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EVALUATING HOSPITAL RANSOMWARE RECOVERY STRATEGIES THROUGH SERVICE RESTORATION TIMES AND PATIENT THROUGHPUT

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Abstract:

This analysis evaluates how recovery horizons alter hospital ransomware response rankings, addressing the distinction between rapid reopening and sustained service continuity. We descriptively reanalyze published simulation summaries from one modeled United States hospital, comprising four cumulative throughput records and six restoration milestones across two recovery packages. Through day 7, payment followed by restoration delivers 102 more discharges than onsite backup recovery, representing a continuity advantage of 7.61 percentage points. Through day 14, onsite backups deliver 28 more discharges, reversing the ranking by 1.05 percentage points. Payment reaches half of baseline daily discharge performance one day earlier, whereas onsite backups reach 90 percent three days earlier. An exploratory interval decomposition attributes the cumulative reversal to 130 additional discharges under backup recovery during the second week. These comparisons concern bundled recovery assumptions. The contribution is a joint interpretation of cumulative service preservation, accumulated shortfalls and restoration milestones that clarifies recovery as a trajectory. Hospital preparedness assessments should compare response packages across matched horizons and successive performance targets.

Key Words: Hospital Resilience; Patient Throughput; Ransomware Recovery; Secondary Analysis; Simulation

1. Introduction:

Restoring hospital information systems does not immediately restore the clinical activity lost during a ransomware disruption. Recovery decisions affect when patients can enter the hospital, how quickly services resume and how much care remains undelivered. These outcomes can favor different response strategies at different stages of recovery. The substantive problem is therefore how to evaluate recovery when earlier reopening and stronger subsequent performance do not produce the same strategy ranking. Hospital activity provides a direct operational perspective on this problem. Ghafur et al., 2019, examined the WannaCry attack using hospital activity records from England and identified reduced admissions at infected hospitals. Their findings connect digital disruption to measurable changes in service delivery. However, evidence concerning the consequences of an actual attack addresses a different question from the comparison of alternative recovery responses under a common hospital configuration. The latter requires consistent benchmarks, reporting horizons and definitions of restoration.

Resilience engineering provides a basis for distinguishing these performance dimensions. Woods, 2015, separates recovery after disruption from robustness and sustained adaptability. Within the recovery perspective, initial service resumption and return toward routine performance represent different points along an operational trajectory. A response that reduces initial closure may preserve more activity early in the disruption, while another response may restore subsequent performance more quickly. Evaluating either response through a single milestone can therefore obscure the service consequences accumulated across the recovery period. The closest quantitative research is the hospital simulation developed by Ghayoomi et al., 2021. Their model compares payment followed by decryption and system restoration with recovery using onsite backups. The payment scenario assumes a shorter emergency department closure, whereas the backup scenario assumes a longer initial closure followed by faster subsequent recovery. Their published results already establish that the relative performance of these packages changes over time. The present analysis builds directly on those results through a secondary comparison of cumulative throughput, discharge shortfalls and restoration thresholds. Its contribution concerns the interpretation of complementary recovery measures and the decisions they support.

The explanatory framework treats payment decision, recovery method and emergency department closure duration as attributes of bundled response packages. These attributes describe how the source model organizes recovery rather than independently estimated influences. The operational logic links the timing of renewed patient entry and subsequent restoration to hospital discharge performance. Bartock et al., 2016, place cyber security recovery within a coordinated process of resource prioritization and restoration of mission functions. Applied to hospitals, this perspective directs attention toward delivered clinical services as the outcome through which recovery acquires practical meaning. Hospital service continuity requires measurement

across both time and performance. Cumulative discharges relative to a matching baseline indicate the share of benchmark activity delivered through a specified horizon. The associated discharge shortfall records the activity deficit accumulated during disruption. Time to a target level of daily discharge performance measures a different feature: the speed at which the hospital reaches a specified operating threshold. Chen and Miller Hooks, 2012, connect resilience assessment to service performance and recovery capability. These distinctions support examining cumulative continuity and restoration milestones together, while preserving their different temporal meanings.

The bounded analytical question is how these measures qualify the interpretation of the same recovery packages. The published hospital simulation documents the temporal reversal, but its decision significance becomes clearer when cumulative service delivery is distinguished from daily performance restoration. A rising continuity percentage can coexist with a growing cumulative discharge shortfall. Likewise, earlier attainment of a lower performance threshold need not imply earlier attainment of a higher threshold. This analysis brings these comparisons into one descriptive framework without treating repeated summaries as independent hospital observations. The evidence consists of published simulation summaries for one modeled urban tertiary hospital in the United States. Four records describe cumulative hospital discharges under two strategies at days 7 and 14. Six records describe the first day each strategy reaches 50, 80 and 90 percent of baseline daily discharge performance. We calculate continuity percentages using corresponding baseline counts, compare cumulative discharge shortfalls and examine restoration timing within common thresholds. This design enables transparent comparisons within the represented setting. As Morris et al., 2019, explain, simulation findings require interpretation against their data generation process and performance measures. Accordingly, the resulting comparisons remain conditional on the source model and its bundled recovery assumptions.

