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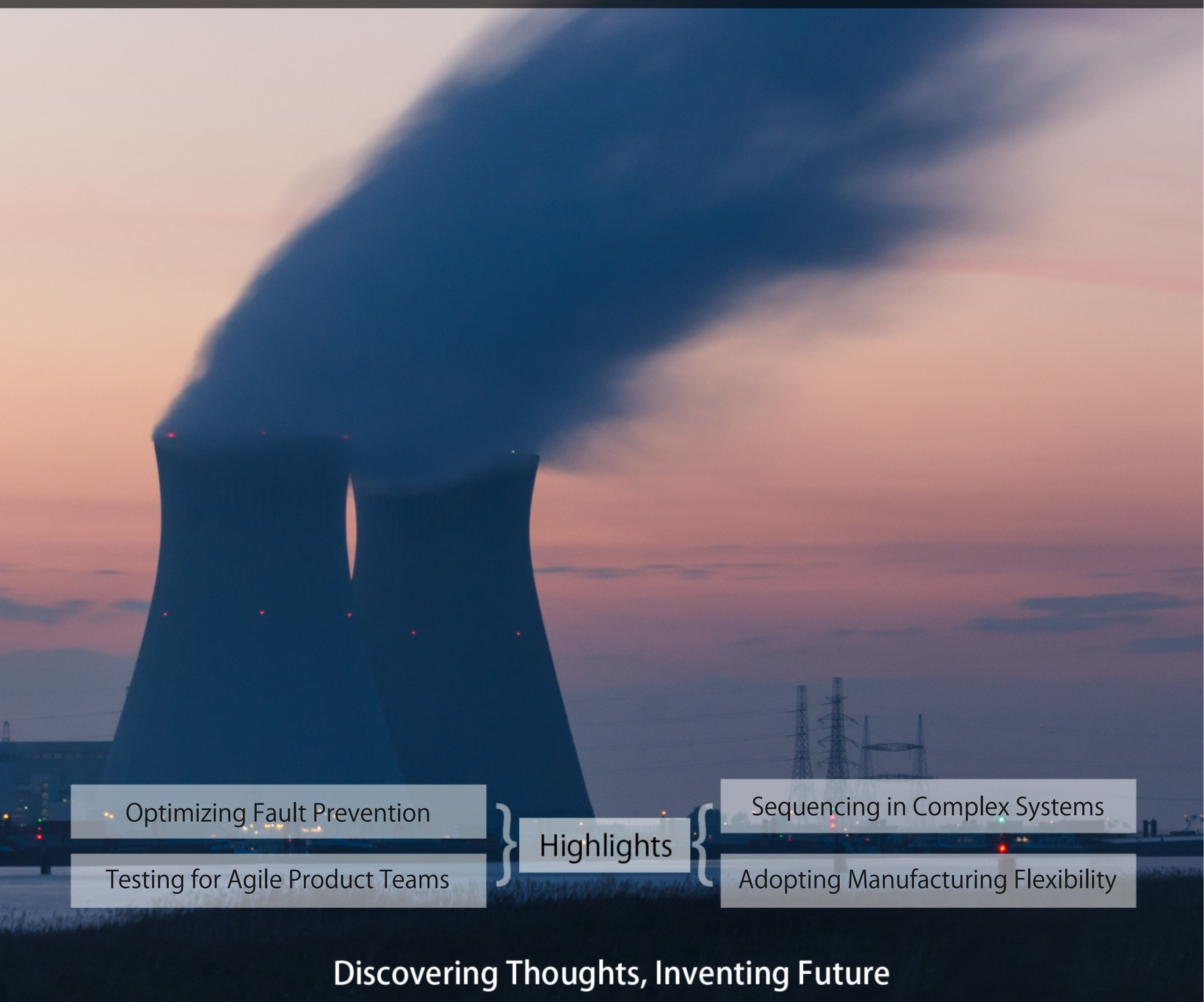

Optimizing Fault Prevention

Testing for Agile Product Teams

Highlights

Sequencing in Complex Systems

Adopting Manufacturing Flexibility

Discovering Thoughts, Inventing Future

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Optimizing Fault Prevention and Repair Sequencing in Complex Systems

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Abstract- Fault prevention and repair (FPR) sequencing plays a critical role in enhancing the resilience of complex infrastructure systems. This study develops four FPR sequencers—a centralized model (*FPR-C*) and three decentralized models (*FPR-DD*, *FPR-DP*, and *FPR-DR*)—to address random failures, cascading failures, and cascading failures with backup capacity. *FPR-DD* minimizes total damage, *FPR-DP* maximizes preventability, and *FPR-DR* repairs faults in random order. The sequencers are implemented in a simulation framework and evaluated on the Western United States power grid through 10,500 experiments. Results show that *FPR-DD* and *FPR-DP* consistently outperform other strategies, with optimal repair resource thresholds varying by failure type. These findings offer actionable guidelines for resource allocation and fault management to improve the resilience of complex engineered networks.

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Keywords: fault prevention, repair sequencing, cascading failures, complex systems, resilience, simulation experiments, resource allocation, power grid, fault management, infrastructure reliability.

Nomenclatures:

γ - Exponent of a power law function

δ^{IN} and δ_j^{IN} - IN degree of a node

δ^{OUT} and δ_j^{OUT} - OUT degree of a node

c_j - Time at which a node v_j is repaired or prevented

d - Degree of a node

d_l - Damage caused by a leaf node v_l over one time unit

$\overline{d}$ - Mean degree of nodes in a network

$\overline{d_l}$ - Mean damage caused by multiple leaf nodes v_l's over one time unit

i and i' - Index of internal nodes

j and j' - Index of nodes

l and l' - Index of leaf nodes

m_r - Repair time for a root node v_r

n - The total number of nodes in a network

n_l - The number of root nodes connected to a leaf node v_l

n_r - The number of leaf nodes connected to a root node v_r

p - The probability that a pair of nodes are connected

r and r' - Index of root nodes

t - Time

t_0 - Time at which the FPR sequence begins

t_c - Current time

t_i, $t_{i'}$, t_j, $t_{j'}$, t_l, $t_{l'}$, t_r, and $t_{r'}$ - Time at which a node becomes faulty

v_i and $v_{i'}$ - Internal node in $G(V^F, A^F)$

v_j and $v_{j'}$ - Node in $G(V^F, A^F)$

v_l and $v_{l'}$ - Leaf node in $G(V^F, A^F)$

v_r and $v_{r'}$ - Root node in $G(V^F, A^F)$

A - Set of arcs in $G(V, A)$

A^F - Set of arcs in $G(V^F, A^F)$

D - Total damage

FPR - Fault Prevention and Repair

FPR-C - Centralized FPR sequencer

FPR-DD - Decentralized FPR sequencer minimizing total damage

FPR-DP - Decentralized FPR sequencer minimizing preventability

FPR-DR - Decentralized FPR sequencer randomly selecting faults for simultaneous repairs

$G(V, A)$ - Directed network of faulty nodes

$G(V^F, A^F)$ - Directed fault network including pseudo nodes

$G(W, Ł)$ - Network (graph) that represents a complex system

I - Set of internal nodes

L - Set of leaf nodes

$Ł$ - Set of links in $G(W, Ł)$

MRT - Maximum Required Total Repair Resources

R - Set of root nodes

V - Set of nodes in $G(V, A)$

V^F - Set of nodes in $G(V^F, A^F)$

W - Set of nodes in $G(W, Ł)$

I. Introduction

Faults are ubiquitous in complex systems. This article designs efficient fault prevention and repair (FPR) sequencers to prevent faults from occurring and minimize their damage. An FPR sequencer determines the sequence of fault repairs. The cost of

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faults includes repair costs and damage caused by faults. The repair cost may be assumed to be the same regardless of the sequence of repairs. The damage caused by a fault depends on the time for which the fault exists, which is affected by the FPR sequencer. A fault causes less damage if it is repaired early. A complex system has multiple faults, and there may be a crippling or cascading effect when a few faults occur. Efficient FPR sequencers help reduce damage caused by faults and prevent catastrophic events from occurring. The rest of this article is organized as follows: Section 2 describes related work; Section 3 is the problem statement and formulates the multi-objective FPR model; Section 4 illustrates the methods of FPR; Section 5 presents simulation experiments to validate and identify efficient FPR sequencers; Section 6 discusses important findings; Section 7 illustrates future research directions; and Section 8 concludes the paper.

II. Related Work

Research on efficient fault repair and infrastructure recovery mainly focused on smart grids and highway systems. For example, power-flow models were developed (Ang, 2006; Salmeron *et al.*, 2004) to identify optimal or near-optimal repair sequences for electrical power grids. Fault repair is part of fault management, which uses automated fault detection and diagnostics (Chen and Nof, 2012, 2014, 2015; Nof and Chen, 2015, 2017). An example of fault management is the emergence of the smart grid, which is an electricity network that utilizes digital technology and has the self-detection and self-diagnostics ability. Many organizations (e.g., Electric Power Research Institute (EPRI)) have invested in grid operations and planning to help improve real-time situation awareness, wide area protection and control performance, and the capability to handle extreme events and restore the system (EPRI, 2012). It is a challenging task to prevent and repair faults with an optimal sequence (Ang, 2006; Jin *et al.*, 2018). The FPR problem is prevalent in many systems. Hospitals are entangled in insurance claim denials due to faults in the claim process. Insurance companies are concerned about faults in claims. For instance, FICO (FICO, 2012) developed the Insurance Fraud Manager to detect fraud, abuse, and error in healthcare claims before payment. The result is an unreasonably long delay for many justified payments. Faults in many systems are not efficiently corrected after they are detected.

A system may be described with mathematical models. For example, the "scale-free network" depicts electrical power grids (Barabasi and Albert, 1999) and the "random network" depicts transportation networks (Barabasi, 2002; Chen, 2009; Jeong, 2003). These mathematical models may be adapted to depict fault networks. Most methods developed earlier exclusively deal with the repair of a single fault (e.g., Dimitrov *et al.*, 2004; Sim and Endrenyi, 1993). Limited research (Ang, 2006; Salmeron *et al.*, 2004) focused on optimal repair sequences. Previous research (Alizadeh and Sriramula, 2017; Chen, 2009; Chen and Nof, 2012; Nageswara Rao and Viswanadham, 1987; Sanislav *et al.*, 2018) suggested tools to effectively detect, diagnose, and predict multiple faults (conflicts and errors). Several studies (e.g., Dong *et al.*, 2019; Zou *et al.*, 2021) proposed to reconstruct faults for fault diagnostics.

This article aims at modeling the fault network and designing the FPR sequencers to prevent faults and minimize the total damage. The methodology applied in this research is part of the effort to control network operations through structural search (Dawande *et al.*, 2011). Structural search is a process to search for useful subsets of nodes in a network. For example, to promote healthy behaviors in social networks (Parsa and Chen, 2013), a subset of a population, i.e., an influential set of opinion leaders and innovators, needs to be identified to maximize the speed and scale of promotion. The primary goal in structural search is to identify useful structures in networks. Moreover, the sequence of operations is of great importance. For example, which node in a terrorist network is removed first and which one is removed next have significant impact on preventing terrorist activities. In an FPR sequencer, the useful structure, i.e., a fault network, is known and comprises all faulty sources and other affected faulty nodes. The sequence of repair, however, needs to be determined. Efficient FPR sequencers designed in this research help advance our understanding of optimizing operations sequences for a useful structure.

III. Problem Statement

a) Modeling Fault Networks

Nodes in a complex system represent components of the system. Links between nodes represent the flow of products, services, or information. Directed links are arcs. Undirected links are edges (Chen and Nof, 2007, 2010, 2012). If a node j is linked to a node j' directly, there is an arc or an edge between the two nodes. When two nodes j and j' are linked indirectly, there is at least one path between j and j' through other nodesso that products, services, or information can be transmitted from j to j' and/or from j' to j. A path does not exist between two nodes if they are not linked directly or indirectly. A fault network is a network of faulty nodes in a system. An edge between two nodes j and j' indicates that a fault at j causes a fault at j' and vice versa; an arc from j to j' indicates that a fault at j causes a fault at j'. Figure 1(a) illustrates a system network with 11 nodes. Arcs in the network represent flows of product, service, or information. Figure 1(b) illustrates a fault network of seven faulty nodes in the system described in Figure 1(a).

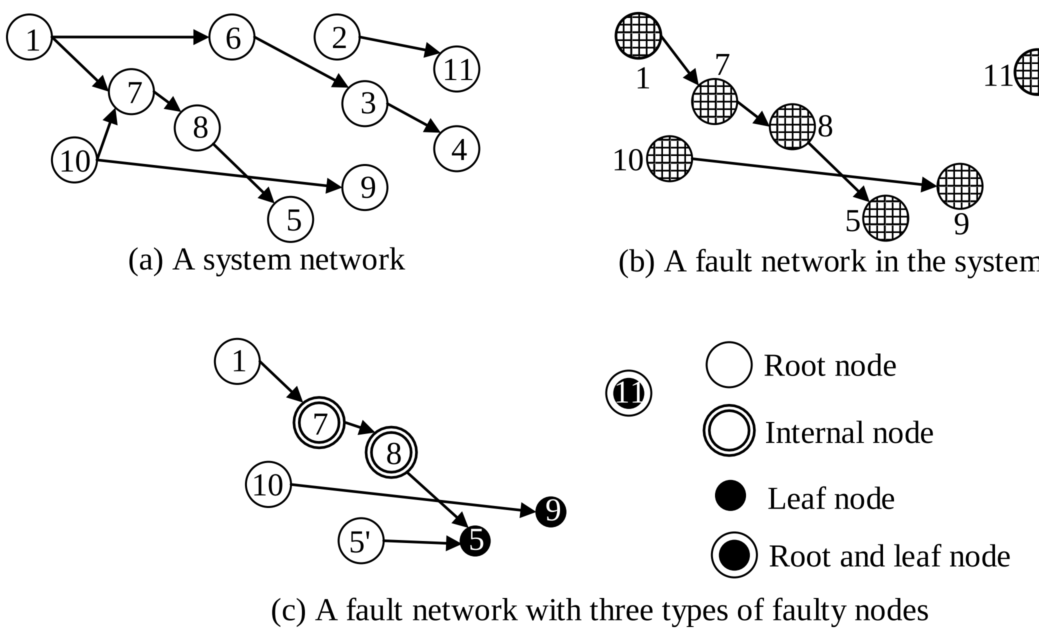

Figure 1: A system and its network of faulty nodes

The number of arcs connected to a faulty node is the degree of the node (Angeles Serrano and De Los Rios, 2007; Dorogovtsev *et al.*, 2001). The IN degree, δ^{IN}, of a faulty node is the number of arcs that point at the node. The OUT degree, δ^{OUT}, is the number of arcs that originate from the node. There are three types of faulty nodes in a network: leaf, internal, and root nodes. A faulty node j is (a) a root node if its fault is not caused by fault(s) at any other faulty node, $\delta_j^{IN} = 0$; (b) a leaf node if it does not cause fault(s) at any other faulty node, $\delta_j^{OUT} = 0$; and (c) an internal node when $\delta_j^{IN} > 0$ and $\delta_j^{OUT} > 0$. A faulty node j is both a root and a leaf node if $\delta_j^{IN} = \delta_j^{OUT} = 0$; the node is an orphan node because it is not connected to any other nodes. A root node requires repair; an internal or a leaf node is repaired or prevented (from having a failure) if and only if all its causes are repaired or prevented. Nodes 1, 10, and 11 in Figure 1(b), are root nodes and require repair; nodes 7 and 8 are internal nodes; and nodes 5, 9, and 11 are leaf nodes. The total cost of FPR includes repair costs and damage caused by faulty nodes. Repair costs are incurred for all root nodes. All faulty nodes could cause damage, which is reflected on leaf nodes.

Suppose node 5 in Figure 1(b) is caused by the faulty node 8 and is also due to a fault that occurs locally at node 5. Figure 1(b) does not show that node 5 requires repair. Repairing node 8 does not remove the fault from node 5. Figure 1(c) clarifies repair requirements by incorporating a pseudo node 5' for node 5. Node 5' is a root node and requires repair. There are four root nodes (1, 10, 11, and 5'), two internal nodes (7 and 8), and three leaf nodes (5, 9, and 11) in Figure 1(c). Node 11 is both a root and a leaf node.

