0.64	48.15	66.8	55	47	65.7
0.66	59.5	74.05	51.05	53.7	58.05
0.68	53.1	72.25	53.75	45.25	65.2
0.7	54.9	59.85	48.9	48.25	54.8
0.72	49.2	60	54.65	49.35	54.15
0.74	48.95	55.8	47	50.9	45.5
0.76	43.65	58.45	48.1	47	48.5
0.78	48.05	59.6	45.05	47.85	49.5
0.8	44.75	62.95	41.5	42.5	52.8
0.82	42.35	47.3	42.6	43.45	46.45
0.84	35.3	46.5	44	43.25	50.95
0.86	44.3	47.6	37.6	42.5	43.65
0.88	40.25	47.35	45.15	39.2	44.95
0.9	46.9	50.75	34.85	44.65	45.45
0.92	38.5	47.1	36.9	42.7	43
0.94	35.95	36.3	33.7	42.55	42.45
0.96	38.75	44.5	34.85	34.4	43
0.98	37.6	39.5	39.1	37.9	42.95
1	38.5	35.2	39.15	38.6	46.5

Table 19: Mean extinction time versus isolation percentage, dynamic removal, Erdos-Renyi, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	97.65	101
0.14	101	101	101	101	101
0.16	98	101	101	98.85	101
0.18	100.1	101	101	101	98.25
0.2	95.7	97.65	94.95	93	101
0.22	91.7	93.15	99.45	85.75	97.1
0.24	90.6	100.5	97.35	79.55	99.05
0.26	83.1	97.3	85.1	86.9	94.15
0.28	77.55	93.35	89.15	74.8	97
0.3	75.1	98.1	88.55	78	90.3
0.32	72.2	89.55	81.8	66.5	86.3
0.34	77.5	86.95	77.85	69.2	78.1
0.36	82.75	89.2	94.3	64.45	69.75
0.38	69.85	79.45	70.8	64.95	72.35
0.4	69.55	76.2	69.35	54.65	64.45
0.42	56.3	78.9	67.25	64.35	63.7
0.44	62.3	70.8	74.9	58.75	63
0.46	60.45	67.25	61.55	64.25	54.5
0.48	54.7	73.9	60.95	54	55.45
0.5	56.55	59.6	58.6	51.35	56.3
0.52	46.9	63.4	52.5	50.9	44.25
0.54	50.2	63	54.3	53.9	45.9
0.56	55.5	69.6	49.85	46.1	46.95
0.58	49.15	71.6	52.15	46.15	48.45
0.6	50.55	64.95	56.25	49.95	52.1
0.62	50.15	69.05	49.1	49.1	46.55
0.64	47.2	62.05	46.25	40.85	40.65
0.66	44.25	54.9	44.7	46.5	48.15
0.68	47.05	52.05	38.6	42.7	39.8
0.7	45.65	54.8	47.8	43.5	42.5
0.72	42.85	52.9	43.6	42.45	41.35
0.74	42.6	48.75	43.3	38.15	42.55
0.76	38.2	44	47	46.35	41.15
0.78	41.8	44.25	41.9	37.25	37.1
0.8	38.75	41.05	42.1	42	46.45
0.82	34.3	45.4	39.35	35.65	39.25
0.84	42.65	49.55	40.2	37.95	45.6
0.86	41.2	38.75	33.05	37.4	46.6
0.88	40.2	38.85	35.5	42.2	46.8
0.9	35.35	41.35	40.2	36.9	38.85
0.92	38.75	41.1	37	38.2	41.3
0.94	41.15	36.85	39.95	43.55	43.3
0.96	34.55	42.25	41.55	39.85	42.8
0.98	34.65	36.4	35.6	39.25	45.1
1	36.95	34.75	40.8	39.15	37.5

Table 20: Mean extinction time versus isolation percentage, dynamic removal, nearly-isolated community, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	**Degree**	**Eigen**	**Closeness**	**Betweenness**	**Random**
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	101
0.16	101	101	101	101	101
0.18	101	101	101	101	101
0.2	101	101	101	101	101
0.22	101	101	101	101	101
0.24	101	101	101	101	101
0.26	101	101	101	101	101
0.28	101	101	101	101	101
0.3	101	101	101	101	101
0.32	101	101	101	101	101
0.34	101	101	101	101	101
0.36	98.5	101	101	101	101
0.38	101	101	101	101	101
0.4	100	101	101	101	101
0.42	101	101	101	101	101
0.44	100.8	101	101	100.4	101
0.46	101	101	101	101	101
0.48	100.2	101	101	101	101
0.5	99.8	101	101	101	101
0.52	97.7	101	97.75	101	101
0.54	101	101	101	99.25	101
0.56	93.55	101	101	98.6	101
0.58	96.85	101	98.15	98.75	101
0.6	97.4	101	99.55	97.1	101
0.62	90.15	101	94.2	94.6	101
0.64	84.55	100.7	96.3	85.5	101
0.66	85.95	101	96.7	95.2	99.35
0.68	81.5	101	90.75	92.2	101
0.7	91.7	98.6	85.5	90.1	98.8
0.72	87.3	101	87.25	89.2	92.25
0.74	80.35	101	77.55	92.95	96.6
0.76	74.85	93.8	81.8	87.35	97.9
0.78	55.7	93.4	73.6	86.05	91.1
0.8	61.4	86.05	73.1	82	93.5
0.82	52.2	90	65.85	78.85	92.8
0.84	47.8	74.55	68.25	82.1	90.35
0.86	47.15	77.35	55.7	77.3	86.25
0.88	44.4	71.85	49.35	72.3	88.8
0.9	42.45	61.95	40.1	71	74
0.92	40.4	64.2	46.8	56.05	72.75
0.94	38	51.5	38.4	53.3	69.3
0.96	33.55	40.75	37.4	44.65	71.15
0.98	39.1	41.85	41.15	43.2	73.25
1	36.05	36.1	43	34.2	64.7