This study aims to clarify how evaluation horizons and performance targets shape the comparison of hospital ransomware recovery strategies. The first research question asks how cumulative hospital discharges and continuity percentages differ between the two packages at days 7 and 14. The second asks how long each package requires to reach 50, 80 and 90 percent of baseline daily discharge performance. The objectives are to compare cumulative service delivery, quantify the associated baseline shortfalls and assess restoration timing across the available thresholds. The completed analysis shows that payment preserves more cumulative throughput through day 7, while onsite backup recovery records greater throughput through day 14. Payment reaches the lower restoration threshold sooner, both packages reach the intermediate threshold on the same day, and onsite backups reach the highest threshold sooner. These findings support a precise contribution: recovery rankings depend on the operational outcome and evaluation point. For hospital decision makers, the transferable insight is to evaluate response plans through both cumulative service preservation and time to successive performance targets. The numerical ranking remains specific to the modeled setting, while the distinction between reopening, restoration and accumulated service loss informs recovery assessment across healthcare systems.

2. Theory Conceptual Framework and Research Questions Development:

This analysis draws on resilience engineering to examine hospital service continuity during ransomware recovery. Hospitals coordinate emergency admissions, diagnostic services, treatment and discharge through shared information systems. Disruption to one function can constrain patient movement across the hospital, making recovery a problem of restoring coordinated services. Woods, 2015, distinguishes recovery after disruption from robustness and sustained adaptability. We apply the recovery perspective to compare how alternative response strategies restore patient throughput over time. The theoretical expectation is that an earlier restart and a faster return to routine performance may favor different recovery strategies. Hospital service continuity denotes the capacity to maintain and restore patient throughput following disruption. We measure continuity through cumulative hospital discharges relative to the corresponding baseline and the elapsed days required to reach specified discharge performance thresholds. These measures connect system restoration to service delivery. Their practical relevance is supported by Ghafur et al., 2019, whose analysis of WannaCry identified reduced admissions at infected hospitals. That evidence supports examining hospital activity as an outcome of cyber disruption, while the present analysis compares published simulation scenarios.

The focal explanatory construct is hospital ransomware recovery strategy, represented by ransom payment decision, system recovery method and emergency department closure duration. These components describe the response packages recorded in the dataset. Contingency planning provides the operational logic connecting recovery arrangements to service continuity. Swanson et al., 2010, explain that organizations should identify operational priorities and select recovery arrangements according to information system requirements. Applied to hospital recovery, this logic suggests that restoring access becomes useful when dependent clinical functions can resume coordinated activity. Ransom payment and restoration from onsite backups represent alternative routes toward recovering system access. Their implications depend on the restoration work that follows. Earlier access may shorten initial closure, whereas system rebuilding and verification may influence the subsequent return to routine performance. Bartock et al., 2016, place recovery within a coordinated process of resource prioritization, planning, testing and restoration of mission functions. This guidance supports

distinguishing the speed of initial reopening from the recovery trajectory that follows. It establishes a conceptual mechanism rather than an empirical estimate of either strategy's advantage.

The published simulation by Ghayoomi et al., 2021, operationalizes this tension through two response packages. The payment scenario assumes that decryption enables an emergency department closure of two days, followed by full system restoration. The alternative uses onsite backup restoration and assumes a closure of three days. The model represents interdependencies among emergency care, intensive care and supporting services, allowing initial closure and subsequent restoration to shape hospital throughput. Its reported results establish that strategy comparisons depend on the recovery horizon under these assumptions. We therefore compare the packages as modeled responses and interpret payment, recovery method and closure duration jointly. The conceptual framework links the recorded recovery strategy to hospital service continuity through the timing of service resumption and subsequent restoration. Strategy characteristics are recorded scenario attributes. Cumulative discharge ratios and restoration milestones are calculated or extracted performance measures. We compare cumulative throughput at days 7 and 14 to assess continuity over different horizons. We also compare the first day each strategy reaches 50, 80 and 90 percent of baseline daily discharge performance. The resulting questions are descriptive and exploratory because they organize a secondary analysis of published simulation summaries.

Research question 1: How does cumulative hospital patient throughput, expressed as discharge counts and percentages of the corresponding baseline, differ between the two recovery strategies at days 7 and 14?
Research question 2: How many days does each recovery strategy require to reach 50, 80 and 90 percent of baseline daily hospital discharge performance?