Let $G(W,Ł)$ represent a complex system where W is a set of nodes (vertices) and Ł is a set of links in the system. $|W|$ is the total number of nodes in W. $|W|$ is an integer and $|W| > 0$. Since faulty nodes are usually linked through arcs, let $G(V,A)$ represent a directed network of faulty nodes in the system where V is a set of faulty nodes and A is a set of arcs. $|V|$ is the total number of faulty nodes in V. $|V|$ is an integer and $|V| \geq 0$. $V \in W$, $A \in Ł$, and $|V| \leq |W|$. Let $G(V^F, A^F)$ represent a directed fault network including pseudo nodes. $|V^F| \geq |V|$, $V^F \cap W = V$, and $A^F \cap Ł = A$. $|V^F|$ is an integer, and $|V^F| \geq 0$. There are three types of nodes v_j's, $v_j \in V^F$: root nodes v_r's, internal nodes v_i's, and leaf nodes v_l's. Let R, I, and L represent a set of root nodes v_r's, internal nodes v_i's, and leaf nodes v_l's, respectively. $|R|$, $|I|$, and $|L|$ are integers. $|R| \geq$; $|I| \geq 0$; and $|L| \geq 0$. Any FPR sequence must repair all root nodes v_r's. v_i's and v_l's are repaired or prevented if and only if v_r's are repaired. Depending on when v_r's are repaired, v_i's and v_l's may be prevented. Time zero, i.e., $t = 0$, is defined to help evaluate the FPR sequences. In practice, the time at which the first fault occurs is often defined as $t = 0$. Let t_c represent current time and t_j represent the time v_j becomes faulty; $t_c, t_j \geq 0$. Suppose $t_{10} < t_c < t_9$ in Figure 1(c). Since v_9 has not become faulty at t_c, v_9 is prevented if v_{10} is repaired before t_9. A fault at a root node cannot be prevented because it has already occurred. For any two nodes v_j and $v_{j'}$, $j \neq j'$, $(v_j, v_{j'}) \in A^F$ if v_j directly causes $v_{j'}$. This also implies that $t_j \leq t_{j'}$.

COROLLARY 1: In a directed network $G(V^F, A^F)$ of faulty nodes, $t_j \leq t_{j'}$ if $(v_j, v_{j'}) \in A^F$. All v_i's and v_l's, $v_i \in I$ and $v_l \in L$, are repaired or prevented if and only if all

v_r's, $v_r \in R$, are repaired. $R \cup I \cup L = V^F$. $|R| \leq |V^F|$, $|I| \leq |V^F|$, and $|L| \leq |V^F|$. $|R| + |I| + |L| \geq |V^F|$.

There are many network structures. A random network (Erdos and Renyi, 1959; Solomonoff and Rapoport, 1951) follows a degree distribution $\binom{n-1}{d} p^d (1-p)^{n-1-d}$, where n is the total number of nodes, d is the degree of a node or the number of links (arcs or edges) connected to the node, and p is the probability that a pair of nodes are connected. The maximum number of links in a random network is $\frac{1}{2}n(n-1)$. The mean degree $\overline{d} = (n-1)p$. The random network is homogeneous and suitable for modeling networks with approximately the same number of links for each node. The random network has other properties, e.g., a phase transition or bond percolation (Angeles Serrano and De Los Rios, 2007; Newman *et al.*, 2006). These properties are explored in applying FPR sequencers to prevent and repair faults. A scale-free network follows a power law degree distribution $d^{-\gamma}$, where γ is between 2.1 and 4. Systems with the structure of a scale-free network are resilient to random faults (Cohen *et al.*, 2000) but are vulnerable to targeted attacks (Cohen *et al.*, 2001). The network structure and its properties underlying a fault network affect the outcome of FPR sequencers and are an integral part of FPR.

b) Formulating the FPR Model

The FPR model has two objectives: (a) minimize total damage, D ($D \geq 0$), caused by faults; and (b) prevent the maximum number of faults from occurring, preventability P ($0 \leq P \leq 1$). The first objective quantifies economic consequences of faults, and the second objective reflects social impacts of faults. Damage is a financial measure whereas preventing faults improves service quality. Let c_j represent the time v_j is repaired or prevented. $c_j < t_j$ indicates v_j is prevented; $c_j > t_j$ indicates v_j is repaired. Let p_j indicate whether v_j is prevented. $p_j = 0$ if $c_j > t_j$; $p_j = 1$ if $c_j < t_j$. Since time is continuous, $c_j \neq t_j$. Preventability P is the percentage of faults that are prevented. $P = \frac{\sum_{j=1}^{|V^F|} p_j}{|V^F|}$. p_j may be expressed in a closed form: $p_j = \frac{c_j - t_j - \sqrt{(c_j - t_j)^2}}{2(c_j - t_j)}$. Let d_l represent the damage caused by v_l over one time unit; $d_l \geq 0$. The damage caused by v_l is $d_l\,(c_l - t_l)(1 - p_l)$ assuming that d_l is the same over a short period of time $c_l - t_l$. The total damage $D = \sum_l d_l (c_l - t_l)(1 - p_l)$, $\delta_l^{OUT} = 0$. The objectives of FPR are to minimize D and maximize P. The FPR problem is described as a multi-objective optimization model (Eq. (1)):

$$\min \sum_l d_l \frac{c_l - t_l + \sqrt{(c_l - t_l)^2}}{2} \qquad \text{(minimize the total damage } D\text{)}$$

$$\max \sum_{j=1}^{|V^F|} \frac{c_j - t_j - \sqrt{(c_j - t_j)^2}}{2|V^F|(c_j - t_j)} \qquad \text{(maximize the preventability } P\text{)}$$

$$\text{s.t.}\, c_j = max(c_{j'})$$

$$j = 1, \ldots, |V^F|;\ (v_{j'}, v_j) \in A^F;\ \delta_l^{OUT} = 0;\ |V^F| > 0;\ d_l \geq 0 \qquad (1)$$

$c_j = max(c_{j'})$ indicates that the time at which v_j (v_i or v_l) is repaired or prevented depends on when all its direct causes $v_{j'}$'s are repaired or prevented. For v_r's, c_r's are determined by the FPR sequencer. The decision variables in Eq. (1) are c_r's for v_r's, which are times at which root nodes are repaired. c_i's for v_i's and c_l's for v_l's are determined by c_r's. d_l's, $|V^F|$, and t_j's including t_l's are parameters. A feasible solution to Eq. (1) is an FPR sequence that repairs all v_r's. The goal is to identify efficient points, each of which achieves objective function values D and P that are together superior to what can be achieved by all other feasible solutions. Whether an FPR sequence is an efficient point depends on the parameters and topology of fault networks. Both objective functions in Eq. (1) are nonlinear and not differentiable, and the constraints are nonlinear. The model in Eq. (2) rewrites Eq. (1) and admits only linear constraints; the first two objective functions remain nonlinear and not differentiable. Heuristic FPR sequencers and simulation experiments need to be developed to identify and validate efficient sequences.

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$$\min \sum_l d_l \frac{c_l - t_l + \sqrt{(c_l - t_l)^2}}{2} \qquad \text{(minimize the total damage } D\text{)}$$

$$\max \sum_{j=1}^{|V^F|} \frac{c_j - t_j - \sqrt{(c_j - t_j)^2}}{2|V^F|(c_j - t_j)} \qquad \text{(maximize the preventability } P\text{)}$$

$$\min c_j \qquad \text{(repair completion time of } v_j\text{)}$$

$$\text{s.t.} c_j \geq c_{j'}$$

$$j = 1, \ldots, |V^F|; \ (v_{j'}, v_j) \in A^F; \ \delta_l^{OUT} = 0; \ |V^F| > 0; \ d_l \geq 0 \qquad (2)$$

IV. Methods

Efficient FPR sequencers prevent faults from occurring and minimize their damage. In many applications, fault repairs are more complex and less automated compared to detection and diagnostics. There are limited resources for FPR. As the order of a fault network increases, more resources are needed to repair faults. With unlimited resources, e.g., unlimited service personnel, all root nodes are repaired simultaneously, which minimizes D and maximizes P. When resources are limited, there is a need to design efficient FPR sequencers that minimize D and maximize P. Figure 2 shows a fault network of $|R| = 4$ root nodes v_1, v_2, v_3, and v_4, and $|L| = 4$ leaf nodes v_5, v_6, v_7, and v_8.d_5, d_6, d_7, and d_8 are damage per unit time for v_5, v_6, v_7, and v_8, respectively. There are no internal nodes in Figure 2. Let m_r represent the time it takes to repair a root node v_r; $m_r \geq 0$. m_1, m_2, m_3, and m_4 are repair times for v_1, v_2, v_3, and v_4, respectively. There are $P_{4,4} = 4! = 24$ possible FPR sequences. In general, there are $|R|$-permutations of $|R|$ FPR sequences, i.e., $|R|!$ FPR sequences, for a fault network of order $|V^F|$; $|R| \leq |V^F|$. Let t_0 represent the time at which an FPR sequence begins repairing faults. All 24 FPR sequences and their respective and are summarized in Table 1.

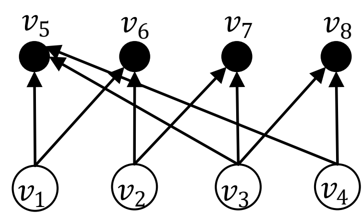

Figure 2: An example of a fault network

Table 1: FPR Sequences, Total Damage, and Preventability for the Fault Network in Figure 2

	FPR Sequence	Total Damage D	Preventability P
1	$v_1 \to v_2 \to v_3 \to v_4$	$d_5 max(m_{1,2,3,4} + t_0 - t_5, 0) + d_6 max(m_{1,2} + t_0 - t_6, 0) + d_7 max(m_{1,2,3} + t_0 - t_7, 0) + d_8 max(m_{1,2,3,4} + t_0 - t_8, 0)$	$2 - \frac{\lvert m_{1,2,3,4} + t_0 - t_5 \rvert}{2(m_{1,2,3,4} + t_0 - t_5)} - \frac{\lvert m_{1,2} + t_0 - t_6 \rvert}{2(m_{1,2} + t_0 - t_6)} - \frac{\lvert m_{1,2,3} + t_0 - t_7 \rvert}{2(m_{1,2,3} + t_0 - t_7)} - \frac{\lvert m_{1,2,3,4} + t_0 - t_8 \rvert}{2(m_{1,2,3,4} + t_0 - t_8)}$
2	$v_2 \to v_1 \to v_3 \to v_4$		
3	$v_1 \to v_3 \to v_2 \to v_4$	$d_5 max(m_{1,2,3,4} + t_0 - t_5, 0) + d_6 max(m_{1,2,3} + t_0 - t_6, 0) + d_7 max(m_{1,2,3} + t_0 - t_7, 0) + d_8\, max(m_{1,2,3,4} + t_0 - t_8, 0)$	$2 - \frac{\lvert m_{1,2,3,4} + t_0 - t_5 \rvert}{2(m_{1,2,3,4} + t_0 - t_5)} - \frac{\lvert m_{1,2,3} + t_0 - t_6 \rvert}{2(m_{1,2,3} + t_0 - t_6)} - \frac{\lvert m_{1,2,3} + t_0 - t_7 \rvert}{2(m_{1,2,3} + t_0 - t_7)} - \frac{\lvert m_{1,2,3,4} + t_0 - t_8 \rvert}{2(m_{1,2,3,4} + t_0 - t_8)}$
4	$v_3 \to v_1 \to v_2 \to v_4$		
5	$v_1 \to v_2 \to v_4 \to v_3$	$d_5 max(m_{1,2,3,4} + t_0 - t_5, 0) + d_6 max(m_{1,2} + t_0 - t_6, 0) + d_7 max(m_{1,2,3,4} + t_0 - t_7, 0) + d_8 max(m_{1,2,3,4} + t_0 - t_8, 0)$	$2 - \frac{\lvert m_{1,2,3,4} + t_0 - t_5 \rvert}{2(m_{1,2,3,4} + t_0 - t_5)} -$
6	$v_2 \to v_1 \to v_4 \to v_3$		

			$\frac{\lvert m_{1,2}+t_0-t_6\rvert}{2(m_{1,2}+t_0-t_6)} - \frac{\lvert m_{1,2,3,4}+t_0-t_7\rvert}{2(m_{1,2,3,4}+t_0-t_7)} - \frac{\lvert m_{1,2,3,4}+t_0-t_8\rvert}{2(m_{1,2,3,4}+t_0-t_8)}$
7	$v_1 \to v_3 \to v_4 \to v_2$	$d_5 max(m_{1,2,3,4}+t_0-t_5,0)+ d_6 max(m_{1,2,3,4}+t_0-t_6,0)+ d_7 max(m_{1,2,3,4}+t_0-t_7,0)+ d_8\ max(m_{1,3,4}+t_0-t_8,0)$	$2-\frac{\lvert m_{1,2,3,4}+t_0-t_5\rvert}{2(m_{1,2,3,4}+t_0-t_5)} - \frac{\lvert m_{1,2,3,4}+t_0-t_6\rvert}{2(m_{1,2,3,4}+t_0-t_6)} - \frac{\lvert m_{1,2,3,4}+t_0-t_7\rvert}{2(m_{1,2,3,4}+t_0-t_7)} - \frac{\lvert m_{1,3,4}+t_0-t_8\rvert}{2(m_{1,3,4}+t_0-t_8)}$
8	$v_1 \to v_4 \to v_3 \to v_2$		
9	$v_3 \to v_1 \to v_4 \to v_2$		
10	$v_4 \to v_1 \to v_3 \to v_2$		
11	$v_1 \to v_4 \to v_2 \to v_3$	$d_5 max(m_{1,2,3,4}+t_0-t_5,0)+ d_6 max(m_{1,2,4}+t_0-t_6,0)+ d_7 max(m_{1,2,3,4}+t_0-t_7,0)+ d_8 max(m_{1,2,3,4}+t_0-t_8,0)$	$2-\frac{\lvert m_{1,2,3,4}+t_0-t_5\rvert}{2(m_{1,2,3,4}+t_0-t_5)} - \frac{\lvert m_{1,2,4}+t_0-t_6\rvert}{2(m_{1,2,4}+t_0-t_6)} - \frac{\lvert m_{1,2,3,4}+t_0-t_7\rvert}{2(m_{1,2,3,4}+t_0-t_7)} - \frac{\lvert m_{1,2,3,4}+t_0-t_8\rvert}{2(m_{1,2,3,4}+t_0-t_8)}$
12	$v_2 \to v_4 \to v_1 \to v_3$		
13	$v_4 \to v_1 \to v_2 \to v_3$		
14	$v_4 \to v_2 \to v_1 \to v_3$		
15	$v_2 \to v_3 \to v_1 \to v_4$	$d_5 max(m_{1,2,3,4}+t_0-t_5,0)+ d_6 max(m_{1,2,3}+t_0-t_6,0)+ d_7 max(m_{2,3}+t_0-t_7,0)+ d_8 max(m_{1,2,3,4}+t_0-t_8,0)$	$2-\frac{\lvert m_{1,2,3,4}+t_0-t_5\rvert}{2(m_{1,2,3,4}+t_0-t_5)} - \frac{\lvert m_{1,2,3}+t_0-t_6\rvert}{2(m_{1,2,3}+t_0-t_6)} - \frac{\lvert m_{2,3}+t_0-t_7\rvert}{2(m_{2,3}+t_0-t_7)} - \frac{\lvert m_{1,2,3,4}+t_0-t_8\rvert}{2(m_{1,2,3,4}+t_0-t_8)}$
16	$v_3 \to v_2 \to v_1 \to v_4$		
17	$v_2 \to v_3 \to v_4 \to v_1$	$d_5 max(m_{1,2,3,4}+t_0-t_5,0)+ d_6 max(m_{1,2,3,4}+t_0-t_6,0)+ d_7 max(m_{2,3}+t_0-t_7,0)+ d_8 max(m_{2,3,4}+t_0-t_8,0)$	$2-\frac{\lvert m_{1,2,3,4}+t_0-t_5\rvert}{2(m_{1,2,3,4}+t_0-t_5)} - \frac{\lvert m_{1,2,3,4}+t_0-t_6\rvert}{2(m_{1,2,3,4}+t_0-t_6)} - \frac{\lvert m_{2,3}+t_0-t_7\rvert}{2(m_{2,3}+t_0-t_7)} - \frac{\lvert m_{2,3,4}+t_0-t_8\rvert}{2(m_{2,3,4}+t_0-t_8)}$
18	$v_3 \to v_2 \to v_4 \to v_1$		
19	$v_2 \to v_4 \to v_3 \to v_1$	$d_5 max(m_{1,2,3,4}+t_0-t_5,0)+ d_6 max(m_{1,2,3,4}+t_0-t_6,0)+ d_7 max(m_{2,3,4}+t_0-t_7,0)+ d_8 max(m_{2,3,4}+t_0-t_8,0)$	$2-\frac{\lvert m_{1,2,3,4}+t_0-t_5\rvert}{2(m_{1,2,3,4}+t_0-t_5)} - \frac{\lvert m_{1,2,3,4}+t_0-t_6\rvert}{2(m_{1,2,3,4}+t_0-t_6)} - \frac{\lvert m_{2,3,4}+t_0-t_7\rvert}{2(m_{2,3,4}+t_0-t_7)} - \frac{\lvert m_{2,3,4}+t_0-t_8,0\rvert}{2(m_{2,3,4}+t_0-t_8,0)}$
20	$v_4 \to v_2 \to v_3 \to v_1$		