Table 21: Mean extinction time versus isolation percentage, dynamic removal, nearly-isolated community, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	**Degree**	**Eigen**	**Closeness**	**Betweenness**	**Random**
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	101
0.16	101	101	101	101	101
0.18	101	101	101	101	101
0.2	101	101	101	101	101
0.22	101	101	101	101	101
0.24	101	101	101	101	101
0.26	101	98.25	101	101	101
0.28	101	101	101	101	101
0.3	101	101	101	101	101
0.32	101	101	98.2	99.5	101
0.34	98.35	101	101	100.6	101
0.36	97.5	101	101	92.6	100.4
0.38	98.5	101	100.85	97.75	100.85
0.4	89.6	101	101	91.15	101
0.42	89.4	97.95	98.25	98.65	94.85
0.44	94.15	101	101	88.9	93.1
0.46	96.95	98.6	97.05	88.8	96.6
0.48	89.7	101	101	89.15	90.3
0.5	84.5	101	99.7	87.65	82.4
0.52	87.75	99.95	99.05	81.45	79.7
0.54	90.1	89.2	101	79.7	76.65
0.56	89.55	96.2	101	82.35	79.6
0.58	82.8	96.75	94.8	66.45	76.7
0.6	79.9	97.3	97.75	79.3	73.65
0.62	71.65	98	75.45	74.5	67.75
0.64	72.25	81.7	84.15	69.95	70
0.66	62.45	98.45	72.85	56.25	59.85
0.68	67.65	87.55	68.4	67.7	63.65
0.7	66.8	89.25	70.75	76.45	49.75
0.72	78.7	74.35	70.15	62.3	54
0.74	55.25	81.4	70.3	70.3	56.3
0.76	49.45	75.95	60.85	50	47.85
0.78	47.15	64.9	52.2	72.85	60.25
0.8	47.8	60.95	51.3	61.4	52.8
0.82	50.3	67.75	54.35	54.75	50.75
0.84	41.75	47.25	44.1	55.25	47.5
0.86	46.9	53.35	39.35	50	43.6
0.88	42.55	44.8	37.3	56.5	45.6
0.9	40.55	46.7	40.8	47.35	53.7
0.92	41.9	42	44.15	39.9	43.4
0.94	38.05	42.25	39.55	43.1	47.5
0.96	37	40.7	39.2	41.85	47.15
0.98	34.75	36.65	40.95	32.25	47.15
1	37.6	36	46.4	34.75	42.1

Table 22: Mean extinction time versus isolation percentage, dynamic removal, nearly-isolated community, Weak Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	100.15
0.16	101	101	101	99.3	101
0.18	99.85	101	97.35	101	101
0.2	101	101	101	101	101
0.22	98.25	101	101	98.25	97.05
0.24	93.45	101	100.1	97.15	98.35
0.26	100.5	101	101	97.25	96.9
0.28	95.9	101	100.15	94.25	88.95
0.3	96.9	101	97.3	96.85	85.6
0.32	89.95	101	99.05	87.8	89
0.34	87.8	95	98.95	81.1	88
0.36	82.8	94.35	96.95	97.65	76.9
0.38	76.45	99.55	96.35	83.1	77.2
0.4	85.15	93.3	95.2	81.7	78.05
0.42	81.45	93.6	90.85	79.25	60.85
0.44	85.85	82.7	87.75	69.15	58.1
0.46	77.1	83.85	90.9	74.55	56.95
0.48	76.85	87.95	75.1	82.45	53.15
0.5	63	97.45	91.4	65.65	53.1
0.52	74.45	85.9	71.45	69.25	60.9
0.54	68.65	89	72.45	72.55	50.3
0.56	64.25	70.1	71.65	70.55	49.45
0.58	68.7	70.15	77.6	64.55	46.2
0.6	53.7	78.8	71.85	72	50.15
0.62	67.2	70.6	66.1	60.4	47.45
0.64	50.25	72.3	68.8	51.3	49.5
0.66	50.6	70.3	62.7	54.05	48.45
0.68	55.15	61.25	64.5	61.05	43.5
0.7	49.55	66.6	57.45	54.15	48.85
0.72	49.45	66.25	60.6	55.6	38.15
0.74	35.65	61.7	40.8	54.65	43.45
0.76	47.2	57.65	46.35	56.6	41.45
0.78	47.7	63.9	51.5	60.4	38.05
0.8	48.8	53.4	42.45	37.15	37
0.82	43.75	45.9	41.4	46.7	41.35
0.84	39.1	43.2	39.2	48.8	40.15
0.86	41.35	40.4	41.2	38.85	40.05
0.88	39	45.2	35.9	40.85	37.15
0.9	37.5	40.85	37.25	44.25	37.9
0.92	40.3	36.55	37.3	35.4	39.4
0.94	40.65	36.6	36.25	39.9	40.7
0.96	39.55	38.8	40.45	36.85	44.35
0.98	34	37.95	37.95	36.2	43.15
1	37.3	36.9	36.3	37.1	41