3. Data:

This analysis uses published hospital simulation summaries to compare ransomware recovery strategies through patient throughput and service restoration times. We document source provenance, sample construction, measurement and reproducible calculations for the descriptive comparisons.

3.1 Data Sources, Population, and Sample Construction:

The numerical evidence comes from Assessing resilience of hospitals to cyber attack by Ghayoomi et al., 2021. Tables 5 and 6 provide restoration milestones and cumulative hospital discharge outcomes. The accompanying description of Figure 2 supplies emergency department closure assumptions. The article is accessible through the publisher and PubMed Central under identifier PMC8638073. The publisher identifies its licence as Creative Commons Attribution Non Commercial No Derivatives 4.0. The supplied workbook records the extraction timestamp and preserves source locations for each numerical record.

The empirical setting is a simulated urban tertiary hospital in the United States. The accessible frame comprises published summaries for two ransomware recovery strategies applied to one hospital model. The target setting is hospital service recovery following ransomware disruption, but the dataset does not constitute a probability sample of hospitals. Selection follows the workbook's focus on hospital discharge performance, retaining the payment and onsite backup recovery scenarios at the available reporting horizons and restoration thresholds. The analytical structure consists of scenario summaries rather than a calendar panel. Four records describe cumulative hospital discharges through days 7 and 14. Six records describe the first day each strategy reaches 50, 80 and 90 percent of baseline daily discharge performance. Cumulative discharges are flows accumulated from attack onset. Discharges recorded at restoration milestones are daily flows. Neither measure represents a patient stock.

Table 1: Sample construction

Stage	Represented Units	Records	Inclusion Rule
Accessible source frame	One hospital model and two recovery strategies	10 relevant summaries	Published hospital discharge entries at the selected horizons and thresholds
Throughput selection	Two strategies at two horizons	4	Cumulative hospital discharges through days 7 and 14
Restoration selection	Two strategies at three thresholds	6	First attainment of 50, 80 and 90 percent of baseline daily discharge performance
Quality review	Same model and strategies	10 retained	No missing required numerical values or duplicate record identifiers
Final throughput comparison	Two strategies	4	Separate comparison within each reporting horizon
Final restoration comparison	Two strategies	6	Separate comparison within each performance threshold

The ten records describe repeated summaries of the same modeled hospital. They do not represent ten hospitals or ten independent experiments. Baseline discharge counts serve as comparison denominators and

remain attached to the relevant records. Selection involves no external dataset merge. All selected records remain in the descriptive analysis.

3.2 Data Integration, Cleaning, and Quality Assurance:

The workbook separates cumulative throughput from restoration milestones because the two tables use different temporal definitions. Throughput records are identified by strategy and reporting horizon. Restoration records are identified by strategy and target performance threshold. Strategy labels consistently distinguish payment followed by decryption and full restoration from recovery using onsite backups. Payment status, recovery method and closure duration remain linked to their source scenario. The quality review identified four unique throughput identifiers and six unique restoration identifiers. Required numerical fields contain no missing values, and stored formula results contain no spreadsheet errors. Repeated payment codes and closure durations are genuine scenario attributes. They are retained because each strategy appears at multiple horizons or thresholds.

We checked that baseline denominators are positive, continuity ratios reproduce the published discharge counts, and discharge shortfalls equal baseline discharges less scenario discharges. We also verified that each recorded milestone discharge count reaches or exceeds its stated fraction of baseline daily discharges. These checks establish internal arithmetic consistency without converting the summaries into independent observations. Published percentages and calculated ratios remain separate. The source reports rounded continuity percentages, whereas the workbook calculates ratios from the reported patient counts. Differences between these representations reflect rounding and are preserved. Calculated measures use the count-based ratios consistently across strategies. The retained values require no imputation, interpolation, replacement with zero, outlier removal or frequency conversion. Time is measured in elapsed days after a hypothetical attack, so calendar alignment and fiscal year adjustments do not apply. The distinction between source inputs, published outputs and subsequent calculations supports a traceable computational record, consistent with the reproducibility principles described by Sandve et al., 2013.

3.3 Variable Measurement, Construction, and Validation:

Hospital ransomware recovery strategy is represented by three recorded attributes: payment decision, system recovery method and emergency department closure duration. These attributes form two bundled response packages. Payment status is coded one for the payment scenario and zero for the onsite backup scenario. Closure duration is a model input of two or three days, respectively. Hospital service continuity is measured through cumulative discharges relative to baseline and elapsed time to specified daily discharge performance thresholds. The framework treats these as observed simulation outputs and calculated performance measures. Woods, 2015, distinguishes recovery from broader forms of resilience, supporting the interpretation of these indicators as recovery performance rather than a comprehensive measure of organizational resilience.