21	$v_3 \rightarrow v_4 \rightarrow v_1 \rightarrow v_2$	$d_5 max(m_{1,2,3,4} + t_0 - t_5, 0) + d_6 max(m_{1,2,3,4} + t_0 - t_6, 0) + d_7 max(m_{1,2,3,4} + t_0 - t_7, 0) + d_8 max(m_{3,4} + t_0 - t_8, 0)$	$2 - \frac{\lvert m_{1,2,3,4} + t_0 - t_5 \rvert}{2(m_{1,2,3,4} + t_0 - t_5)} - \frac{\lvert m_{1,2,3,4} + t_0 - t_6 \rvert}{2(m_{1,2,3,4} + t_0 - t_6)} - \frac{\lvert m_{1,2,3,4} + t_0 - t_7 \rvert}{2(m_{1,2,3,4} + t_0 - t_7)} - \frac{\lvert m_{3,4} + t_0 - t_8 \rvert}{2(m_{3,4} + t_0 - t_8)}$
22	$v_4 \rightarrow v_3 \rightarrow v_1 \rightarrow v_2$		
23	$v_3 \rightarrow v_4 \rightarrow v_2 \rightarrow v_1$	$d_5 max(m_{1,2,3,4} + t_0 - t_5, 0) + d_6 max(m_{1,2,3,4} + t_0 - t_6, 0) + d_7 max(m_{2,3,4} + t_0 - t_7, 0) + d_8 max(m_{3,4} + t_0 - t_8, 0)$	$2 - \frac{\lvert m_{1,2,3,4} + t_0 - t_5 \rvert}{2(m_{1,2,3,4} + t_0 - t_5)} - \frac{\lvert m_{1,2,3,4} + t_0 - t_6 \rvert}{2(m_{1,2,3,4} + t_0 - t_6)} - \frac{\lvert m_{2,3,4} + t_0 - t_7 \rvert}{2(m_{2,3,4} + t_0 - t_7)} - \frac{\lvert m_{3,4} + t_0 - t_8 \rvert}{2(m_{3,4} + t_0 - t_8)}$
24	$v_4 \rightarrow v_3 \rightarrow v_2 \rightarrow v_1$		

In Table 1, multiple subscripts in m_r represent the summation of repair times. For instance, $m_{1,2,3,4} = m_1 + m_2 + m_3 + m_4$. Some FPR sequences, e.g., the FPR sequences 1 and 2, have the same D and P. Let a pair of brackets, $\langle \quad \rangle$, represent that a group of FPR sequences have the same D and P. There are 10 such groups in Table 1: $\langle 1,2 \rangle$, $\langle 3,4 \rangle$, $\langle 5,6 \rangle$, $\langle 7,8,9,10 \rangle$, $\langle 11,12,13,14 \rangle$, $\langle 15,16 \rangle$, $\langle 17,18 \rangle$, $\langle 19,20 \rangle$, $\langle 21,22 \rangle$, and $\langle 23,24 \rangle$. Table 2 shows the comparison between two groups $\langle 1,2 \rangle$ and $\langle 3,4 \rangle$. Group $\langle 3,4 \rangle$ causes more damage and has smaller preventability than $\langle 1,2 \rangle$. $\langle 1,2 \rangle$ is better than $\langle 3,4 \rangle$ in terms of both D and P, which can be expressed as $\langle 1,2 \rangle \geq \langle 3,4 \rangle$. Other comparisons among the 10 groups show that $\langle 1,2 \rangle \geq \langle 5,6 \rangle$, $\langle 1,2 \rangle \geq \langle 11,12,13,14 \rangle$, $\langle 15,16 \rangle \geq \langle 3,4 \rangle$, $\langle 5,6 \rangle \geq \langle 11,12,13,14 \rangle$, $\langle 21,22 \rangle \geq \langle 7,8,9,10 \rangle$, $\langle 23,24 \rangle \geq \langle 7,8,9,10 \rangle$, $\langle 17,18 \rangle \geq \langle 19,20 \rangle$, $\langle 23,24 \rangle \geq \langle 19,20 \rangle$, and $\langle 23,24 \rangle \geq \langle 21,22 \rangle$. Total eight out of 24 FPR sequences, or four out of 10 groups of FPR sequences, $\langle 1,2 \rangle$, $\langle 15,16 \rangle$, $\langle 17,18 \rangle$, and $\langle 23,24 \rangle$, have better performance in D and P than other FPR sequences. Depending on the values of d_l's, m_r's, t_0, and t_l's, one or more of the eight FPR sequences minimize D and maximize P. This example indicates that the optimal FPR sequence is determined by the structure of a fault network and parameters in FPR (Eqs. (1) and (2)). Four FPR sequencers are developed to produce various FPR sequences, which are illustrated in the next two sections, 4.1 and 4.2.

Table 2: Comparison between $\langle 1,2 \rangle$ and $\langle 3,4 \rangle$

Comparison/Condition	Total Damage D	Preventability P
$\langle 3,4 \rangle - \langle 1,2 \rangle$	$d_6 max(m_{1,2,3} + t_0 - t_6, 0) - d_6 max(m_{1,2} + t_0 - t_6, 0)$	$\frac{\lvert m_{1,2} + t_0 - t_6 \rvert}{2(m_{1,2} + t_0 - t_6)} - \frac{\lvert m_{1,2,3} + t_0 - t_6 \rvert}{2(m_{1,2,3} + t_0 - t_6)}$
$t_6 < m_{1,2} + t_0$	$d_6 m_3$	0
$m_{1,2} + t_0 < t_6 < m_{1,2,3} + t_0$	$d_6(m_{1,2,3} + t_0 - t_6)$	-1
$t_6 > m_{1,2,3} + t_0$	0	0

a) *Centralized FPR Sequencer: FPR-C*

The centralized FPR sequencer (*FPR-C*) repairs one root node at a time. For each root node, the *FPR-C* compares the required repair resources and available repair resources. If the required repair resources are less than or equal to available repair resources, the root node is repaired; otherwise, the root node is not repaired. The *FPR-C* has the centralized control of repairs and does not employ parallelism (simultaneous repairs of multiple root nodes). The *FPR-C* is expected to have the worst performance with the lower bounds (maximum D and minimum P) for the performance of all FPR sequencers.

The FPR-C sequencer:

Step 1: Randomly select a root node v_r;v_r has not been repaired;

Step 2: Compare the required repair resources for v_r and available repair resources;

If the required repair resources $\leq$ available repair resources.

Step 3: Repair v_r;
Else

Go to *Step 4:*

Step 4: Go to *Step 1* if not all v_r's are repaired; otherwise stop.

b) Decentralized FPR Sequencers

A decentralized FPR sequencer repairs multiple root nodes at the same time. The number of root nodes that can be repaired simultaneously is subject to available repair resources. Depending on how root nodes are chosen for repairs and the objective of a FPR sequencer, there are three decentralized FPR sequencers.

i. *Decentralized FPR Sequencer with Random Selection: FPR-DR*

The decentralized FPR sequencer with random selection (*FPR-DR*) repairs multiple root nodes at the same time. The *FPR-DR* randomly selects root nodes for repair. When available repair resources are sufficient, the *FPR-DR* repairs all root nodes at the same time, which provides the best performance, i.e., the upper bound (minimum D and maximum P) for the performance of all FPR sequencers.

The FPR-DR sequencer:

Step 1: Randomly select a root node v_r;v_r has not been repaired or is not being repaired;

Step 2: Compare the required repair resources for v_r and available repair resources;

If the required repair resources ≤ available repair resources

Step 3: Start to repair v_r;
Else

Go to *Step 4;*

Step 4: Go to Step 1 if not all v_r's are repaired or are being repaired; otherwise stop.

ii. *Decentralized FPR Sequencer Minimizing Total Damage: FPR-DD*

The decentralized FPR sequencer minimizing D (*FPR-DD*) aims to minimize D for a fault network. The *FPR-DD* guarantees that D is minimized for a fault network comprised of disconnected components, each of which has one root node (LEMMA 1). Figure 3 shows an example of such a fault network in which v_2 should be repaired before v_1 to minimize D because $n_2 = 9 > n_1 = 6$. The condition that $m_{r/r'} \gg |t_{l/i/r} - t_{l'/i'/r'}|$ is common in many systems. For example, when a smart grid experiences a cascading failure, many nodes such as generators, transformers, and substations become faulty in a short period of time. To repair each faulty node, however, takes a relatively long time.

The FPR-DD sequencer:

Step 1: Select an unrepaired root node v_r such that $n_r \geq n_{r'}$ for $\forall\, v_{r'}$;$v_{r'}$ is unrepaired. n_r and $n_{r'}$ are the number of leaf nodes v_l's and $v_{l'}$'s, respectively, to which there exists at least one path from v_r and $v_{r'}$, respectively. Randomly select a root node v_r if there are multiple unrepaired v_r's with the same n_r;

Step 2: Compare the required repair resources for v_r and available repair resources;

If the required repair resources ≤ available repair resources

Step 3: Repair v_r;

Else

Step 3: Go to *Step 4;*

Step 4: Go to *Step 1* if not all v_r's are repaired or are being repaired; otherwise stop.

LEMMA 1: In a fault network $G(V^F, A^F)$, v_r shall be selected for repair to minimize D if there exists at least one path from v_r to $n_r v_l$'s and $n_r \geq n_{r'}$ for $\forall\, v_{r'}$;v_r and $v_{r'}$ are unrepaired. $G(V^F, A^F)$ meets four conditions: (a) for $\forall v_l$, except the orphan nodes, there is only one v_r such that there exists at least one path from v_r to v_l; (b) $m_{r/r'} \gg |t_{l/i/r} - t_{l'/i'/r'}|$ for $\forall v_{l/l'}$, $v_{i/i'}$, and $v_{r/r'}$; (c) $d_l \approx d_{l'}$ for $\forall v_{l/l'}$; and (d) $m_r \approx m_{r'}$ for $v_{r/r'}$.

Proof:

Let v_r and $v_{r'}$ represent two root nodes in a fault network $G(V^F, A^F)$. v_r is a direct or indirect cause of total n_r leaf nodes v_l's, $n_r > 0$; there exists at least one path from v_r to any v_l. All v_l's are repaired or prevented if and only if v_r is repaired, i.e., any v_l is not caused directly or indirectly by any root node other than v_r. The damage caused by v_l over one time unit is d_l. The total damage caused by v_l's is $\sum_l d_l \frac{c_l - t_l + \sqrt{(c_l - t_l)^2}}{2}$. Suppose the difference between the times at which faults occur is much smaller than the repair time for a faulty node, i.e., $m_r \gg |t_{l/i/r} - t_{l'/i'/r'}|$. Since t_0 represents the time at which the FPR sequence begins repairs and $t_0 \geq 0$, $m_r + t_0 \gg |t_{l/i/r} - t_{l'/i'/r'}|$. Because $c_l - t_l \geq m_r + t_0$, $c_l - t_l \gg |t_{l/i/r} - t_{l'/i'/r'}|$ for $\forall v_l$. The total damage caused by v_l's is $\sum_l d_l(c_l - t_l)$. For $v_{r'}$, the total damage caused by $v_{l'}$'s is $\sum_{l'} d_{l'}(c_{l'} - t_{l'})$; $v_{r'}$ is a direct or indirect cause of total $n_{r'}$ leaf nodes $v_{l'}$'s, $n_{r'} > 0$. Because the difference between the times at which faults occur is small, $t_{l/i/r} \approx t_{l'/i'/r'} = t$, the total damages caused by v_l's and $v_{l'}$'s are $\sum_l d_l(c_l - t)$ and $\sum_{l'} d_{l'}(c_{l'} - t)$, respectively. If v_r is repaired before $v_{r'}$, i.e., $c_l - t = m_r$ and $c_{l'} - t = m_r + m_{r'}$, the total damage caused by v_l's and $v_{l'}$'s is $n_r m_r \overline{d_l} + n_{r'}(m_r + m_{r'})\overline{d_{l'}}$, where $\overline{d_l}$ and $\overline{d_{l'}}$ are the mean unit time damages caused by v_l's and $v_{l'}$'s, respectively. If $v_{r'}$ is repaired before v_r, the total damage caused by v_l's and $v_{l'}$'s is $n_r(m_r + m_{r'})\overline{d_l} + n_{r'} m_{r'} \overline{d_{l'}}$. If we further assume that $\overline{d_l} \approx \overline{d_{l'}} = \overline{d}$, $\overline{d} > 0$, and $m_r \approx m_{r'} = m_{r\ r'}$, $m_{r\ r'} > 0$, the total damage is $n_r m_{r\ r'} +$

$2n_{r'}m_{r/r'})\overline{d}$ if v_r is repaired before $v_{r'}$, and $(2n_r m_{r/r'} + n_{r'}m_{r/r'})\overline{d}$ if $v_{r'}$ is repaired before v_r. To minimize the total damage D, v_r is repaired first if $n_r > n_{r'}$; $v_{r'}$ is repaired first if $n_{r'} > n_r$; either v_r or $v_{r'}$ can be repaired first if $n_r = n_{r'}$.

This completes the proof of *LEMMA 1.*

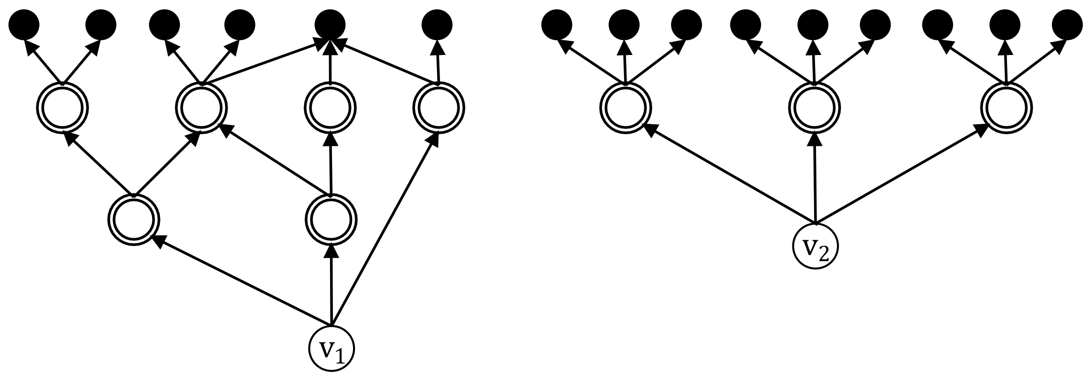

Figure 3: A fault network comprised of two disconnected components. Each component has one root node

iii. *Decentralized FPR Sequencer Maximizing Preventability: FPR-DP*

The FPR sequencer maximizing P *(FPR-DP)* aims to maximize P for a fault network. The *FPR-DP* guarantees that P is maximized for a fault network comprised of disconnected components, each of which has one leaf node *(LEMMA 2)*. In Figure 4, v_1, v_2, v_3, and v_4 should be repaired before v_5, v_6, v_7, v_8, v_9, and v_{10}. Faults in many complex systems may be prevented. For example, most nodes become faulty almost instantaneously when a smart grid experiences a cascading failure. Some leaf nodes have backup power supply and may sustain operations for a certain period of time. Faults at these nodes may be prevented if root nodes are repaired before the backup power runs out.

The FPR-DP sequencer:

Step 1: Select a leaf node v_l, at which faults have not occurred, such that $n_l \leq n_{l'}$ for $\forall\, v_{l'}$; faults at $v_{l'}$ have not occurred. n_l and $n_{l'}$ are the number of root nodes v_r's and $v_{r'}$'s, respectively, from which there exists at least one path to v_l and $v_{l'}$, respectively. Randomly select a leaf node v_l if there are multiple v_l's with the same n_l;

Step 2: Repair all $n_l v_r$'s;

Step 3: Go to *Step 1* if not all v_l's are prevented; otherwise go to *Step 4;*

Step 5: Randomly select a root node v_r;v_r has not been repaired;

Step 6: Compare the required repair resources for v_r and available repair resources;

If the required repair resources ≤ available repair resources

Step 7: Repair v_r;
Else

Step 6: Go to *Step 4;*

Step 7: Go to *Step 4* if not all v_r's are repaired or are being repaired; otherwise stop.