Table 23: Mean extinction time versus isolation percentage, dynamic removal, community-affiliation, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	101	101	101	101	101
0.12	101	101	101	101	101
0.14	101	101	101	101	101
0.16	101	101	101	99.8	101
0.18	100.05	101	101	99.85	101
0.2	99.9	101	101	100.45	101
0.22	95.45	101	99.8	95.55	101
0.24	97.8	101	98.2	95.4	101
0.26	92.8	101	99.45	90.6	101
0.28	86.75	95.55	95.3	84.9	101
0.3	90.7	96.65	92.2	92.55	101
0.32	88.7	98.2	90.3	86.6	101
0.34	72.6	92.45	88.9	80.4	101
0.36	82.8	96.25	96.35	80	101
0.38	73.6	100.05	78.15	80.95	101
0.4	74.8	97.6	88.85	65.4	101
0.42	61.9	96.7	87.25	70.1	101
0.44	72.75	100.15	75.95	56.9	101
0.46	63.85	96.7	78.1	56.75	101
0.48	66.05	97.1	66.8	60.65	101
0.5	68.6	94.45	66.2	55.65	98.7
0.52	57.85	98.9	71.45	54.7	100.9
0.54	55.7	96	60.05	52.05	98.6
0.56	55.7	95.45	60.25	56.05	94.2
0.58	54.35	92.95	57	49.9	99.95
0.6	41.1	97	49.65	48.05	97.6
0.62	44.9	92.3	44.6	53.1	87.4
0.64	42.4	91.3	44.4	51.4	91.95
0.66	44.2	83.95	50.6	47.4	84.65
0.68	43.6	81.9	48.25	41.55	80.15
0.7	44.75	73.6	41.85	39.75	89.8
0.72	39.2	76.25	40.4	44.2	78.35
0.74	44.4	58.25	44.35	46.1	69.15
0.76	41.2	73.45	40.35	40.75	75.65
0.78	38.9	69.25	37.7	40.05	74.35
0.8	37.15	53.5	35.45	45.9	69.05
0.82	38.8	58.6	37.4	34.15	77.55
0.84	41.35	59.1	39.55	40.25	64.1
0.86	39.7	49.45	34.95	40.2	65.6
0.88	38.8	52.55	33.85	34.9	68.7
0.9	37	44.35	33.8	37.9	63.35
0.92	34.55	43.2	35.3	34.8	60.6
0.94	35.35	42.6	35.5	40.05	54.85
0.96	38.05	30.7	34.1	33.6	46.15
0.98	32.85	40.65	33.3	33.6	58.35
1	31.95	38.65	37	42.25	56.1

Table 24: Mean extinction time versus isolation percentage, dynamic removal, community-affiliation, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	101	101	101	101
0.06	101	101	101	101	101
0.08	101	101	101	101	101
0.1	99.2	99.5	101	98.95	101
0.12	98.9	101	101	97.65	101
0.14	97.95	101	101	98.7	101
0.16	91.15	98.2	95.5	86.7	101
0.18	81.7	101	95.15	99.25	101
0.2	86.1	97.3	98.85	80.8	101
0.22	92.25	96.35	87.15	84.55	101
0.24	81.55	95.05	84.7	86.3	101
0.26	77.05	93.7	87.05	68.35	100.7
0.28	76.7	73.85	87.6	81.05	99.95
0.3	68.45	87.75	67.1	58.8	96.55
0.32	62.35	88.1	73.3	75.3	101
0.34	66.65	84.45	70.25	63.85	95.5
0.36	70.3	78.55	70.1	60.95	93.9
0.38	63.75	74.4	65.65	48.55	89.5
0.4	64.8	79.35	70.6	52.3	85.65
0.42	61.45	79.1	68.95	53.05	83.65
0.44	56	82.75	55.2	54.25	72.5
0.46	53.4	68.95	56.95	50.3	79.7
0.48	53.9	85.05	52.85	45.9	71.1
0.5	47.9	57.95	48.2	45.75	69.35
0.52	49.5	73.35	49.5	42.5	66.1
0.54	44.85	83.6	50.1	39.55	62.1
0.56	47.8	82.8	51.75	47.4	68.9
0.58	42.25	61.1	41.5	39.3	65.05
0.6	41.85	70.75	44.7	42.15	62.65
0.62	45.55	66.3	39.1	44.05	57.4
0.64	38.35	63.55	47.15	40.75	54.6
0.66	39.85	58.55	40.55	50.9	47.55
0.68	41.1	63.25	45.3	42.6	52.45
0.7	36.9	50.45	38.2	40.7	58.05
0.72	38.95	55.35	36.2	35.35	46.65
0.74	42.7	55.4	39.5	38.55	49.25
0.76	38.55	47.5	38.25	36.15	51.1
0.78	44.6	43.3	34.9	36	47.4
0.8	38.9	47.2	35.05	39.8	42.75
0.82	37.2	49.55	37.9	41.6	43.9
0.84	35.2	45.5	33	42.5	43.4
0.86	35.15	43	34.95	39	46.75
0.88	34.45	39.5	37.15	42.45	50.25
0.9	39.75	41.45	33.65	36.3	44.4
0.92	35.5	40.6	37	40.3	38.35
0.94	37.05	43.45	35.45	41.15	38.8
0.96	35.5	40.4	36.1	35.9	42.9
0.98	34.2	34.85	34.35	37.45	39.3
1	39.2	38.3	36.8	40.8	44.9