Table 2: Variable dictionary

Variable or Indicator	Analytical Role	Definition and Construction	Source and Identifier	Unit and Frequency	Transformation and Direction	Missing Value Rule	Coverage and Limitation
Recovery strategy	Comparison category	Payment and restoration, or onsite backup restoration	Source scenario descriptions	Category per scenario	Retained as a category	Complete	Two bundled strategies
Payment decision	Strategy attribute	One for payment and zero for no payment	Source scenario descriptions	Binary per scenario	One identifies payment	Complete	Changes jointly with other attributes
Recovery method	Strategy attribute	Decryption followed by restoration, or onsite backup restoration	Source methods	Category per scenario	No numerical ranking	Complete	Two scenario specific methods
Emergency department closure	Strategy attribute	Assumed period without emergency department entry	Figure 2 description	Days per scenario	Higher values indicate longer closure	Complete	Model assumption
Reporting horizon	Comparison index	Elapsed time over which discharges accumulate	Table 6	Days 7 and 14	No transformation	Complete	Two cumulative horizons
Hospital discharges	Outcome	Published cumulative discharges under each strategy	Table 6	Patients through each horizon	Higher values indicate greater throughput	Complete	Four aggregate records
Baseline discharges	Benchmark	Corresponding cumulative discharges without an attack	Table 6	Patients through each horizon	Denominator for continuity	Complete	Shared within each horizon
Continuity percentage	Calculated outcome	Scenario discharges divided by baseline discharges, multiplied by 100	Table 6 and workbook formulas	Percent per horizon	Higher values indicate greater continuity	Complete	Calculated from rounded source counts
Discharge shortfall	Calculated outcome	Baseline discharges less scenario discharges	Table 6 and workbook	Patients through each	Higher values indicate greater	Complete	Depends on the reporting

Variable or Indicator	Analytical Role	Definition and Construction	Source and Identifier	Unit and Frequency	Transformation and Direction	Missing Value Rule	Coverage and Limitation
			formulas	horizon	service loss		horizon
Performance threshold	Comparison index	Target fraction of baseline daily discharge performance	Table 5	Fractions 0.50, 0.80 and 0.90	Higher values specify a stricter target	Complete	Three published thresholds
Restoration time	Outcome	First reported day reaching the target performance level	Table 5	Days per threshold	Lower values indicate earlier restoration	Complete	Six aggregate records
Milestone daily discharges	Supporting outcome	Daily discharges when a threshold is first reached	Table 5	Patients per day	Higher values indicate greater daily throughput	Complete	Discrete attainment can exceed the target
Baseline daily discharges	Benchmark	Published routine hospital discharge performance	Table 5	191 patients per day	Common threshold benchmark	Complete	One modeled hospital

Equation 1 defines the implemented continuity calculation.

$$C_{s,t} = 100\frac{D_{s,t}}{B_t}$$

Here, $C_{s,t}$ is continuity expressed as a percentage for strategy s through elapsed day t. $D_{s,t}$ is cumulative scenario discharges, and $B_t$is cumulative baseline discharges through the same day. Matching numerator and denominator horizons prevent comparisons between different exposure periods. Performance relative to a service benchmark follows the recovery measurement logic developed by Chen and Miller Hooks, 2012. Table 3 reports descriptive statistics calculated from the retained summaries. Standard deviations use the sample convention. These statistics describe the extracted records rather than variation across hospitals.

Table 3: Descriptive statistics

Measure	Valid Records	Mean	SD	Median	Minimum	Maximum
Cumulative hospital discharges	4	1152.50	611.79	1171.00	573.00	1695.00
Calculated continuity percentage	4	54.66	9.90	56.30	42.73	63.32
Cumulative discharge shortfall	4	856.50	166.77	875.00	666.00	1010.00
Restoration time in days	6	9.33	4.76	11.00	3.00	15.00
Milestone daily discharges	6	147.67	31.28	154.00	108.00	180.00

Pooled throughput statistics combine different reporting horizons, while pooled restoration statistics combine different target thresholds. Accordingly, substantive comparisons retain the horizon or threshold as the comparison condition. Measurement validation consists of source traceability, denominator checks and arithmetic reconciliation.

3.4 Analytical Framework, Identification, and Reproducibility:

The analysis is descriptive and compares published recovery packages within a common simulated hospital setting. The quantities of interest are strategy differences in cumulative discharges, continuity percentages and days to target performance. Throughput comparisons use identical reporting horizons and baseline denominators. Restoration comparisons use identical target thresholds. For each horizon, the workbook subtracts payment scenario discharges from onsite backup scenario discharges. Positive values indicate greater cumulative throughput under onsite backup recovery. Differences between continuity percentages are interpreted as percentage point differences. For each restoration threshold, the workbook subtracts payment scenario restoration time from onsite backup restoration time. Negative values indicate earlier attainment under onsite backup recovery.