LEMMA 2: In a fault network $G(V^F, A^F)$, all $n_l v_r$'s shall be selected for repair to maximize P if there exists at least one path from v_r to v_l and $n_l \leq n_{l'}$ for $\forall\, v_{l'}$; faults at v_l and $v_{l'}$ have not occurred. $G(V^F, A^F)$ meets three conditions: (a) for $\forall v_r$, except the orphan nodes, there is only one v_l such that there exists at least one path from v_r to v_l; (b) $t_l \approx t_{l'}$ for $\forall v_{l/l'}$; and (c) $m_r \approx m_{r'}$ for $v_{r/r'}$.

Proof:

Let v_l and $v_{l'}$ represent two leaf nodes in a fault network $G(V^F, A^F)$. Faults at v_l and $v_{l'}$ have not occurred and may be prevented. v_l is caused by total n_l root nodes v_r's, $n_l > 0$; there exists at least one path from any v_r to v_l. v_l is repaired or prevented if and only if all $n_l v_r$'s are repaired. Any v_r does not cause faults at other leaf nodes other than v_l. Similarly, $v_{l'}$ is caused by total $n_{l'}$ root nodes $v_{r'}$'s, $n_{l'} > 0$; there exists at least one path from any $v_{r'}$ to $v_{l'}$. Any $v_{r'}$ does not cause faults at other leaf nodes other than $v_{l'}$.

Repairing root nodes can prevent faults at leaf nodes from occurring. Assume that $t_l \approx t_{l'} > 0$, i.e., faults at leaf nodes occur at the same time, and $m_r \approx m_{r'} > 0$, i.e., repair time for any root node is the same. Without losing generality, assume that $n_l \leq n_{l'}$. Therefore $m_r n_l \leq m_{r'} n_{l'}$. $m_r n_l$ is the minimum required time to repair or prevent faults at v_l. $m_{r'} n_{l'}$ is the minimum required time to repair or prevent faults at $v_{l'}$. t_0 is the time at which the FPR sequence begins repairs; $t_0 \geq t_r$ and $t_0 \geq t_{r'}$. The time at which faults at the leaf nodes occur, t_l or $t_{l'}$, falls into four intervals: $t_{l/l'} < m_r n_l + t_0$, $m_r n_l + t_0 \leq t_{l/l'} < m_{r'} n_{l'} + t_0$, $m_{r'} n_{l'} + t_0 \leq t_{l/l'} < m_r n_l + m_{r'} n_{l'} + t_0$, and $t_{l/l'} \geq m_r n_l + m_{r'} n_{l'} + t_0$.

If $t_{l/l'} < m_r n_l + t_0$, $t_{l/l'} < m_{r'} n_{l'} + t_0$ because $m_r n_l \le m_{r'} n_{l'}$. Neither v_l nor $v_{l'}$ can be prevented. $P = 0$. If $m_r n_l + t_0 \le t_{l/l'} < m_{r'} n_{l'} + t_0$, $v_{l'}$ cannot be prevented. To maximize P, v_r's are repaired before the repair of $v_{r'}$'s. $P = \frac{1}{|V^F|}$ if all $n_l v_r$'s are repaired. $P = 0$ if $v_{r'}$'s are repaired first or a mix of v_r's and $v_{r'}$'s are repaired such that not all $n_l v_r$'s are repaired by $t_{l/l'}$. If $m_{r'} n_{l'} + t_0 \le t_{l/l'} < m_r n_l + m_{r'} n_{l'} + t_0$, either v_l or $v_{l'}$ can be prevented, but not both. $P = \frac{1}{|V^F|}$ if all $n_l v_r$'s are repaired first or all $n_{l'} v_{r'}$'s are repaired first. $P = 0$ if a mix of v_r's and $v_{r'}$'s are repaired; not all $n_l v_r$'s are repaired by time $t_{l/l'}$ and neither are $n_{l'} v_{r'}$'s. If $t_{l/l'} \ge m_r n_l + m_{r'} n_{l'} + t_0$, both v_l and $v_{l'}$ are prevented and $P = \frac{2}{|V^F|}$ regardless of the FPR sequence. In summary, repairing all $n_l v_r$'s first always maximizes P.

This completes the proof of *LEMMA 2.*

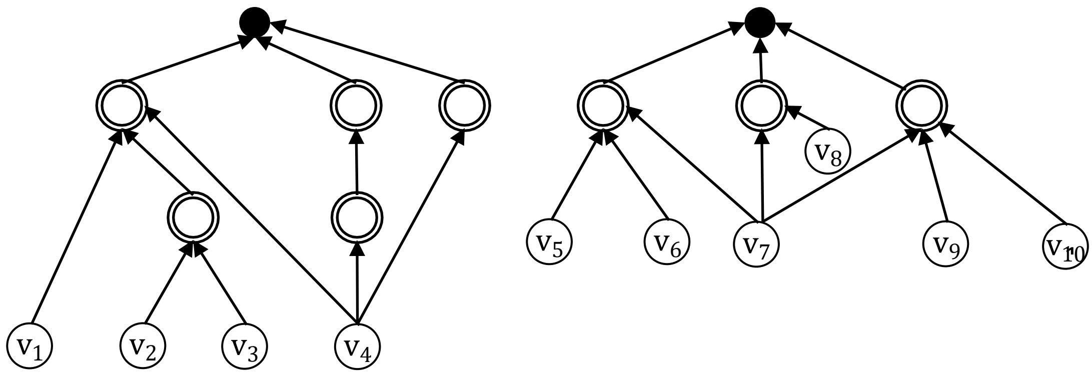

Figure 4: A fault network comprised of two disconnected components. Each component has one leaf node

V. Results

To compare and validate the FPR sequencers, Monte-Carlo simulation experiments (Nasiruzzaman *et al.*, 2014) are designed and conducted using AutoMod (Applied Materials, 1988-2009). Many real-world complex systems may not satisfy conditions in *LEMMA 1*or *LEMMA 2.* The objectives of the experiments are to examine whether (a) the *FPR-C* results in the highest total damage D and lowest preventability P; (b) the *FPR-DD* minimizes D; (c) the *FPR-DP* maximizes P; and (d) the *FPR-DR* performs better than the *FPR-C* but worse than the *FPR-DD* and *FPR-PP*.

Whether the *FPR-DD* can minimize D and the *FPR-DP* can maximize Pdepend on conditions in *LEMMA 1* and *LEMMA 2.* In *LEMMA 1,* it is assumed that (a) each leaf node, except the orphan node, has only one root node; (b) nodes become faulty at almost the same time; (c) damage caused by failures at each leaf node is approximately the same; and (d) repair resources, e.g., repair personnel, required for each root node is approximately the same. In *LEMMA 2,* it is assumed that (a) each root node, except the orphan node, has only one leaf node; (b) all leaf nodes become faulty at almost the same time; and (c) repair resources, e.g., repair personnel required for each root node are approximately the same.

The structure of a fault network is derived from the structure of a complex system, and rarely satisfies condition (a) in either *LEMMA 1* or *LEMMA 2.* In general, a root node may have multiple leaf nodes and a leaf node may have multiple root nodes. Condition (b) in *LEMMA 1* and *LEMMA 2* specifies the type of failures in a complex system. Three types of failures, random, cascading, and cascading with backup capacity, are studied in the experiments. Most random failures are independent of each other and occur over a long period of time. Random failures do not satisfy condition (b) in either *LEMMA 1* or *LEMMA 2.* A cascading failure in a complex system (Nedic *et al.*, 2006) occurs in a relatively short period of time and includes multiple faults most of which are caused by a few faulty sources (root nodes in a fault network; Hoffmann and Payton, 2014). A cascading failure satisfies condition (b) because nodes become faulty almost at the same time. A cascading failure with backup capacity does not satisfy condition (b) since leaf nodes become faulty at different times depending on the amount of backup capacity each leaf node has. Conditions (c) and (d) in *LEMMA 1* and condition (c) in *LEMMA 2* are valid for many complex systems. A fault network's properties along the four conditions in *LEMMA 1* and *LEMMA 2* determine the structure of the fault network.

In each experiment, a fault network is first generated; an FPR sequencer is used to generate an FPR sequence, which is emulated to prevent and repair faults. D and P are calculated for each experiment. The experiments use the electrical power grid of the Western United States (Watts and Strogatz, 1998), which has 4,941 nodes, including generators, transformers, and substations. In a simulation experiment, each node has 0.1 probability of becoming faulty. Resources required

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to repair failures at a root node are assumed to be randomly and uniformly distributed between 3 and 10 units. For example, to repair faults at a node may require a crew of 6 people, i.e., 6 units of resources. The damage per second caused by faults at a node is randomly and uniformly distributed between $5 and $15. Each simulation experiment emulates an FPR sequence for 24 hours.

Total repair resources affect the performance of FPR sequencers. The *FPR-C* repairs one root node at a time. Since the maximum amount of resources needed to repair a root node is 10 units, total repair resources for the *FPR-C* are 10 units, which are sufficient for the repair of any root node. The decentralized FPR sequencers, *FPR-DD, FPR-DP,* and *FPR-DR* repair multiple root nodes at the same time. The electrical power grid of the Western United States has 4,941 nodes and each nodes has 0.1 probability of having faults in the experiments. There are on average 494 nodes that become faulty in an experiment. Since only root nodes, including orphan nodes that are both root and leaf nodes, require repair, different levels of total repair resources are applied in the experiments according to the number of root nodes.

a) Random Failures

Many complex systems have random failures most of which occur independent of each other. In the simulation experiments, the time at which random failures occur is uniformly distributed between 0 and 86,400 seconds (24 hours = 86,400 seconds). One-hundred experiments are conducted for each combination of an FPR sequencer and a certain amount of total repair resources, which are 10 units for the *FPR-C.* It is necessary to determine the maximum required total repair resources (MRT), which is the amount of resources sufficient to repair all root nodes simultaneously. The simulation experiments show that the maximum number of root nodes with random failures is 523, with a mean of 464 and a standard deviation of 19. Since a root node requires at most 10 units to repair, the MRT for random failures is about 5,000 units. For scalability evaluation, 14 levels of total repair resources are used in the experiments for each of the *FPR-DD, FPR-DP,* and *FPR-DR:* 10, 50, 100, 200, 300, 400, 500, 1,000, 1,500, 2,000, 2,500, 5,000, 7,500, and 10,000 units. A decentralized FPR sequencer is expected to have the best performance when total repair resources are at or greater than the MRT. The two levels, 7,500 and 10,000 units, are included in the experiments to validate the best performance of an FPR sequencer. Total 4,300 experiments (100 experiments for *FPR-C* plus three decentralized FPR sequencers times 14 levels of total repair resources times 100 experiments) are conducted to compare and validate the performance of FPR sequencers for random failures.

Figures 5-15 and Table 3 summarize experiment results, which provide several important findings for managing random failures:

(a) All decentralized FPR sequencers perform better than the *FPR-C,* which is a centralized FPR sequencer and has the maximum D and minimum P. At the same level of total repair resources, 10 units, all three decentralized FPR sequencers significantly decrease D and increase P compared to the *FPR-C.* Because Monte-Carlo simulation allows for sampling of the entire population with 100 experiments for each combination of the FPR sequencer and level of total available repair resources, statistically significant tests are not necessary, and the difference shown in Figures 5-15 is the actual difference between the FPR sequencers;

(b) Decentralized FPR sequencers have the best performance, i.e., minimum D and maximum P, when total repair resources are at least the MRT. Note that the upper limit for P is the percentage of leaf nodes in a fault network. The experiments show that the mean and standard deviation of the percentage of leaf nodes are 0.05990 and 0.01088, respectively. The mean 0.05990 is just slightly greater than the mean for P once the performance levels off;

(c) The performance of decentralized FPR sequencers first improves as total repair resources increase, and then reaches the best performance and levels off;

(d) For total damage D, the performance of decentralized FPR sequencers levels off once repair resources reach 200 units. In other words, if total repair resources are sufficient to repair on average 6.63% (≈200/6.5/464) of all root nodes, increasing the level of repair resources further does not affect the mean or standard deviation of D;

(e) For preventability P, the performance of decentralized FPR sequencers levels off once repair resources reach 100 units. In other words, if total available repair resources are sufficient to repair on average 3.32% (≈100/6.5/464) of all root nodes, increasing the level of repair resources further does not affect the mean or standard deviation of P; and

(f) The *FPR-DD* and *FPR-DP* perform almost the same, and better than the *FPR-DR* before the performance levels off. This experiment finding validates *LEMMA 1* and *LEMMA 2.*

In summary, either the *FPR-DD* or *FPR-DP* should be used to sequence repairs of random failures in a complex system. Increasing total repair resources up to the amount that is sufficient to repair on average 3.32% of all root causes prevents more faults from occurring. After the amount is reached, further increasing total repair resources does not increase the number of faults prevented. Increasing total repair resources up to the amount that is sufficient to repair on average 6.63% of all root causes decreases total damage caused by faults. After the amount is reached, further increasing total repair resources does not decrease total damage.

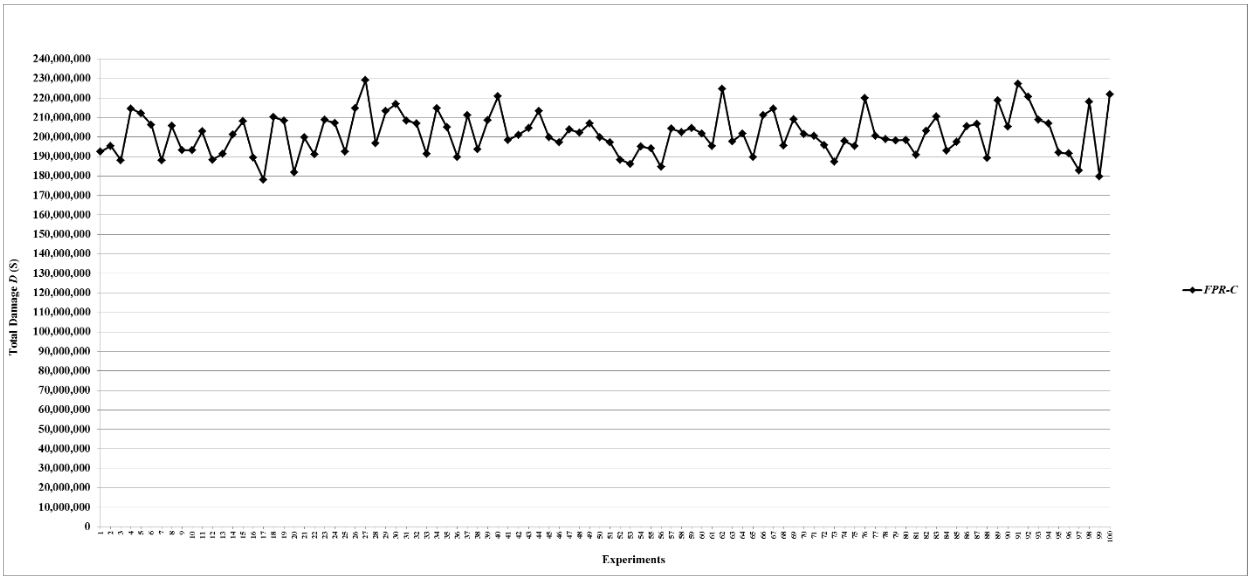

Figure 5: Total damage D of fault networks with random failures using the *FPR-C*