Table 25: Mean extinction time versus isolation percentage, dynamic removal, community-affiliation, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	**Degree**	**Eigen**	**Closeness**	**Betweenness**	**Random**
0	101	101	101	101	101
0.02	101	101	101	101	101
0.04	101	100.65	101	101	101
0.06	99.25	90.95	101	101	101
0.08	96.35	96.8	91.6	97.7	101
0.1	90.15	93.5	98.35	93.2	101
0.12	82.05	92	90.75	84.4	98.25
0.14	74.5	98.4	82.4	86.7	99.65
0.16	77.5	80.15	77.35	80.55	92.5
0.18	76.35	78.25	81.85	73.1	89.1
0.2	64.05	86.05	76.8	76.1	92.05
0.22	51.05	85.9	71.15	69.95	87.6
0.24	52.8	75.3	63.25	55	92
0.26	59.35	72.85	59.4	57.35	79.3
0.28	53.25	74.6	58.7	52.6	73.6
0.3	59.3	60.75	61.75	63.05	68.4
0.32	53.1	64.15	57.65	59.15	60.05
0.34	47.95	62	53.05	45.35	62.35
0.36	57	52.1	52.3	56.35	71.2
0.38	70.6	70.7	56.7	47.8	59.4
0.4	43.3	56.3	46.85	47.8	62.8
0.42	41.4	58.45	46.45	45.6	50.95
0.44	44.95	62.3	53.25	43.95	53.85
0.46	54.5	48.05	42	47.9	49.05
0.48	44.05	47.9	46.5	40.25	42.5
0.5	46.65	61.5	47	44.4	45.95
0.52	43.35	65.65	46.9	40.6	48.6
0.54	41.65	51.2	42.55	35.95	43.45
0.56	37.35	53.4	34.9	38.35	43.9
0.58	37.85	54.6	38.1	39.1	52.15
0.6	37.55	57.9	39.3	41.3	44.95
0.62	43.25	52.25	42.3	41.25	40.55
0.64	38.75	53.9	38.45	46.6	39.45
0.66	43.3	46.95	43.1	37.9	37.9
0.68	40.95	40.5	39.1	38.85	42.25
0.7	43.5	46.15	35.1	39.1	42.15
0.72	40.35	44.3	37.5	39.75	43.05
0.74	34.35	46.55	39	37.2	38.75
0.76	39.7	44.05	35.75	32.1	38.05
0.78	39.45	42.4	42.05	38.15	40.05
0.8	36.1	39.65	36.95	39.1	40.9
0.82	40	47.85	39.4	34.95	43.2
0.84	37	46.95	35.15	40.65	39.85
0.86	40.15	38.55	38.5	38.65	39.45
0.88	37.3	37.25	38.05	38.1	38.6
0.9	36.5	36.5	38.55	36.25	36.95
0.92	32.5	39.3	37.25	30.9	39.4
0.94	32.6	41.45	40.75	40.7	38.5
0.96	39.1	34.6	33.75	33.95	39.95
0.98	35.75	41.55	37.85	34.45	35.75
1	33.9	34.5	39.35	37.9	36.3

Table 26: Mean total costs versus isolation percentage, dynamic removal, Erdos-Renyi, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	6124778	6133293	6127146	6135840	6136297
0.02	5964724	5966924	5991142	5935933	5965836
0.04	5940042	5988346	5952793	5905507	5906339
0.06	5896599	6042915	6082326	5795710	6050505
0.08	5891595	6151978	6137516	5936623	6029247
0.1	5706996	6213480	6204493	5962039	6128516
0.12	5773028	6359771	6243127	5834393	6281287
0.14	5443912	6342139	6323470	5855485	6469414
0.16	5317529	6186415	6445554	5507085	6548248
0.18	5044409	5908795	6250231	5167901	6722336
0.2	4544074	5846290	5771446	4732069	6853058
0.22	3886599	5500281	5516077	4445495	6955116
0.24	3621178	5183106	4881059	3940030	6895993
0.26	3314949	4691281	4501115	3597940	6970185
0.28	3003269	4592331	4612505	3134937	6767582
0.3	2816906	4295442	3815208	2665803	7181671
0.32	2591254	3966334	3388024	2478531	6863666
0.34	2397691	3798049	3481020	2194482	7198459
0.36	2228350	3455874	2976646	1797071	6961382
0.38	1925704	3408215	2573159	1595868	7079486
0.4	1904740	3450236	2367391	1493909	6813712
0.42	1483646	3308246	2177070	1260620	6892197
0.44	1407051	3343134	1876471	1283844	6858397
0.46	1343533	3351361	1612786	1052122	6738770
0.48	1170340	3043790	1483654	994786	6734075
0.5	1130856	3154776	1422239	890077	6348478
0.52	1044364	2624455	1218336	856872	5995315
0.54	976661	2718539	1133492	849189	5879970
0.56	786111	2555371	1073846	661346	5628079
0.58	700051	2550372	897925	786667	5544396
0.6	704975	2262753	853632	689951	5129565
0.62	634017	2087631	687722	605890	5048561
0.64	560417	1861458	615574	536914	4713413
0.66	548462	1910964	589906	531082	4701318
0.68	480416	1408358	500831	534491	4202286
0.7	474423	1417805	452291	442095	3574210
0.72	417733	1214195	476916	495409	3371018
0.74	420007	1092003	440386	422774	3079646
0.76	348247	828290	401370	472918	2922872
0.78	346702	785348	338756	404566	2604514
0.8	343976	691013	360203	418482	2606721
0.82	356884	580695	355036	395134	2219519
0.84	306473	501549	342018	379885	1652333
0.86	329236	478042	307633	308509	1808259
0.88	288269	420916	289527	315876	1372785
0.9	309224	410396	285057	303744	1161545
0.92	276187	349391	272224	314479	1274950
0.94	271417	314393	289546	336388	1256709
0.96	277966	311324	291759	313206	1024182
0.98	296409	294484	265979	314951	926148
1	257296	283217	264349	274283	1013812