The source reports averages across repeated simulation run, while the supplied dataset contains published aggregate summaries. The comparison therefore describes outcomes conditional on the source model and its response assumptions. Payment, restoration method and closure duration vary together, preventing attribution of the package difference to one component. Simulation interpretation must remain tied to the specified data generation process and performance measures, as emphasized by Morris et al., 2019. The implemented consistency assessment compares source reported percentages with ratios recalculated from patient counts. It also evaluates strategy performance at both available horizons and all three restoration thresholds. These comparisons reveal how interpretation depends on the evaluation point while retaining the same source scenarios. The workbook preserves extracted values, record identifiers, source locations, variable definitions and editable calculation formulas. This structure allows the descriptive results to be reconstructed from the published summaries. The analytical contribution is a transparent comparison of recovery performance across horizons and thresholds. Its interpretation remains specific to the represented simulation setting.

4. Methods:

4.1 Research Design and Comparative Framework:

This analysis uses a descriptive secondary analysis of published hospital simulation summaries to compare two ransomware recovery packages. The comparison addresses cumulative service delivery through elapsed days 7 and 14 and the time required to reach specified daily discharge performance thresholds. The source simulation represents one urban tertiary hospital and reports results averaged across 250 simulation runs per scenario. We analyze its published summaries without conducting additional simulations. The payment package assumes decryption followed by system restoration and an emergency department closure of two days. The onsite backup package assumes restoration without payment and a closure of three days. These assumptions define the response packages described by Ghayoomi et al., 2021. Payment decision, restoration method and closure duration change jointly across scenarios. The analytical contrast therefore concerns the complete packages under the source assumptions. The unit of analysis is a strategy and reporting horizon combination for cumulative throughput, or a strategy and performance threshold combination for restoration timing. Useful variation comes from comparing the two packages at identical horizons and thresholds. A common hospital configuration and matching baseline provide consistent comparison conditions. The design answers how the published packages differ within that setting. Interpretation remains conditional on the modeled hospital, recovery assumptions and selected outcomes, consistent with the simulation reporting principles described by Morris et al., 2019.

4.2 Measurement and Comparison Specifications:

The sample construction table and variable dictionary define the retained records, measurement units and source locations. Four records provide cumulative hospital discharge outcomes, and six provide restoration milestones. All records enter their corresponding descriptive comparisons. Continuity is calculated using Equation 1 as cumulative scenario discharges divided by cumulative baseline discharges through the same horizon, multiplied by 100. Matching the numerator and denominator prevents differences in elapsed time from entering the comparison. Baseline discharge counts are benchmarks for the modeled hospital, rather than additional hospital observations. This service benchmark approach is consistent with the recovery capability measurement developed by Chen and Miller Hooks, 2012. Equation 2 defines the cumulative discharge contrast.

$$\Delta D_t = D_{B,t} - D_{P,t}$$

Here, ΔD_t is the difference in cumulative hospital discharges through elapsed day t,$D_{B,t}$ is cumulative discharges under onsite backup recovery, and $D_{P,t}$is cumulative discharges under payment and restoration. Positive values favor onsite backup recovery. The index ttakes the values 7 and 14. Equation 3 defines the continuity contrast.

$$\Delta C_t = C_{B,t} - C_{P,t}$$

Here, ΔC_t is the continuity difference in percentage points at horizon twhile $C_{B,t}$and $C_{P,t}$are the corresponding continuity percentages calculated using Equation 1. Percentage point differences describe the distance between the two percentages, not their relative percentage change. Equation 4 defines accumulated service loss.

$$L_{s,t} = B_t - D_{s,t}$$

Here, $L_{s,t}$ is the cumulative discharge shortfall for strategy sthrough day $t, B_t$is the corresponding baseline discharge count, and $D_{s,t}$is the scenario discharge count. The strategy index sidentifies payment or onsite backup recovery. Larger shortfalls indicate more benchmark activity undelivered during the reporting period. Equation 5 defines the restoration timing contrast.

$$\Delta T_q = T_{B,q} - T_{P,q}$$

Here, ΔT_q is the difference in elapsed days to performance threshold $q, T_{B,q}$is the published first attainment day under onsite backup recovery, and $T_{P,q}$is the corresponding day under payment and restoration. The threshold q takes the values 0.50, 0.80 and 0.90 of baseline daily discharge performance. Negative differences indicate earlier attainment under onsite backup recovery. An exploratory interval decomposition subtracts cumulative discharges through day 7 from cumulative discharges through day 14. Applying the same subtraction to baseline counts produces a matching benchmark for days 8 through 14. The resulting comparison identifies how activity delivered during that interval contributes to the cumulative strategy difference.