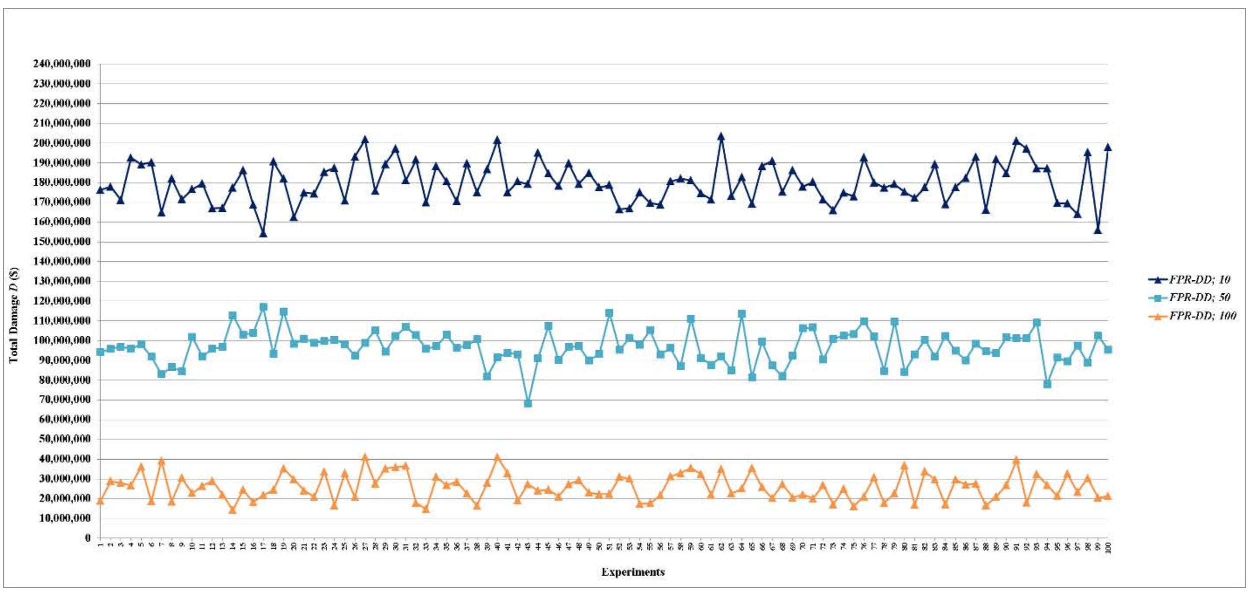

Figure 6: Total damage D of fault networks with random failures using the *FPR-DD* with resources 10, 50, and 100 units

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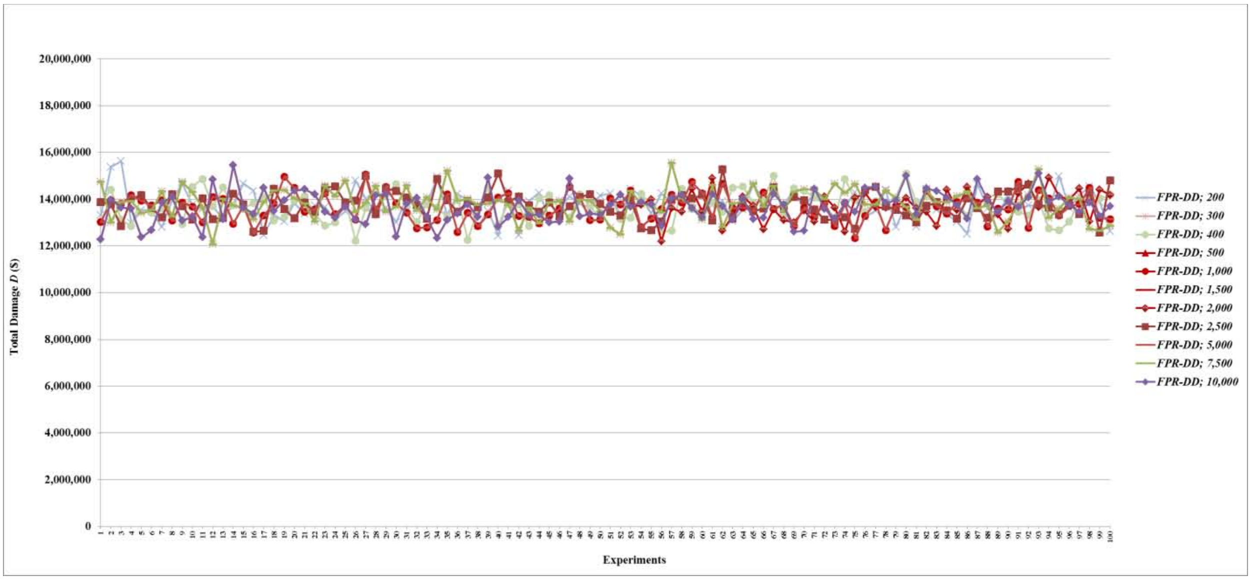

Figure 7: Total damage D of fault networks with random failures using the *FPR-DD* with resources 200, 300, 400, 500, 1,000, 1,500, 2,000, 2,500, 5,000, 7,500, and 10,000 units

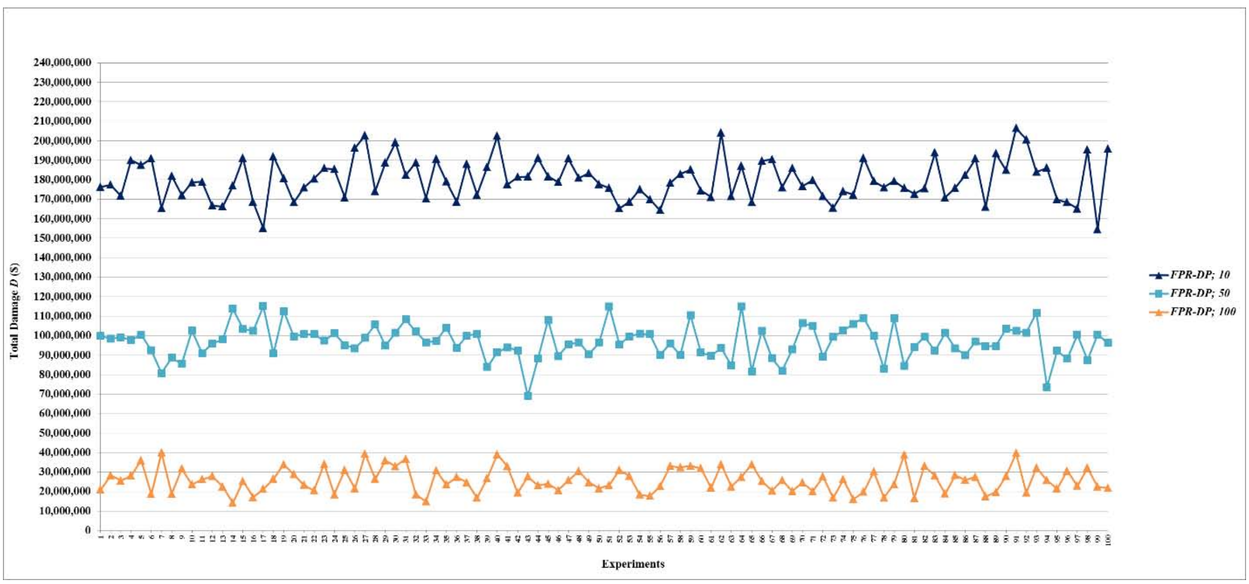

Figure 8: Total damage D of fault networks with random failures using the *FPR-DP* with resources 10, 50, and 100 units

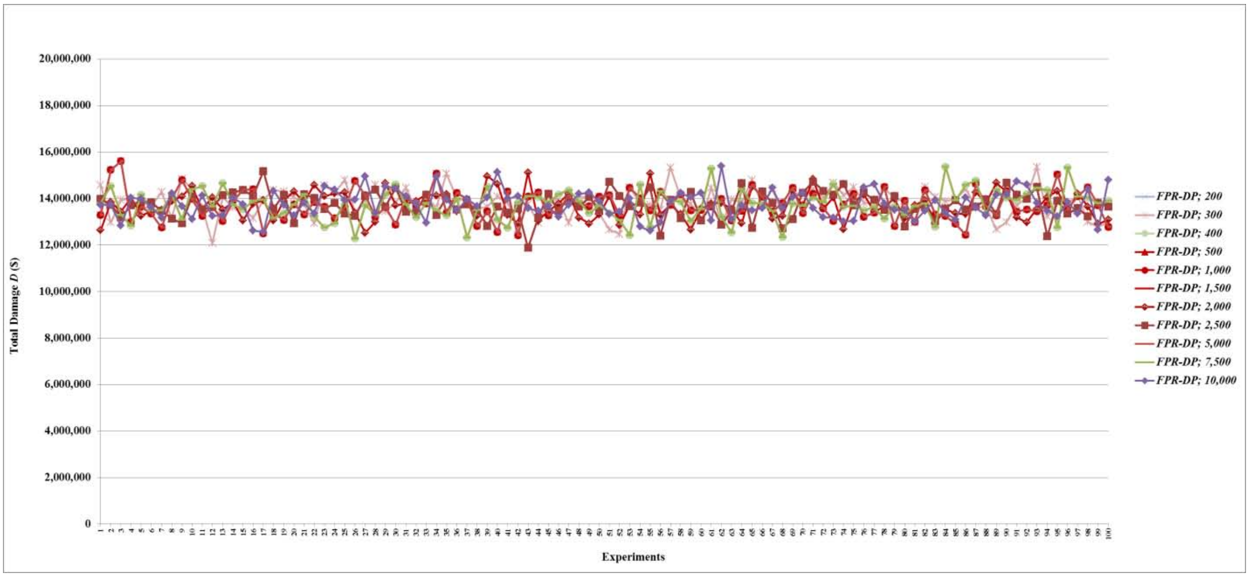

Figure 9: Total damage D of fault networks with random failures using the *FPR-DP* with resources 200, 300, 400, 500, 1,000, 1,500, 2,000, 2,500, 5,000, 7,500, and 10,000 units

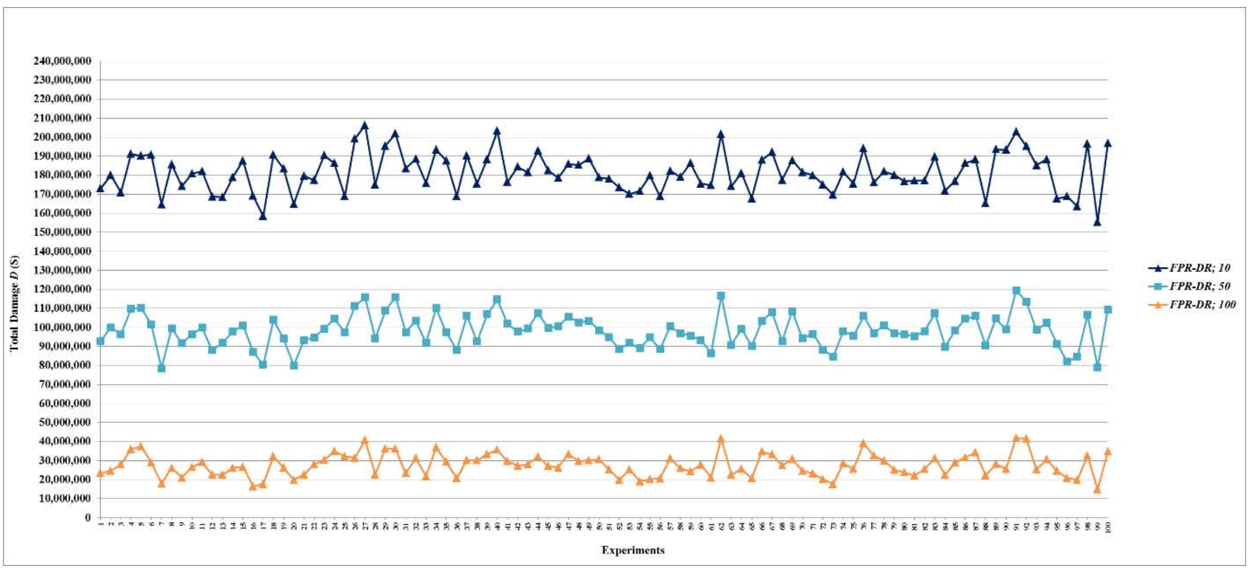

Figure 10: Total damage D of fault networks with random failures using the *FPR-DR* with resources 10, 50, and 100 units

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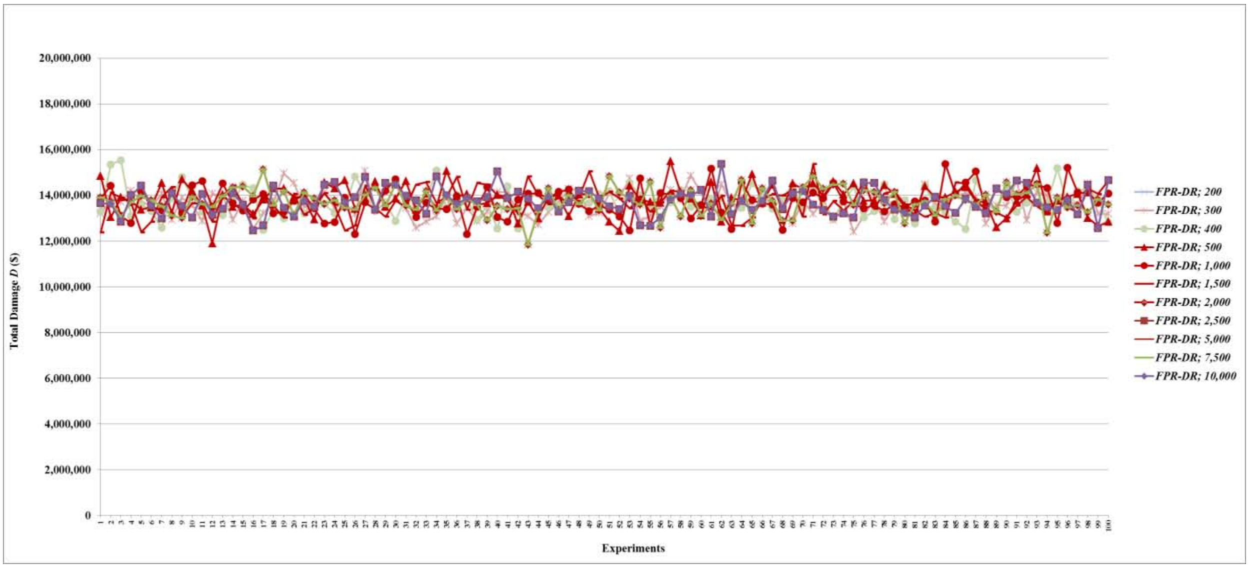

Figure 11: Total damage D of fault networks with random failures using the *FPR-DR* with resources 200, 300, 400, 500, 1,000, 1,500, 2,000, 2,500, 5,000, 7,500, and 10,000 units

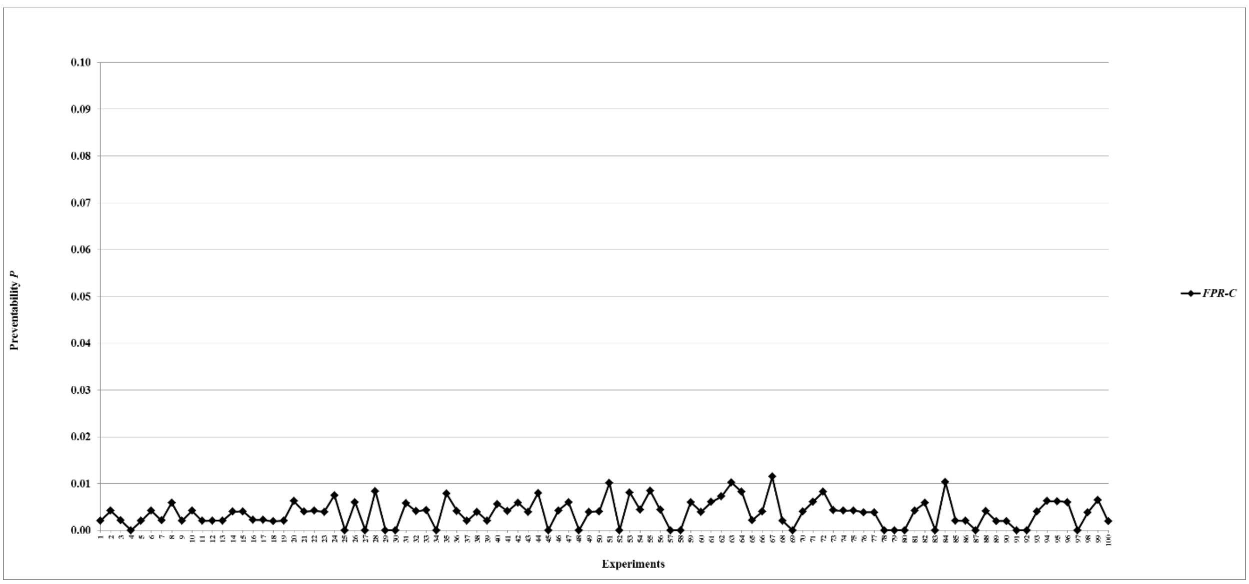

Figure 12: Preventability P of fault networks with random failures using the *FPR-C*