Table 27: Mean total costs versus isolation percentage, dynamic removal, Erdos-Renyi, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	5329825	5343236	5409682	5415387	5392133
0.02	4971423	5000623	5033540	4909034	5099246
0.04	4740370	4794356	4794645	4648217	4915613
0.06	4519009	4534661	4586950	4463392	4772837
0.08	4348562	4294942	4395859	4321476	4741418
0.1	4035919	4146572	4276230	4005527	4724732
0.12	3733582	3920910	3974335	3879077	4724121
0.14	3116848	3506954	3741170	3487569	4570231
0.16	2999042	3470559	3316819	2991842	4641688
0.18	2775920	3092841	3269665	2545966	4689528
0.2	2240253	2963816	2779716	2365084	4472086
0.22	2106521	2582117	2421346	2062393	4530180
0.24	1804010	2439531	2111965	1534176	4394800
0.26	1664065	2164241	2083586	1479377	4203999
0.28	1344537	2074842	1819436	1199964	4072437
0.3	1206009	1983492	1634511	1045275	3898504
0.32	1189793	1823286	1453217	915094	3513698
0.34	1064523	1739995	1298966	776566	3341876
0.36	1010548	1615852	1131115	749601	3189058
0.38	820151	1489343	992921	637076	2864920
0.4	714701	1446645	912243	646890	2509915
0.42	713298	1354809	813701	558016	2194384
0.44	621347	1285060	766102	563792	2143926
0.46	596930	1080219	715782	535080	1818788
0.48	667785	1024177	625707	443726	1726684
0.5	503899	1023388	653012	485241	1417781
0.52	484655	984646	505834	376163	1129043
0.54	478364	921758	515249	422314	1205922
0.56	418850	864506	521803	416873	925143
0.58	369483	720009	430544	429118	817524
0.6	414745	689526	399099	378480	752129
0.62	343852	575733	380075	360902	771986
0.64	420964	572157	371349	336656	660164
0.66	368440	577921	332398	345951	662817
0.68	346838	476030	356791	349594	584230
0.7	345277	490754	359911	370726	563289
0.72	331618	513863	317806	314484	577980
0.74	327115	440035	309703	324879	549652
0.76	292796	426643	311892	317054	516439
0.78	289704	459328	283924	321733	435420
0.8	266582	396905	336283	312550	494834
0.82	287550	353210	264529	303607	501878
0.84	305925	347589	286556	318119	487087
0.86	249905	346615	253064	319173	443302
0.88	294358	319822	284861	268212	494100
0.9	269067	301936	275285	299512	481093
0.92	277576	311741	292206	306695	384767
0.94	266076	292343	282908	277342	436416
0.96	257350	321886	278372	275961	460558
0.98	289083	267146	295701	269871	401535
1	250494	281920	286607	262799	389500

Table 28: Mean total costs versus isolation percentage, dynamic removal, Erdos-Renyi, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	3707012	3663044	3690584	3738920	3573818
0.02	3217156	3210473	3239224	3256894	3241093
0.04	2926034	2829391	2830876	2861567	3117562
0.06	2561535	2578657	2613776	2466158	2934414
0.08	2169976	2148364	2209535	2203613	2731175
0.1	1806370	2082660	2017110	1956371	2542470
0.12	1744915	1745224	1816278	1700168	2450680
0.14	1478373	1505370	1543467	1396797	2363035
0.16	1359177	1444252	1403653	1166196	1967198
0.18	968319	1272514	1220075	1105504	1710789
0.2	906609	1069084	1071423	920334	1837360
0.22	820381	1092164	910773	860548	1666874
0.24	702233	917166	887609	692509	1304690
0.26	707163	845474	775481	600132	1056443
0.28	667207	786257	609764	557536	936258
0.3	567809	752033	631400	469814	953334
0.32	505338	613601	612974	413156	726025
0.34	517035	661718	571684	453516	595301
0.36	421425	542527	492585	444206	618791
0.38	436210	567764	445992	404758	623518
0.4	362312	542252	416200	339957	516419
0.42	362327	461157	393451	374340	556271
0.44	319692	443047	342207	374890	516879
0.46	394625	461078	391596	309423	390476
0.48	336281	426719	340573	339708	381817
0.5	328739	388181	346787	332198	376861
0.52	303477	412076	331954	322107	401839
0.54	328103	357874	302304	289198	404804
0.56	341849	353063	308987	299800	374273
0.58	297962	430667	322613	295356	412368
0.6	258004	379289	303467	299059	358644
0.62	293682	357218	290068	290581	346561
0.64	288369	343000	300703	257462	358693
0.66	252599	320499	285058	309858	335228
0.68	270655	348952	302878	328468	389978
0.7	222764	354435	279461	290037	330353
0.72	276503	298986	260440	268781	324085
0.74	283441	326437	303054	255836	343039
0.76	270603	326371	283093	274404	325737
0.78	276165	276426	271061	288741	302809
0.8	264785	278268	258813	262906	316341
0.82	273779	295685	291685	283741	320597
0.84	280351	308381	282610	282271	320007
0.86	266618	279870	255536	287244	331986
0.88	262594	299951	253466	293506	301831
0.9	245791	304052	284615	279211	326858
0.92	279075	277073	273948	247573	342584
0.94	287290	275692	260671	280826	307738
0.96	277523	249423	258307	272203	291595
0.98	277875	261843	265002	278087	308354
1	288984	272288	275021	271234	312908