4.3 Analytical Procedures and Consistency Assessment:

Processing begins with the extracted values in the Patient throughput and Restoration milestones worksheets. Strategy labels identify the response package, while reporting horizons and performance thresholds identify the comparison conditions. Throughput and milestone records remain separate because cumulative discharges and daily performance attainment have different temporal meanings. The analysis first checks record identifiers and required numerical fields. It then verifies positive baseline denominators, recalculates continuity using Equation 1 and calculates discharge shortfalls using Equation 4. Equations 2 and 3 compare throughput and continuity within each horizon. Equation 5 compares restoration timing within each threshold. The interval decomposition follows these primary comparisons and is identified as exploratory. Published whole percentage

values remain separate from percentages recalculated using discharge counts. The consistency assessment compares the direction and magnitude of strategy differences under both representations. This check evaluates sensitivity to reporting precision while preserving the source values.

Restoration checks compare daily discharges at each milestone with the stated fraction of baseline daily discharges. Attainment requires the recorded discharge count to equal or exceed the target. Because the source reports daily milestones, the attained count can exceed the threshold. We retain the published attainment day without interpolating between days. Descriptive statistics comprise valid counts, arithmetic means, sample standard deviations, medians, minima and maxima. These summarize the retained records and do not describe a population distribution of hospitals. Interpretation prioritizes comparisons within matching horizons and thresholds because pooled summaries combine different observation conditions. The selected numerical records are complete. All remain in the analysis without imputation, interpolation or outlier removal. Spreadsheet formulas implement continuity ratios, discharge shortfalls and strategy contrasts. Additional arithmetic calculations reproduce the descriptive summaries and exploratory interval decomposition.

4.4 Interpretation and Reproducibility:

The reported quantities are descriptive contrasts between published simulation summaries. Their substantive interpretation follows the direction and magnitude specified in Equations 2 through 5. Cumulative throughput, accumulated shortfall and restoration timing remain distinct outcomes because improvement in one does not necessarily imply improvement in another. The repeated summaries share the same modeled hospital and response scenarios. Their dependence prevents interpretation as independent hospital observations. The analysis therefore reports computed differences without attaching newly estimated sampling uncertainty. Its evidential scope is the comparison of the represented packages at the available evaluation points.

Replication materials consist of the consolidated workbook, source identifiers, extraction locations, variable definitions and editable comparison formulas. Source Table 6 supplies cumulative hospital discharges and reported continuity percentages. Source Table 5 supplies restoration milestones and baseline daily discharge performance. The description accompanying source Figure 2 supplies closure assumptions. This separation allows a reader to trace each calculation to its numerical inputs. Maintaining that connection between source evidence and analytical outputs follows the reproducibility principles described by Sandve et al., 2013. The methodological contribution is a transparent application of established descriptive comparisons. Matching horizons, denominators and thresholds aligns the calculations with the research questions. Separating cumulative service delivery from restoration timing allows the analysis to identify when the preferred response changes with the evaluation criterion, while retaining the assumptions that define the comparison.

5. Findings:

This analysis compares hospital service continuity under payment followed by system restoration and recovery using onsite backups. We examine cumulative patient throughput at days 7 and 14, followed by the time required to reach specified daily discharge thresholds. The findings answer the two research questions through descriptive comparisons of published simulation summaries. The analytical sample contains four throughput records and six restoration milestone records from one simulated hospital. Both recovery strategies have complete observations at the selected horizons and thresholds. These records describe repeated summaries of the same modeled setting rather than independent hospitals. Payment decision, recovery method and emergency department closure duration define bundled response packages. Consequently, the comparisons concern package performance under the source assumptions. The underlying simulation was published by Ghayoomi et al., 2021. Cumulative throughput shows a reversal in strategy ranking between the two reporting horizons. Through day 7, the payment scenario records 675 hospital discharges, compared with 573 under onsite backup recovery. Against the common baseline of 1,341 discharges, these counts represent continuity of 50.34 percent and 42.73 percent, respectively. Payment therefore has an initial advantage of 102 discharges and 7.61 percentage points of baseline throughput. By day 14, onsite backup recovery records 1,695 discharges, exceeding the payment scenario’s 1,667 discharges. Relative to the baseline of 2,677 discharges, continuity reaches 63.32 percent under onsite backup recovery and 62.27 percent under payment. The later advantage therefore favors onsite backups by 28 discharges and 1.05 percentage points.