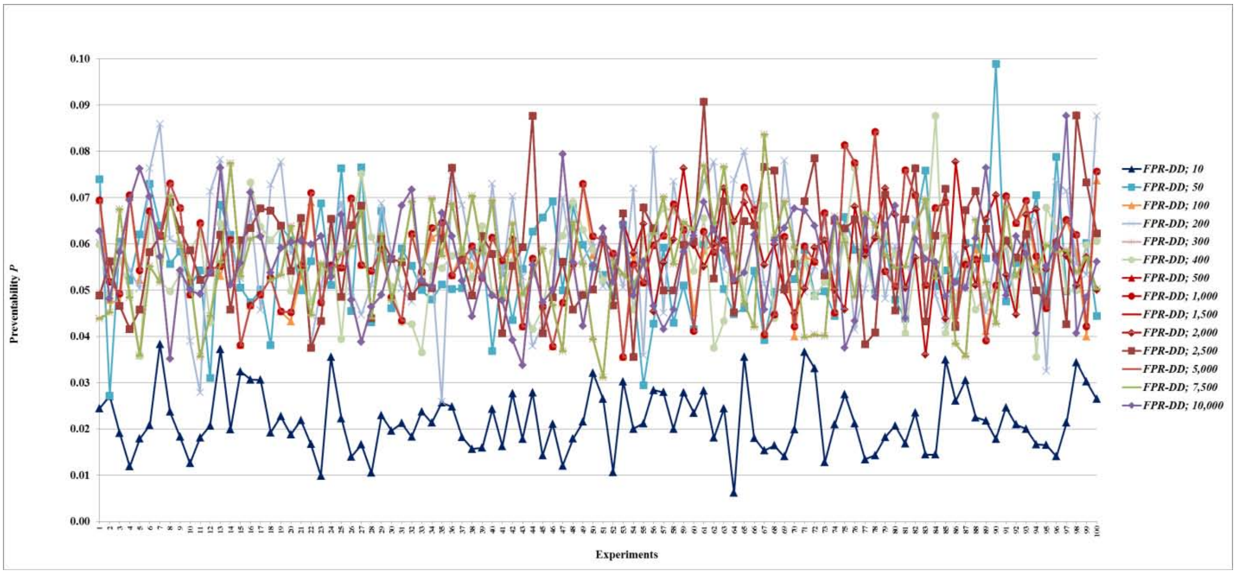

Figure 13: Preventability P of fault networks with random failures using the *FPR-DD*

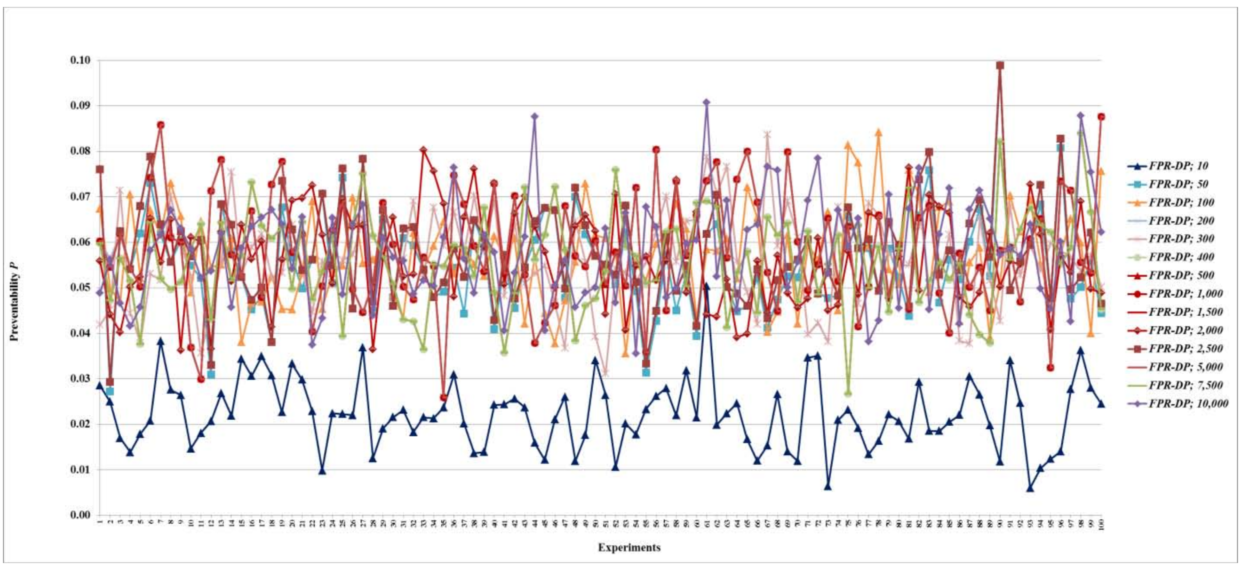

Figure 14: Preventability P of fault networks with random failures using the *FPR-DP*

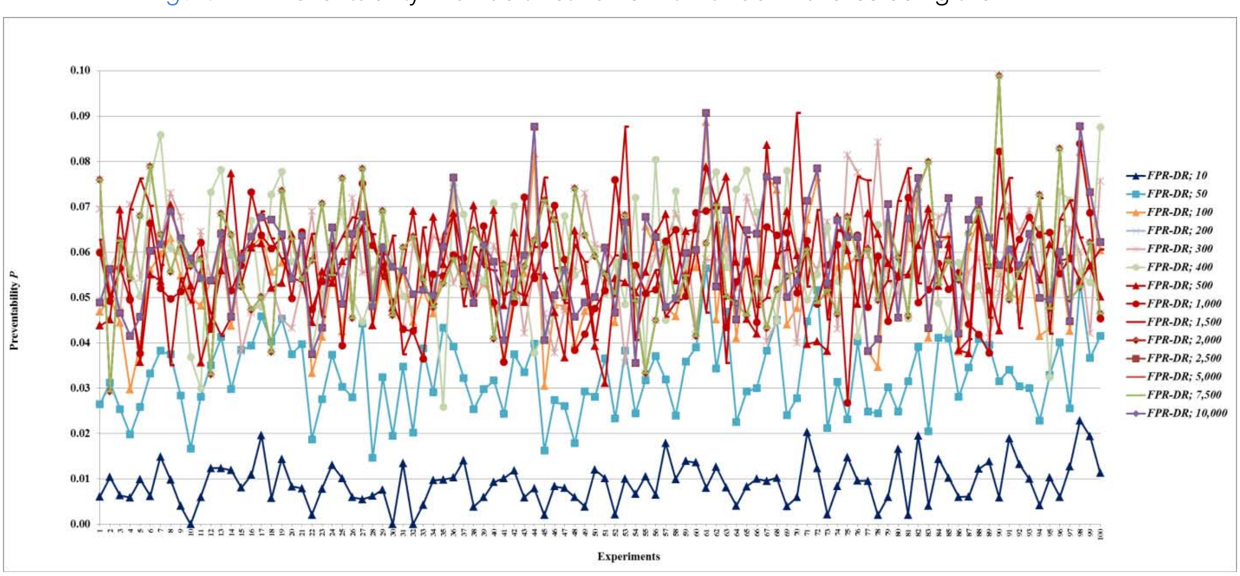

Figure 15: Preventability P of fault networks with random failures using the *FPR-DR*

Table 3: Total Damage and Preventability of Fault Networks with Random Failures

FPR Sequencer; Total Available Repair Resources	Total Damage ***D***		Preventability ***P***	
	Mean	Standard Deviation	Mean	Standard Deviation
FPR-C	201621025	10828850	0.00374	0.00280
FPR-DD; 10	180006159	10313564	0.02169	0.00679
FPR-DD; 50	96732479	8447916	0.05502	0.01098
FPR-DD; 100	25934287	6586766	0.05713	0.01023
FPR-DD; 200	13735920	619541	0.05819	0.01251
FPR-DD; 300	13830873	627624	0.05627	0.01033
FPR-DD; 400	13717879	584635	0.05566	0.00952
FPR-DD; 500	13758247	569952	0.05815	0.01138
FPR-DD; 1,000	13630487	570632	0.05748	0.01032
FPR-DD; 1,500	13830873	627624	0.05627	0.01033
FPR-DD; 2,000	13630578	666306	0.05704	0.00973
FPR-DD; 2,500	13758247	569952	0.05815	0.01138
FPR-DD; 5,000	13630487	570632	0.05748	0.01032
FPR-DD; 7,500	13830873	627624	0.05627	0.01033
FPR-DD; 10,000	13675877	643748	0.05621	0.01009
FPR-DP; 10	180111362	10611192	0.02233	0.00769
FPR-DP; 50	96873761	8561127	0.05538	0.01104
FPR-DP; 100	25867769	6277847	0.05707	0.01032
FPR-DP; 200	13722287	621941	0.05825	0.01248
FPR-DP; 300	13833200	617975	0.05622	0.01042
FPR-DP; 400	13739117	637874	0.05608	0.01044
FPR-DP; 500	13725355	561576	0.05768	0.01126
FPR-DP; 1,000	13720615	621869	0.05823	0.01248
FPR-DP; 1,500	13739117	637874	0.05608	0.01044
FPR-DP; 2,000	13714074	564894	0.05680	0.01039
FPR-DP; 2,500	13725355	561576	0.05768	0.01126
FPR-DP; 5,000	13720615	621869	0.05823	0.01248
FPR-DP; 7,500	13739117	637874	0.05608	0.01044
FPR-DP; 10,000	13760036	581581	0.05815	0.01138
FPR-DR; 10	181502337	10358006	0.00916	0.00472
FPR-DR; 50	98257539	8680622	0.03252	0.00845
FPR-DR; 100	27572124	5995100	0.05421	0.01164
FPR-DR; 200	13731751	557508	0.05774	0.01137
FPR-DR; 300	13619331	566126	0.05734	0.01029
FPR-DR; 400	13719841	626493	0.05817	0.01243
FPR-DR; 500	13834270	626768	0.05635	0.01046
FPR-DR; 1,000	13730883	634684	0.05610	0.01047
FPR-DR; 1,500	13712596	590669	0.05815	0.01120
FPR-DR; 2,000	13730156	556901	0.05774	0.45707
FPR-DR; 2,500	13743341	577436	0.05832	0.01131
FPR-DR; 5,000	13730156	556901	0.05774	0.01137
FPR-DR; 7,500	13730156	556901	0.05774	0.01137
FPR-DR; 10,000	13743341	577436	0.05832	0.01131

b) Cascading Failures

A cascading failure may occur within a few minutes to a few hours (Andersson *et al.*, 2005). For example, significant failures in the U.S.-Canadian blackout of August 14, 2003, occurred in less than an hour. In the simulation experiments, the time at which faults as part of a cascading failure occur is uniformly and randomly distributed between 42,300 and 44,100 seconds (43,200 ± 900), i.e., faults occur within 30 minutes. The simulation experiments show that the maximum number of root nodes is 94 with a mean of 66 and a standard deviation of 9. Since a root node requires at most 10 units to repair, the MRT for a cascading failure is about 1,000 units. For scalability evaluation, 10 levels of total repair resources are used in the experiments for each of the *FPR-DD, FPR-DP,* and

FPR-DR: 10, 50, 100, 200, 300, 400, 500, 1,000, 1,500, and 2,000 units. Total 3,100 experiments (100 experiments for *FPR-C* plus three decentralized FPR sequencers times 10 levels of total repair resources times 100 experiments) are conducted to compare and validate the performance of FPR sequencers for cascading failures.

Figures 16-22 and Table 4 summarize experiment results, which provide several important findings for managing cascading failures:

(a) The preventability P of all FPR sequencers is zero. This is often the case in a complex system where a cascading failure occurs in a short period of time, and no faults may be prevented once the cascading failure begins unfolding;

(b) All decentralized FPR sequencers have smaller D than the *FPR-C* with the same amount of total repair resources;

(c) Decentralized FPR sequencers have the minimum D when total repair resources are at least the MRT;

(d) Decentralized FPR sequencers first decrease D as total repair resources increase, and then reaches the minimum D, which levels off once repair resources reach 500 units. In other words, if total repair resources are sufficient to repair on average 100% (≈500/6.5/66) of all root nodes in a cascading failure, increasing the level of repair resources further does not affect the mean or standard deviation of D; and

(e) The *FPR-DD* and *FPR-DP* have almost the same D, which is less than that of the *FPR-DR* before D levels off. This experiment finding validates *LEMMA 1* and *LEMMA 2.*

In summary, either the *FPR-DD* or *FPR-DP* should be used to sequence repairs of a cascading failure in a complex system. Increasing total repair resources up to the amount that is sufficient to repair all root nodes decreases total damage caused by faults. After the amount is reached, further increasing total repair resources does not reduce total damage. Compared to random failures, a cascading failure has less damage with the same level of total repair resources. This is because most faults in a cascading failure are caused by a few root nodes (with a mean of 66) whereas most faults in random failures are root nodes (with a mean of 464) and require repairs. In the simulation experiments, it is assumed that approximately the same number of faults (with a mean of 494) occur in random failures within 24 hours and in a cascading failure within 30 minutes. In real-world complex systems, however, these faults in random failures may occur across a much longer time period, for instance, two to three years. Total damage caused by random failures is greater but over a more extended period.

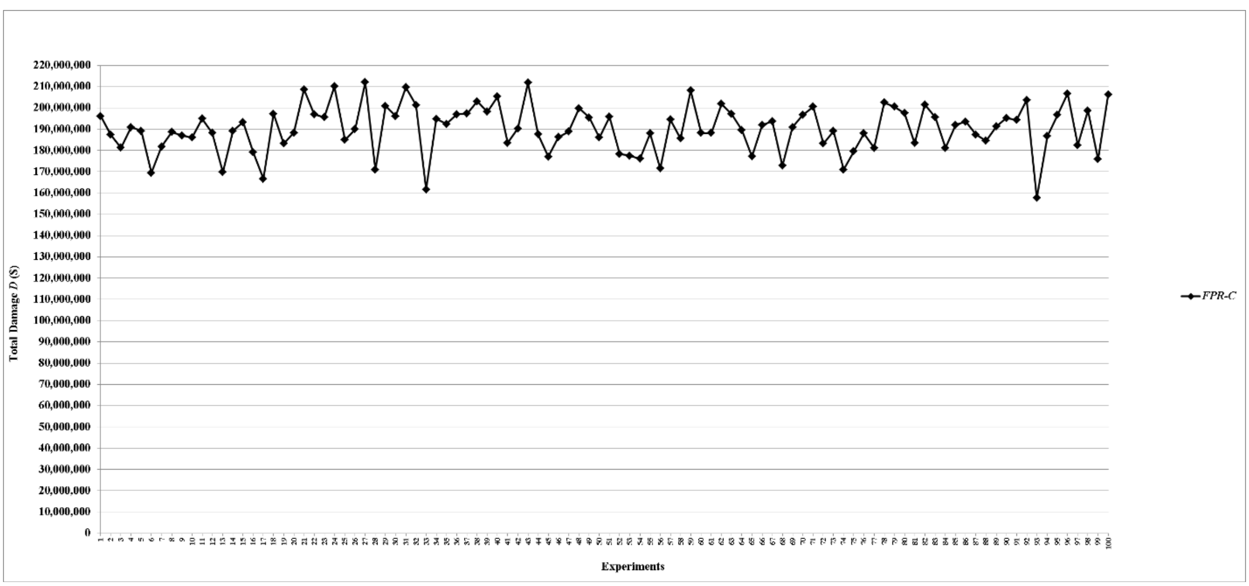

Figure 16: Total damage D of fault networks with cascading failures using the *FPR-C*

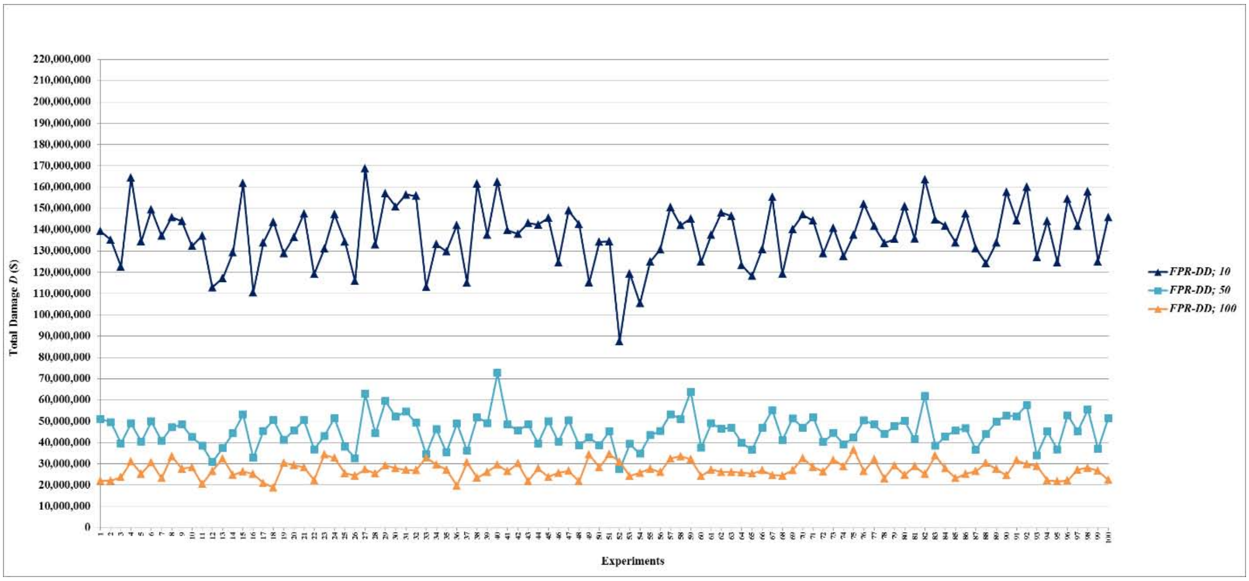

Figure 17: Total damage D of fault networks with cascading failures using the *FPR-DD* with resources 10, 50, and 100 units