Table 29: Mean total costs versus isolation percentage, dynamic removal, nearly-isolated community, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	6158064	6157711	6182506	6180389	6153767
0.02	6090373	6089522	6080089	6041341	6042130
0.04	6155783	6202034	6097294	6056275	6079975
0.06	6338387	6341173	6226513	6191338	6181988
0.08	6499474	6685482	6317014	6373926	6393145
0.1	6733798	6893450	6641119	6442378	6636397
0.12	6983722	7073875	6842352	6657647	6905787
0.14	7137957	7157997	6989835	6710508	7124278
0.16	6839894	6803194	7074485	6476774	7254493
0.18	6665577	5972408	6975782	6512761	7499045
0.2	6116822	5248838	6268268	6123884	7706200
0.22	5677949	5280700	5606820	6058971	8099066
0.24	5252960	5235372	4953339	5748964	8129035
0.26	4532451	5524414	4725612	4794208	8488654
0.28	4427416	5394267	4469205	4977540	8428696
0.3	4052930	5660146	3825620	4765890	8478630
0.32	3731619	5229682	3545294	4176887	8631286
0.34	3493513	5545705	3387813	3873024	8686903
0.36	3376268	5464821	2855029	3530239	8769669
0.38	2859404	5349735	2683084	3349970	8572862
0.4	2836197	5523478	2624779	2859137	8405906
0.42	2427021	5166589	2429843	2721466	8577602
0.44	2241370	5156480	2292942	2438641	8416477
0.46	2256353	4872241	2254962	2519255	8171081
0.48	2014556	4859618	1953403	2214231	7987144
0.5	1863824	4710767	1811340	2109638	8063355
0.52	1659384	4353784	1793929	1912986	7846643
0.54	1600944	4206215	1618137	1712076	7640172
0.56	1339491	3861956	1450076	1599483	7095031
0.58	1321417	3620700	1246862	1467427	6778560
0.6	1093721	3314645	1229791	1454185	5989800
0.62	1033654	3238471	1121106	1260206	6208527
0.64	950575	2710195	1026923	1192183	5266155
0.66	886747	2425597	845488	1221463	4971226
0.68	751706	2132011	892867	1179737	4805446
0.7	725335	1875469	677609	1298603	3709865
0.72	634642	1494324	623569	1062825	4634632
0.74	572023	1574390	563831	932180	3709958
0.76	492476	1155413	570801	737363	3422298
0.78	476238	1157613	530075	773603	3195182
0.8	447871	903156	513025	706931	2255541
0.82	438330	807521	528271	641721	2509189
0.84	398108	699698	433227	694635	2302248
0.86	381177	564861	405321	657715	1600580
0.88	370987	573544	380953	647620	1801776
0.9	375226	484653	372269	604178	1828936
0.92	344603	421049	328066	500055	1355495
0.94	371450	425144	387127	434633	1305131
0.96	358798	356135	299835	414213	1277864
0.98	331757	335450	359104	332808	1276698
1	323266	321189	351979	333714	1124972

Table 30: Mean total costs versus isolation percentage, dynamic removal, nearly-isolated community, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	5572880	5591714	5564030	5579777	5601062
0.02	5306678	5346653	5250201	5304137	5353208
0.04	5193412	5205974	5157859	5163212	5181854
0.06	5092941	5185434	5156522	4985864	5182140
0.08	4993465	5095093	4862611	5073925	5129203
0.1	4704530	4864918	4866703	4526019	5308588
0.12	4541534	4477618	4508479	4731182	5240738
0.14	3943902	3946004	4235474	4325371	5366877
0.16	3606472	3520190	3962560	3962778	5300872
0.18	3249252	3113202	3456795	3439753	5452903
0.2	2965692	2919489	3116217	3167785	5407763
0.22	2985161	2933606	3003189	2838542	5067228
0.24	2452108	2950223	2767802	2510611	5290110
0.26	2361603	3048562	2393997	2329808	4865577
0.28	2416368	3081437	2332143	1980672	4741420
0.3	1890988	3121047	2256061	1892620	4625627
0.32	1719264	2823968	2013086	1691499	4347348
0.34	1591184	2897755	1875090	1642429	3879540
0.36	1596618	2656807	1591865	1337525	3804847
0.38	1418786	2624989	1495625	1322096	3199341
0.4	1322268	2498824	1471104	1172559	2819423
0.42	1169022	2417068	1358989	1198668	2636104
0.44	1127701	2265822	1369284	1087997	2271208
0.46	1094084	2117806	1208245	991396	1966748
0.48	952925	2047120	1001602	906616	1775403
0.5	936844	1815000	1000349	903960	1768061
0.52	867902	1793751	861603	1042336	1303935
0.54	679779	1488965	803104	714268	1215652
0.56	682143	1617112	751470	848072	1211335
0.58	745258	1511175	732631	737478	1044657
0.6	625874	1279471	692613	802236	988095
0.62	565952	1168913	662006	664723	1012654
0.64	483448	985790	604071	645559	871051
0.66	486863	910760	553555	659227	728035
0.68	442342	880868	510820	569558	772015
0.7	481577	769339	495269	644334	742227
0.72	379000	670271	428912	557136	743886
0.74	380562	594824	420040	558074	698569
0.76	375106	556800	389369	547325	697415
0.78	375463	582349	400189	539850	688465
0.8	336322	479550	382155	550752	606508
0.82	352722	481069	370069	449201	592082
0.84	382984	433047	385749	460247	602452
0.86	329296	419128	349956	423607	598999
0.88	328560	387605	346528	433002	567660
0.9	349231	395161	339612	413092	588491
0.92	356591	371062	342167	409775	575447
0.94	353396	378599	348505	364652	541452
0.96	343897	342312	327403	380137	491522
0.98	358304	342856	346457	382904	524970
1	311019	344830	336001	385621	499215