Table 4: Cumulative hospital throughput and continuity by recovery strategy

Reporting Horizon	Recovery Strategy	Hospital Discharges	Baseline Discharges	Continuity Percent	Discharge Shortfall
Day 7	Payment and restoration	675	1341	50.34	666
Day 7	Onsite backup recovery	573	1341	42.73	768
Day 14	Payment and restoration	1667	2677	62.27	1010
Day 14	Onsite backup	1695	2677	63.32	982

Reporting Horizon	Recovery Strategy	Hospital Discharges	Baseline Discharges	Continuity Percent	Discharge Shortfall
	recovery				

The baseline comparison distinguishes improved continuity from accumulated service loss. Although both strategies achieve higher continuity percentages at day 14, their cumulative discharge shortfalls increase. Payment rises from a shortfall of 666 to 1,010 discharges, while onsite backup recovery rises from 768 to 982. Thus, a higher cumulative continuity ratio does not imply that previously lost throughput has been recovered. The ratio measures the share of benchmark activity delivered through each horizon. This interpretation follows the distinction between achieved service performance and benchmark recovery capacity developed by Chen and Miller Hooks, 2012. An exploratory decomposition clarifies the reversal. Subtracting day 7 cumulative discharges from day 14 cumulative discharges yield 992 additional discharges under payment and 1,122 under onsite backup recovery during days 8 through 14. The corresponding baseline increment is 1,336 discharges. During this interval, payment delivers 74.25 percent of baseline activity, compared with 83.98 percent under onsite backups. The backup package therefore records 130 additional discharges during the second interval, offsetting its initial deficit of 102 and producing the cumulative advantage of 28 at day 14. This calculation describes interval performance derived from the published totals.

Restoration milestones reveal a related change in ranking across performance targets. Payment reaches 50 percent of baseline daily discharge performance on day 3, one day earlier than onsite backup recovery. Both strategies first reach 80 percent on day 11. Onsite backup recovery then reaches 90 percent on day 12, compared with day 15 under payment. The backup package therefore reaches the highest reported threshold three days earlier, equivalent to 20 percent fewer elapsed days relative to the payment scenario.

Table 5: Time to baseline daily discharge performance thresholds

Target Performance	Payment Restoration Day	Onsite Backup Restoration Day	Timing Comparison	Payment Daily Discharges	Onsite Backup Daily Discharges
50 percent	3	4	Payment earlier by 1 day	112	108
80 percent	11	11	Same reported day	154	154
90 percent	15	12	Onsite backups earlier by 3 days	178	180

The milestone evidence separates early service resumption from restoration toward routine performance. The payment package reaches the lower threshold sooner, but this advantage disappears at 80 percent and reverses at 90 percent. Neither package dominates across every evaluation point. The findings are consistent with a recovery perspective in which performance depends on the trajectory and evaluation horizon, rather than the first reopening milestone alone. Woods, 2015, identifies recovery after disruption as a distinct dimension of resilience. The results remain descriptive comparisons of aggregate simulation outputs. The extracted records contain no variation across independent hospitals from which to estimate population effects. Differences of 102 discharges, 28 discharges and three restoration days express modeled practical magnitudes. Their interpretation remains conditional on the hospital configuration and bundled recovery assumptions. Morris et al., 2019, emphasize that simulation findings must be interpreted against their data generation process and reported performance measures.

The consistency assessment preserves the substantive ranking when continuity is expressed through either source reported percentages or ratios recalculated from discharge counts. Source percentages show an initial payment advantage of 7 percentage points and a later backup advantage of 1 percentage point. Recalculated differences are 7.61 and 1.05 percentage points. Rounding changes the displayed magnitude but preserves the direction of both comparisons. The first research question is resolved by the horizon dependent ranking: payment delivers greater cumulative throughput through day 7, while onsite backup recovery delivers greater throughput through day 14. The second is resolved by the restoration milestones: payment reaches 50 percent sooner, both packages reach 80 percent on the same day, and onsite backups reach 90 percent sooner. Hospital activity is a relevant operational outcome beyond this modeled setting, as Ghafur et al., 2019, documented reduced admissions at hospitals affected by WannaCry. The present findings establish the comparison within the represented simulation and support evaluating recovery through both cumulative service delivery and time to performance targets.