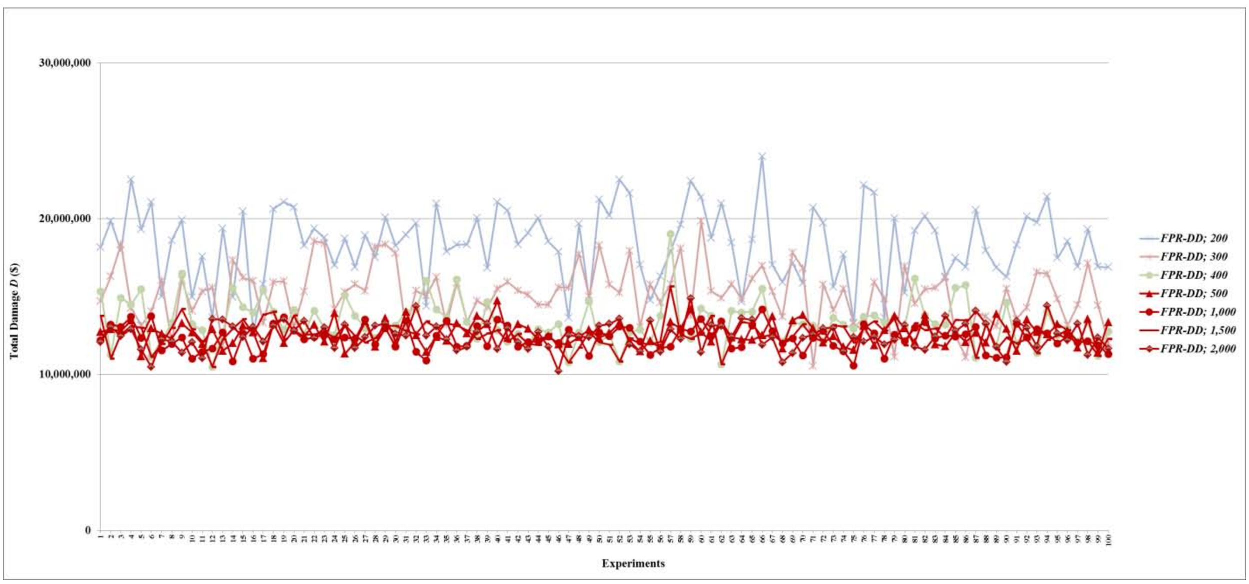

Figure 18: Total damage D of fault networks with cascading failures using the *FPR-DD* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

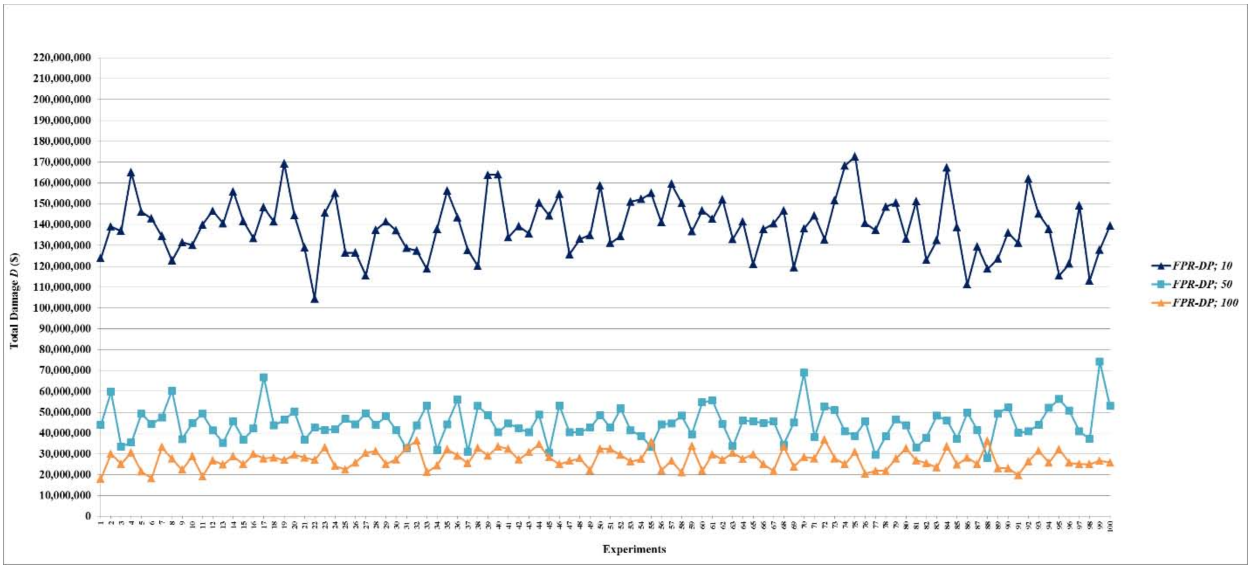

Figure 19: Total damage D of fault networks with cascading failures using the *FPR-DP* with resources 10, 50, and 100 units

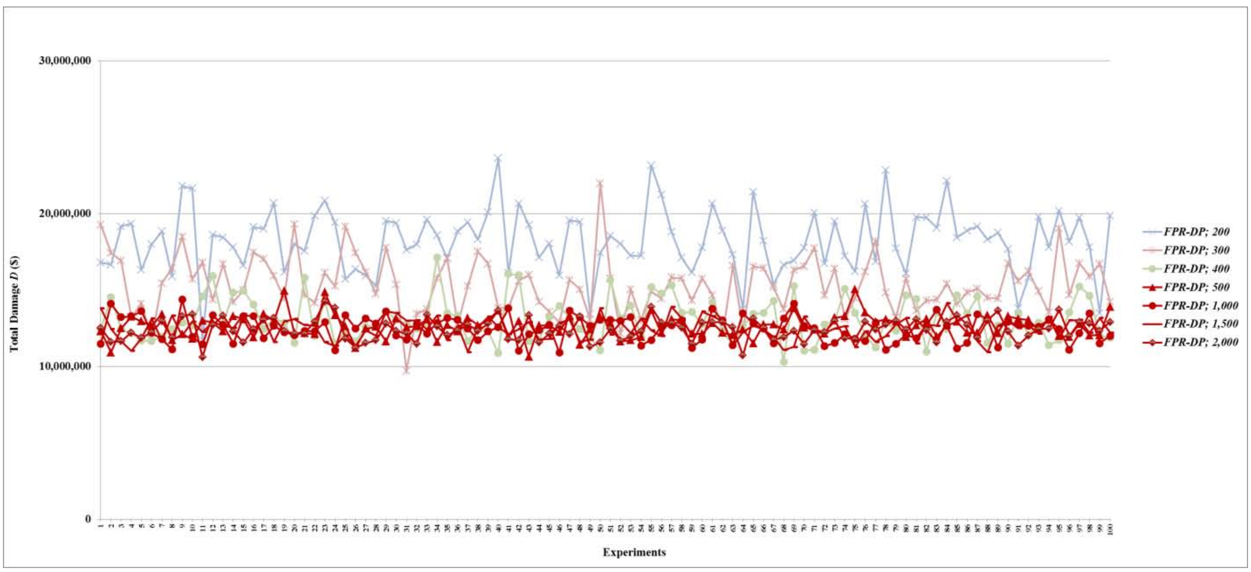

Figure 20: Total damage D of fault networks with cascading failures using the *FPR-DP* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

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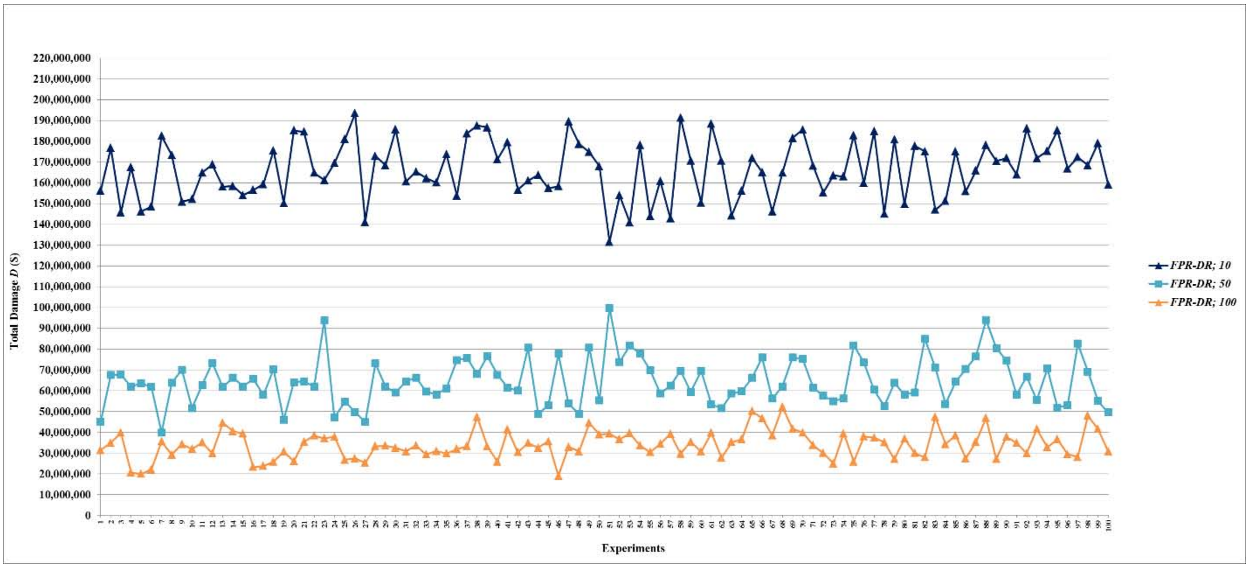

Figure 21: Total damage D of fault networks with cascading failures using the *FPR-DR* with resources 10, 50, and 100 units

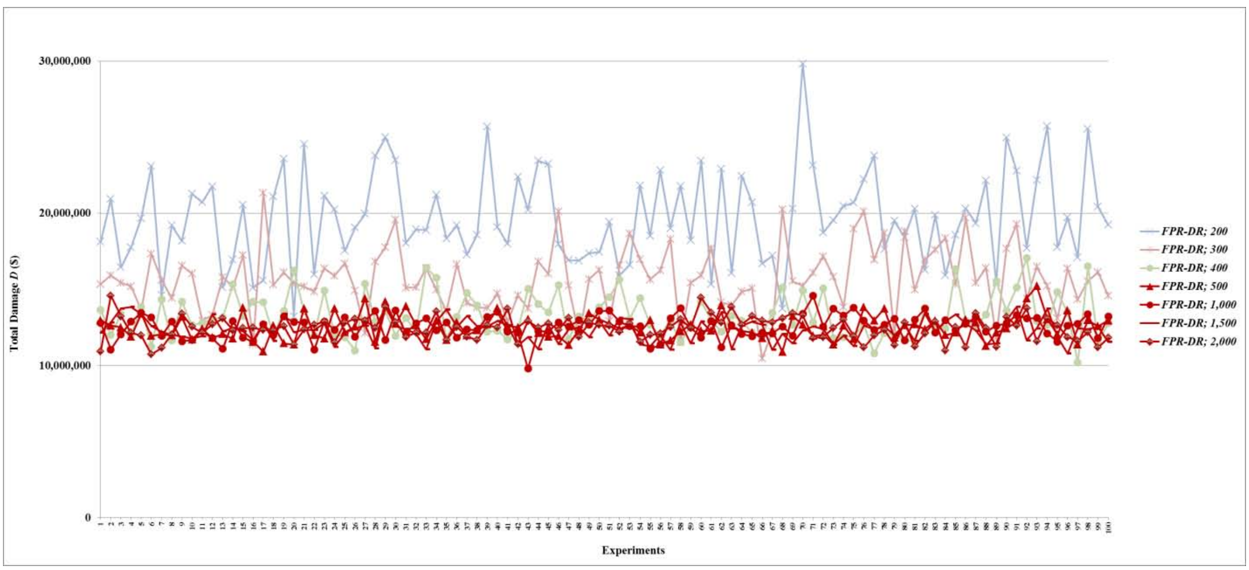

Figure 22: Total damage D of fault networks with cascading failures using the *FPR-DR* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

Table 4: Total Damage and Preventability of Fault Networks with Cascading Failures

FPR Sequencer; Total Available Repair Resources	Total Damage D		Preventability P	
	Mean	Standard Deviation	Mean	Standard Deviation
FPR-C	190139716	11025184	0	0
FPR-DD; 10	137672499	14383251		
FPR-DD; 50	45621092	7608045		
FPR-DD; 100	27230279	3718585		
FPR-DD; 200	18404599	2339505		
FPR-DD; 300	15184690	1780278	0	0
FPR-DD; 400	13356829	1417712		
FPR-DD; 500	12634203	749992		
FPR-DD; 1,000	12331616	772317		
FPR-DD; 1,500	12556581	812326		
FPR-DD; 2,000	12504073	857407		

FPR-DP; 10	139356587	13829297	0	0
FPR-DP; 50	44591923	8105005		
FPR-DP; 100	27451992	4244597		
FPR-DP; 200	18238043	2105204		
FPR-DP; 300	15364209	1846987		
FPR-DP; 400	13084820	1393448		
FPR-DP; 500	12647448	747807		
FPR-DP; 1,000	12471665	815878		
FPR-DP; 1,500	12484797	719505		
FPR-DP; 2,000	12434897	698778		
FPR-DR; 10	166405486	13711462	0	0
FPR-DR; 50	64516423	11201280		
FPR-DR; 100	34109806	6667700		
FPR-DR; 200	19711150	3022102		
FPR-DR; 300	15668666	2105001		
FPR-DR; 400	13244631	1415352		
FPR-DR; 500	12501641	808187		
FPR-DR; 1,000	12544864	755824		
FPR-DR; 1,500	12324953	733180		
FPR-DR; 2,000	12444661	763936		

c) Cascading Failures with Backup Capacity

Many critical nodes in a complex system have backup capacity in case of failures. For example, consumers in a smart grid can have backup power that provides uninterrupted power supply when there is a random failure or a cascading failure. Backup power may be fueled by gasoline, diesel, propane, natural gas, battery, and other energy sources. Some provide protection against failures and others require a short period of time, for example, 30 seconds, to resume power supply. Backup power may last for a few minutes to a few days, depending on its capacity and power usage. In theory, some generators provide an endless electricity supply using natural gas from the utility company. In practice, however, these generators require periodical maintenance, for example, replacing engine oil, or cooling. There is always a limit on how long backup power can continuously supply electricity.

In the simulation experiments, the time at which root and internal nodes become faulty is uniformly and randomly distributed between 42,300 and 44,100 seconds, which is the same for root and internal nodes in a cascading failure without backup capacity (Section 5.2). The time at which leaf nodes become faulty is uniformly and randomly distributed between 46,800 and 86,400 seconds, i.e., leaf nodes with backup power become faulty approximately between 1 hour and 12 hours after their corresponding root nodes become faulty. The simulation experiments show that the maximum number of root nodes is 102, with a mean of 66 and a standard deviation of 9. Since a root node requires at most 10 units to repair, the MRT for a cascading failure with backup capacity is about 1,000 units. For scalability evaluation, 10 levels of total repair resources are used in the experiments for each of the *FPR-DD, FPR-DP,* and *FPR-DR:* 10, 50, 100, 200, 300, 400, 500, 1,000, 1,500, and 2,000 units. Total 3,100 experiments (100 experiments for *FPR-C* plus three decentralized FPR sequencers times 10 levels of total repair resources times 100 experiments) are conducted to compare and validate the performance of FPR sequencers for cascading failures with backup capacity.