Table 31: Mean total costs versus isolation percentage, dynamic removal, nearly-isolated community, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	3954658	3988847	3948100	3864680	3870629
0	3533481	3613972	3525502	3599468	3569143
0	3177582	3340864	3334229	3228002	3273719
0	2952526	2982667	2955537	2868603	3198334
0	2640676	2570422	2772434	2656181	2989353
0	2216654	2291318	2471738	2306893	2949487
0	1940326	1989017	2240157	2041756	2754593
0	1741833	1844534	1800105	1893619	2534411
0	1416191	1571635	1632671	1634649	2309646
0	1252702	1550762	1710100	1437430	1976506
0	1262867	1601110	1476694	1289738	1880070
0	1102979	1431072	1292515	1156579	1504754
0	963784	1534008	1177893	1078779	1427225
0	931278	1451413	990667	1048301	1245366
0	896365	1288532	985260	904513	1118042
0	817495	1321747	964958	876317	865189
0	778778	1171087	937524	761917	794124
0	670665	1134976	868041	673477	864923
0	637570	1115663	823350	660229	683145
0	581788	978326	703405	670437	590068
0	595852	935189	677774	637256	658275
0	579156	960399	602610	582875	604895
0	567565	880707	636435	550387	564749
0	516745	814122	577103	605526	569303
0	437237	790137	557755	510837	530943
1	412164	708889	564813	519846	497116
1	466282	600771	502051	496820	536305
1	419527	667581	475919	466338	470198
1	398889	558961	414599	460877	472660
1	432323	518711	445892	468227	474357
1	398375	565874	391378	429462	419461
1	363499	519812	414053	454141	426854
1	370382	444265	404137	432154	410799
1	383934	466228	380350	405628	430964
1	334573	461284	363087	385228	450377
1	362682	402165	375851	407322	451292
1	386216	424939	373438	355486	400713
1	333255	378292	326456	414694	433069
1	317201	446422	366380	390687	430410
1	332293	391661	378095	395053	412260
1	321183	380265	365615	350898	424743
1	302917	373725	374341	387868	385705
1	340223	379254	321260	394304	362530
1	311406	331668	306738	356026	436876
1	350966	376076	356796	382338	455393
1	337900	356157	344709	350851	361637
1	305616	359029	337429	353169	402807
1	316172	336563	353634	348349	406615
1	306934	338393	339276	361252	396977
1	348537	339154	317472	344096	366244
1	341621	364778	329647	336297	370373

Table 32: Mean total costs versus isolation percentage, dynamic removal, community-affiliation, COVID-19 parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	4329558	4377802	4206399	4450136	4435010
0.02	3945539	4026035	3936193	3809860	4093048
0.04	3444177	3801615	3754662	3550482	4111371
0.06	3421299	3443606	3756046	3310686	3967724
0.08	2695794	3453361	3560545	2952325	3785377
0.1	2651602	3231643	3397935	2669456	3849692
0.12	2133883	2757562	2817102	2445452	3793057
0.14	2132986	2572739	2576291	2246688	3760279
0.16	1582321	2277700	2614343	1776576	3878964
0.18	1465043	2544414	2061160	1888960	3826241
0.2	1379112	2094103	2024732	1520012	3680874
0.22	1121577	1906390	1442173	1397237	3609331
0.24	1144054	1764652	1594504	1119860	3613019
0.26	1020806	1574631	1183053	961855	3765142
0.28	740038	1410490	1109399	749472	3452294
0.3	694843	1361701	1034488	781014	3518808
0.32	643885	1186888	926056	719002	3370976
0.34	649994	1428045	731250	547788	3637194
0.36	506568	1284934	693218	538333	3324838
0.38	452829	1111391	577866	451172	3196157
0.4	474860	1240526	635586	425025	2896041
0.42	401882	1172985	548265	459764	3004421
0.44	470588	1006012	454330	463420	2892180
0.46	369418	1119176	434226	395005	2851448
0.48	285501	992800	381470	289806	2712343
0.5	294237	1171339	379958	277663	3060440
0.52	272034	1209991	335094	331218	2380046
0.54	329151	1210255	256737	313020	2546031
0.56	300393	1070521	244577	295524	1823551
0.58	235757	924681	235397	256134	2304010
0.6	214254	913056	217206	264716	2537215
0.62	213204	875864	213645	226952	1666985
0.64	216518	725337	223032	258820	1538207
0.66	216545	757725	214769	220539	1255137
0.68	197578	556334	209626	238149	1748713
0.7	201244	526146	208272	203508	1258847
0.72	205715	487627	191550	244475	1081908
0.74	193592	397188	174215	204746	945045
0.76	174698	343290	184295	224736	776816
0.78	181323	332198	187700	203163	849697
0.8	191042	275181	180476	175957	774879
0.82	171618	307905	181459	185874	910181
0.84	158456	242941	154206	193284	711686
0.86	176089	246741	175581	189647	608348
0.88	174459	219773	161693	182758	581516
0.9	192294	211962	160837	208621	524692
0.92	174812	205372	174287	195008	563383
0.94	198110	192528	177358	193444	548233
0.96	179785	182948	169193	191943	395003
0.98	177265	187927	188939	206468	447019
1	191782	155045	163049	180857	408653