6. Discussion:

A faster restart does not necessarily deliver greater service continuity across the recovery period. Table 4 shows that the payment package's initial throughput advantage reverses by the later reporting horizon, while Table 5 shows that earlier attainment of the lower performance threshold does not extend to the highest threshold. Equation 1 makes this distinction explicit by evaluating delivered activity against a matching

baseline. The analytical contribution is the joint interpretation of cumulative throughput, accumulated service loss and restoration milestones. The temporal reversal was already present in the simulation reported by Ghayoomi et al., 2021. This analysis clarifies its decision significance: recovery strategy rankings depend on both the evaluation horizon and the performance criterion. Consequently, a strategy described as faster requires a specified operational target. The response packages expose a tension between initial access restoration and subsequent service recovery. The payment scenario combines a shorter emergency department closure with decryption and further restoration, whereas the backup scenario combines a longer closure with onsite recovery. Table 5 indicates that the initial timing advantage disappears at the intermediate threshold and reverses as performance approaches baseline. These results are consistent with different recovery trajectories, but the bundled scenario attributes do not identify separate transmission effects. Their practical meaning is that reopening and restoration should be evaluated as connected operational stages. Bartock et al., 2016, frame cyber security recovery around prioritized resources and continuity of mission functions. The present comparison gives that distinction an observable service interpretation through elapsed restoration days and patient throughput.

The interval decomposition explains how the ranking reverses without implying that either package dominates throughout recovery. Onsite backup recovery delivers 130 more discharges during the second interval, offsetting its initial deficit of 102 and producing the later cumulative advantage shown in Table 4. The theoretical signal concerns the balance between early service loss and subsequent recovery performance. Equation 1 captures cumulative continuity, while Table 5 identifies when specified daily performance levels become attainable. Together, these measures show why a single restoration milestone cannot represent the complete recovery trajectory. Chen and Miller Hooks, 2012, connect resilience measurement to service performance and recovery capability. This analysis extends that measurement logic within the hospital comparison by showing how cumulative and milestone indicators can favor different response packages at different evaluation points. An operational constraint becomes visible when improving continuity percentages coexist with increasing cumulative discharge shortfalls. Table 4 shows that both packages deliver a larger share of benchmark activity over the longer horizon, yet neither eliminates the service deficit accumulated since attack onset. Recovery therefore has two distinct performance dimensions: restoring the rate of service delivery and limiting total activity lost during disruption. Table 5 captures progress toward routine daily performance, but reaching a threshold does not establish that earlier throughput losses have been recovered. Woods, 2015, distinguishes recovery after disruption from broader resilience capabilities. The findings sharpen this distinction by demonstrating that apparent recovery progress can coexist with a continuing cumulative service burden. Decision makers therefore need both measures when assessing operational restoration.

The international relevance lies in evaluating cyber recovery through delivered hospital services rather than technical availability alone. Ghafur et al., 2019, documented reduced admissions at hospitals affected by WannaCry, establishing that cyber disruption can alter clinical activity in an operational healthcare system. Their observational evidence and the present simulated comparison address different questions: the former measures disruption in practice, while this analysis compares recovery packages under specified assumptions. Tables 4 and 5 support a transferable assessment approach, comprising cumulative throughput, baseline shortfall and time to successive performance thresholds. They do not establish a universal preference between payment and backup recovery. The evidence supports evaluating response plans against multiple service objectives and retaining the common baseline in Equation 1. This changes the decision criterion from selecting the earliest reopening to assessing how much service each response preserves throughout recovery.

7. Conclusion and Implications:

Hospitals can reopen sooner while preserving less care over the full recovery period. This analysis shows that the preferred response depends on when performance is evaluated and which service objective guides the comparison. Earlier resumption favors one recovery package, while subsequent restoration favors the alternative. The contribution is a structured interpretation of published simulation evidence that distinguishes reopening speed, cumulative service preservation and progress toward routine performance. This distinction refines recovery assessment by showing that improving operating performance can coexist with an expanding service deficit. Recovery therefore requires evaluation across complementary outcomes rather than a single completion milestone. Hospital leaders should compare response plans using common service benchmarks, successive restoration targets and accumulated activity losses. Such comparisons can improve alignment between technical restoration priorities and clinical operating objectives. Preparedness exercises should track both the pace of renewed service delivery and the care deficit accumulated during disruption. For policymakers, the evidence supports recovery reporting that connects digital restoration to hospital activity. Its international relevance lies in this assessment approach, while the ranking of individual response packages remains conditional on the modeled setting. Keeping delivered care central to recovery decisions provides a practical basis for evaluating how response plans serve patients throughout disruption.

The evidence comprises aggregate summaries from one simulated hospital, creating opportunities for validation across observed incidents and different hospital configurations. Future research should obtain detailed

recovery trajectories and independently vary initial closure, restoration procedures and access recovery assumptions. These extensions would help distinguish component contributions from bundled response performance. Comparisons across healthcare systems could assess how staffing, diagnostic dependencies and emergency demand alter recovery rankings. Linking operational trajectories to delayed treatment and patient outcomes would extend the service perspective. Reporting uncertainty across repeated simulations and observed cases would strengthen the basis for transferring recovery assessment across institutional and technological settings.

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