Table 33: Mean total costs versus isolation percentage, dynamic removal, community-affiliation, Epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	3134659	3228396	3398167	3348215	3234287
0.02	2790419	2755534	2936127	2789547	3211853
0.04	2636697	2465107	2420905	2432197	2916825
0.06	1928749	2181412	2296543	1833638	2836337
0.08	1711900	1946475	2040698	1819758	2513091
0.1	1430993	1679638	1511598	1543347	2489726
0.12	1116049	1588818	1474663	1363626	2551255
0.14	1108119	1129218	1454653	1134905	2428739
0.16	792610	1207506	1168934	1053760	2245234
0.18	871733	1238632	972181	731583	2182755
0.2	712546	915872	641139	711433	2035957
0.22	525974	1011654	689020	553915	1940655
0.24	583457	745289	702294	525059	2117548
0.26	480538	690919	654994	471977	1798711
0.28	389882	646688	493441	359608	1965586
0.3	385751	591585	435011	432672	1554699
0.32	337751	513537	473754	346990	1373009
0.34	367225	516259	368256	298413	1462443
0.36	292000	500122	338799	264266	1236161
0.38	255889	590004	298801	312790	1334145
0.4	264778	416667	252139	275433	1100349
0.42	262697	484253	257366	231599	908828
0.44	224336	394950	259640	231033	793280
0.46	211324	457679	250614	250614	843894
0.48	250116	395339	235168	199147	562681
0.5	232025	392766	198485	226354	720018
0.52	215753	428699	220611	201724	472605
0.54	210603	384111	206457	204480	464840
0.56	182106	418106	197769	190958	490805
0.58	187907	366369	200588	188862	453255
0.6	204785	377989	186692	204634	357728
0.62	180641	305294	187644	170708	386572
0.64	167909	333499	179996	210968	371662
0.66	172336	308714	191309	199001	308479
0.68	185100	293242	184716	189417	312942
0.7	196717	284764	169273	187840	270982
0.72	188270	240626	166902	176096	312698
0.74	170090	266263	175953	184873	296109
0.76	186614	237362	174842	175704	283531
0.78	173147	241968	176212	176248	280727
0.8	171001	223839	156087	176694	315109
0.82	162798	198930	192952	178975	246333
0.84	185061	213010	158469	182118	281581
0.86	178455	201360	183919	171878	250863
0.88	174329	191531	182129	196484	259115
0.9	170227	185501	171069	176234	254748
0.92	168151	193390	177061	179372	275639
0.94	160522	179246	178762	199842	233407
0.96	175975	181920	155593	180625	243863
0.98	167274	192105	180130	184573	232087
1	176422	171949	178859	156213	244647

Table 34: Mean total costs versus isolation percentage, dynamic removal, community-affiliation, Weak epidemic parameter set. Performance of removal based on degree-, eigen-, closeness-, and betweenness centrality are compared with each other and with the performance of random dynamic removal.

iso%	Degree	Eigen	Closeness	Betweenness	Random
0	1972070	1853964	1825470	1850653	1939157
0.02	1556219	1538791	1504777	1455029	1918333
0.04	1230715	1061056	1138550	1263779	1597532
0.06	921956	1004977	906719	940102	1319035
0.08	842487	907844	989348	817387	1234269
0.1	659290	662954	658113	775016	1141075
0.12	511924	654617	648951	525952	1061858
0.14	445365	486747	468862	515717	1087859
0.16	406896	477544	379702	487876	940121
0.18	366984	354939	419600	420098	748737
0.2	330042	392844	313409	375767	808731
0.22	276490	348603	346940	272323	556540
0.24	294564	332150	273812	267001	527050
0.26	282004	304860	248231	273021	496364
0.28	246513	262643	262155	282584	418159
0.3	221931	272923	284231	267350	367351
0.32	222639	246648	249530	231642	373843
0.34	236348	241490	221340	219100	371781
0.36	218269	257332	229744	216571	311960
0.38	184197	245353	210001	185843	303712
0.4	219853	211811	226288	210961	279709
0.42	192621	209286	196660	192060	259835
0.44	193488	215971	190276	188824	287813
0.46	196722	241823	200279	205270	251734
0.48	188610	205447	182044	184336	227735
0.5	212054	253486	177105	188604	250271
0.52	174024	242456	171195	179466	250631
0.54	159510	224819	172926	174940	233497
0.56	175153	244146	171628	181797	207363
0.58	167703	209928	181673	202460	227945
0.6	191342	194427	179183	167774	232024
0.62	184853	225732	183761	163276	190138
0.64	166562	226968	162954	164140	202592
0.66	176616	202047	159766	151934	194882
0.68	192539	204544	175012	177930	215309
0.7	161745	199740	164993	184787	197483
0.72	151063	230923	163343	192058	215805
0.74	152319	193287	183052	169834	200405
0.76	184971	188540	171587	187206	197014
0.78	159807	189331	180503	162690	198485
0.8	179009	211596	195052	191832	196992
0.82	165780	181282	186123	187410	218111
0.84	154006	181910	160172	170092	213652
0.86	155602	188052	166742	165357	212354
0.88	182357	197085	178246	179974	203832
0.9	170010	173924	172947	191523	201725
0.92	168302	182843	206495	153705	202002
0.94	152758	196219	169136	185643	200437
0.96	176905	184543	195271	182177	217953
0.98	189014	172933	153826	193300	208708
1	178095	169559	178473	189018	202832