Figures 23-36 and Table 5 summarize experiment results, which provide several important findings for managing cascading failures with backup capacity:

(a) All decentralized FPR sequencers perform better than the *FPR-C,* which has the maximum D and minimum P. At the same level of total repair resources, 10 units, all three decentralized FPR sequencers significantly decrease D and increase P compared to the *FPR-C;*

(b) Decentralized FPR sequencers have the best performance, i.e., minimum D and maximum P, when total repair resources are at least the MRT. The upper limit for P is the percentage of leaf nodes. The experiments show that the mean and standard deviation of the percentage of leaf nodes are 0.39720 and 0.01615, respectively. The mean 0.39720 is just slightly greater than the mean for P once the performance levels off;

(c) The performance of decentralized FPR sequencers first improves as total repair resources increase, and then reaches the best performance and levels off;

(d) For total damage D, the performance of decentralized FPR sequencers levels off once repair resources reach 500 units. In other words, if total repair resources are sufficient to repair on average 100% (≈500/6.5/66) of all root nodes in a cascading failure with backup capacity, increasing the level of repair resources further does not affect the mean or standard deviation of D;

(e) For preventability P, the performance of decentralized FPR sequencers levels off once repair resources reach 300 units. In other words, if total repair resources are sufficient to repair on average 69.93% (≈300/6.5/66) of all root nodes in a cascading failure with backup capacity, increasing the level of repair resources further does not affect the mean or standard deviation of P; and

(f) The *FPR-DD* and *FPR-DP* perform almost the same, and better than the *FPR-DR,* before the performance levels off. This experiment finding validates *LEMMA 1* and *LEMMA 2.*

In summary, either the *FPR-DD* or *FPR-DP* should be used to sequence repairs of a cascading failure with backup capacity in a complex system. Increasing total repair resources up to the amount that is sufficient to repair on average 69.93% of all root nodes prevents more faults from occurring. After the amount is reached, further increasing total repair resources does not increase the number of faults prevented. Increasing total repair resources up to the amount that is sufficient to repair 100% of all root nodes decreases total damage caused by faults. After the amount is reached, further increasing total repair resources does not reduce total damage. Compared to a cascading failure without backup capacity, a cascading failure with backup capacity has lower damage with the same amount of total repair resources. The preventability of a cascading failure with backup capacity is greater than that of a cascading failure without backup capacity, which is zero regardless of the amount of repair resources. These comparison results are expected because the time that leaf nodes become faulty is delayed because of backup capacity, which reduces total damage and allows FPR sequencers to prevent more faults. Compared to random failures, a cascading failure with backup capacity has lower damage and higher preventability with the same amount of total repair resources.

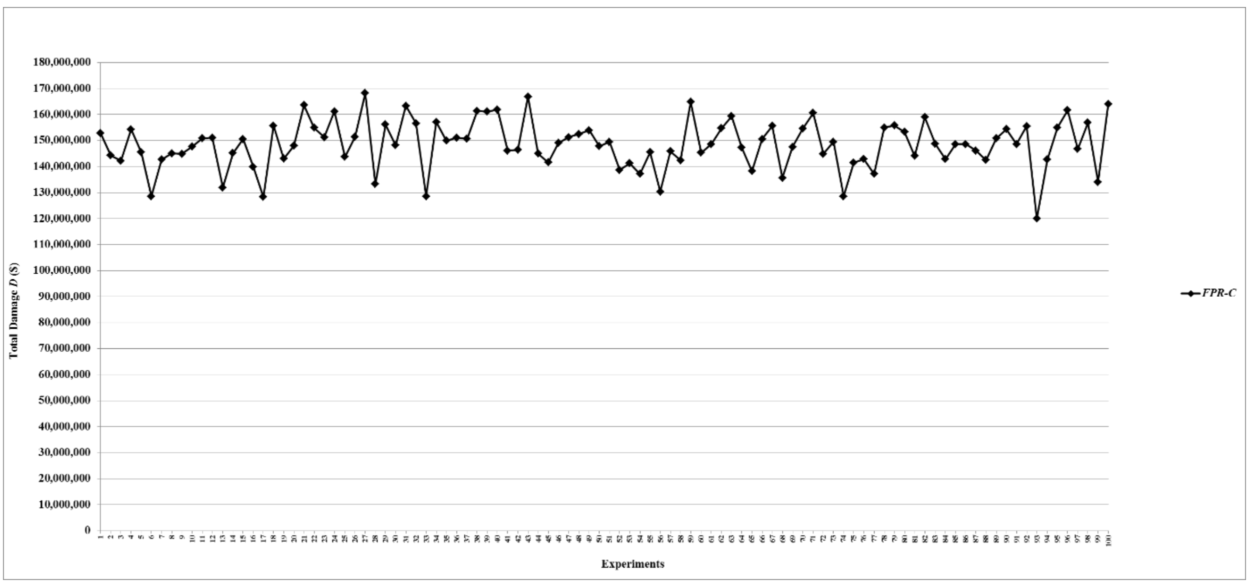

Figure 23: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-C*

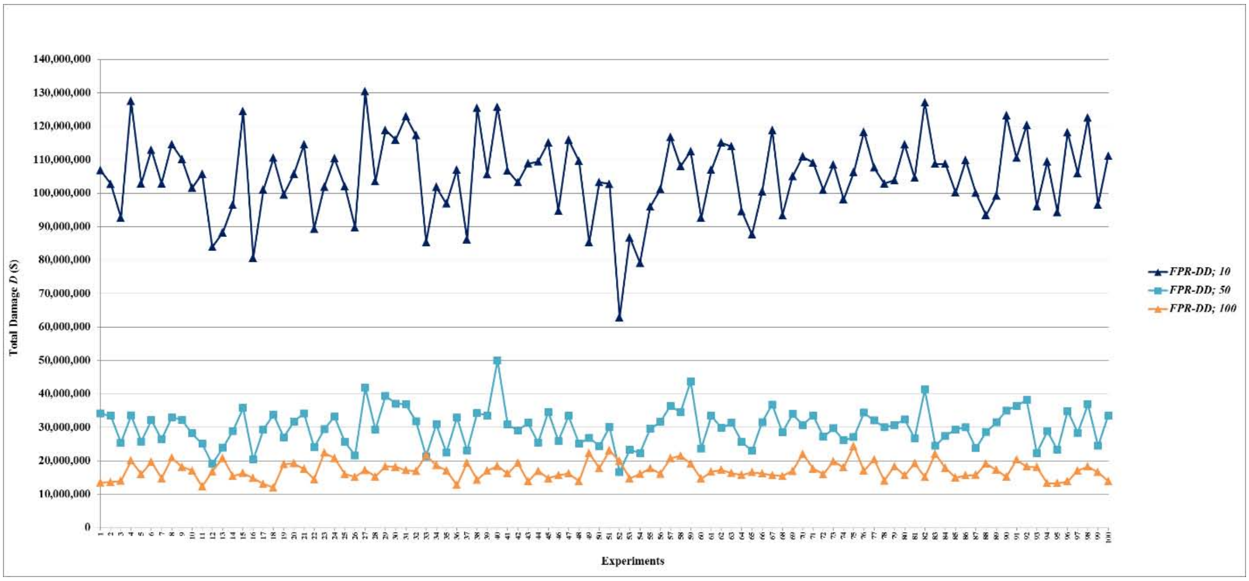

Figure 24: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DD* with resources 10, 50, and 100 units

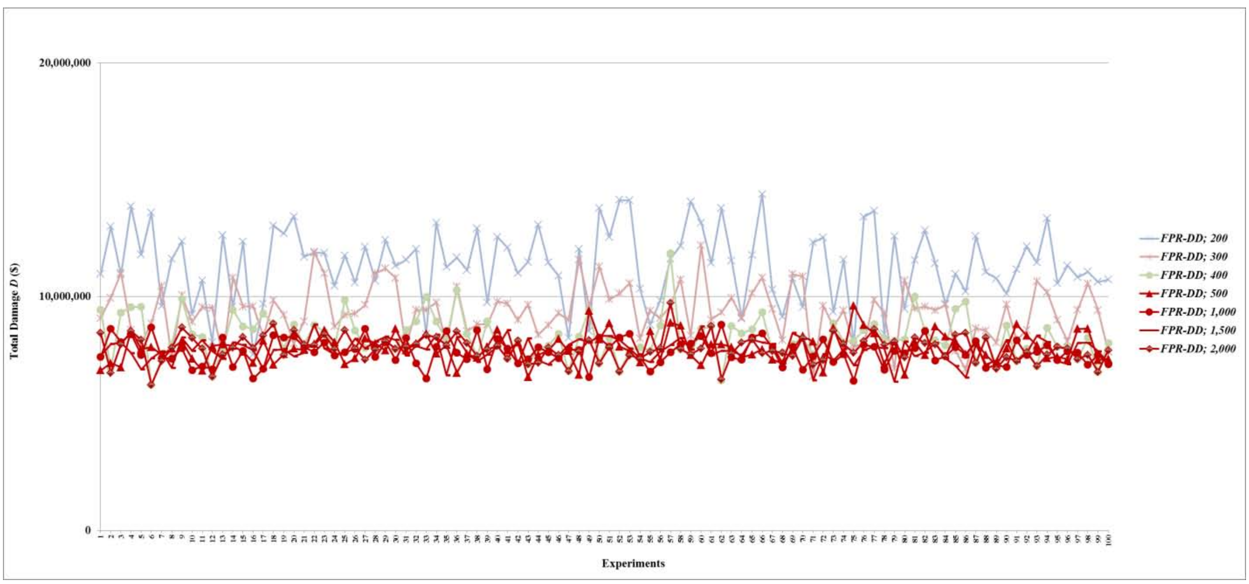

Figure 25: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DD* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

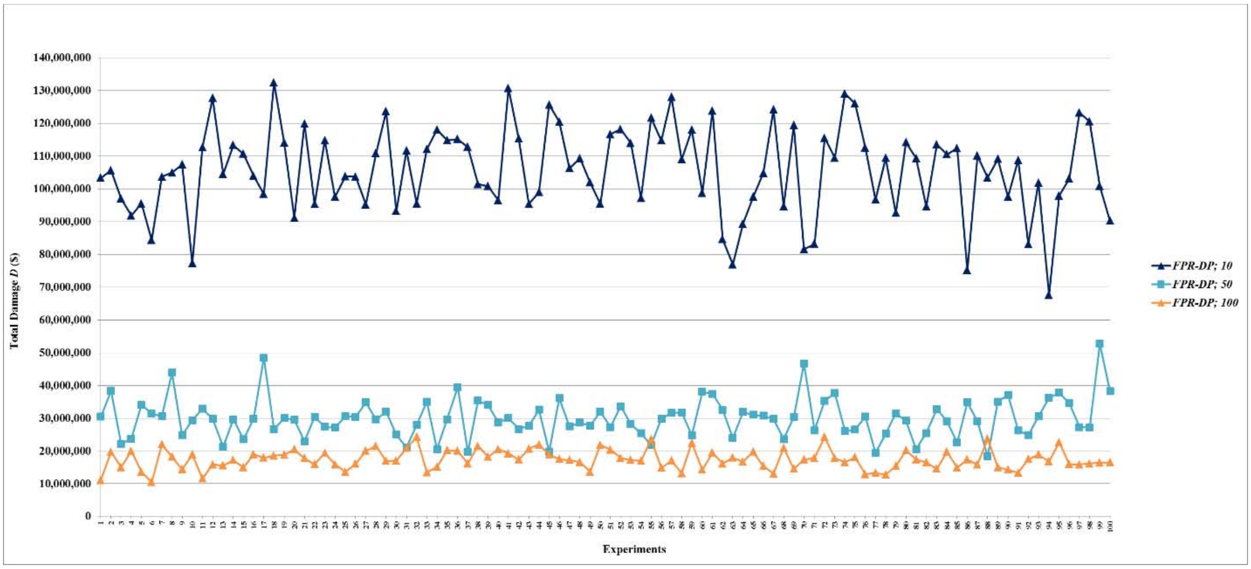

Figure 26: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DP* with resources 10, 50, and 100 units

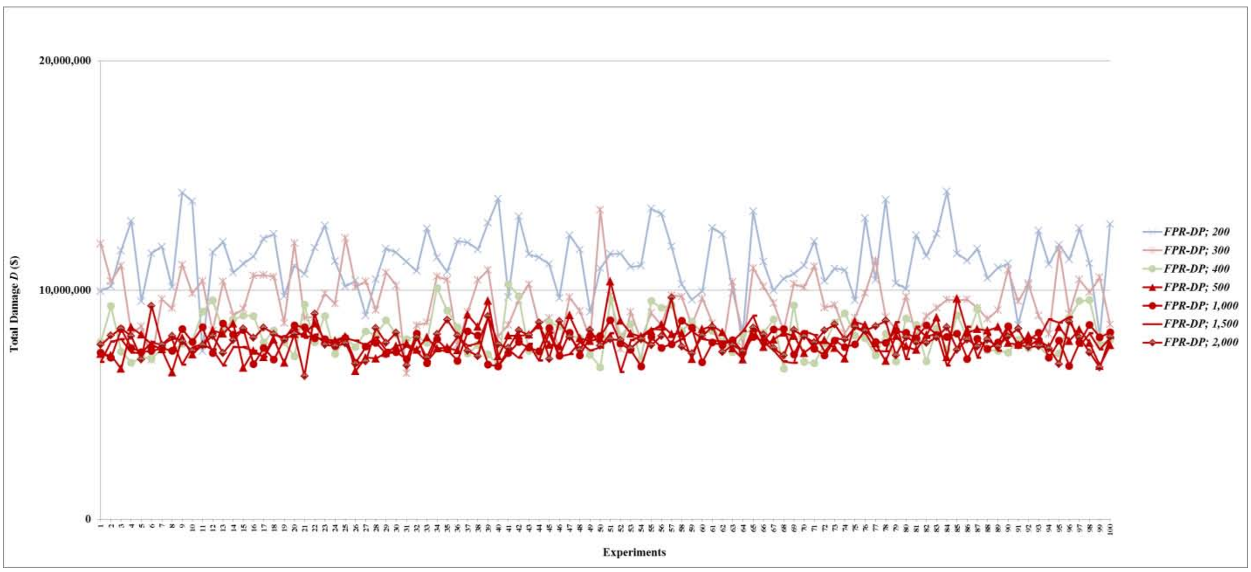

Figure 27: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DP* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

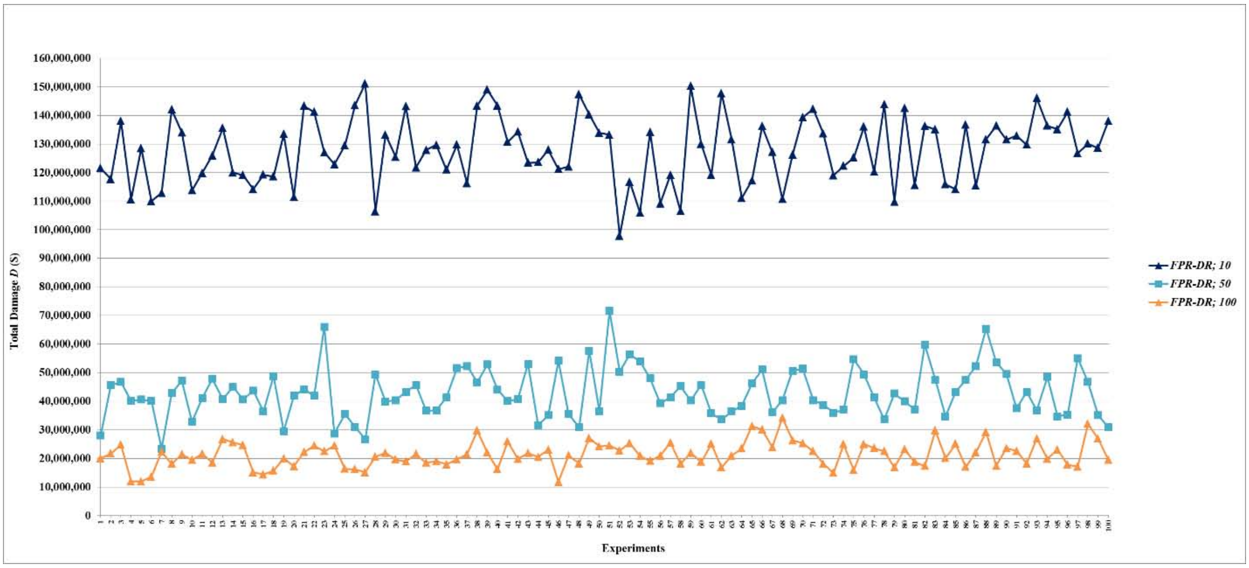

Figure 28: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DR* with resources 10, 50, and 100 units

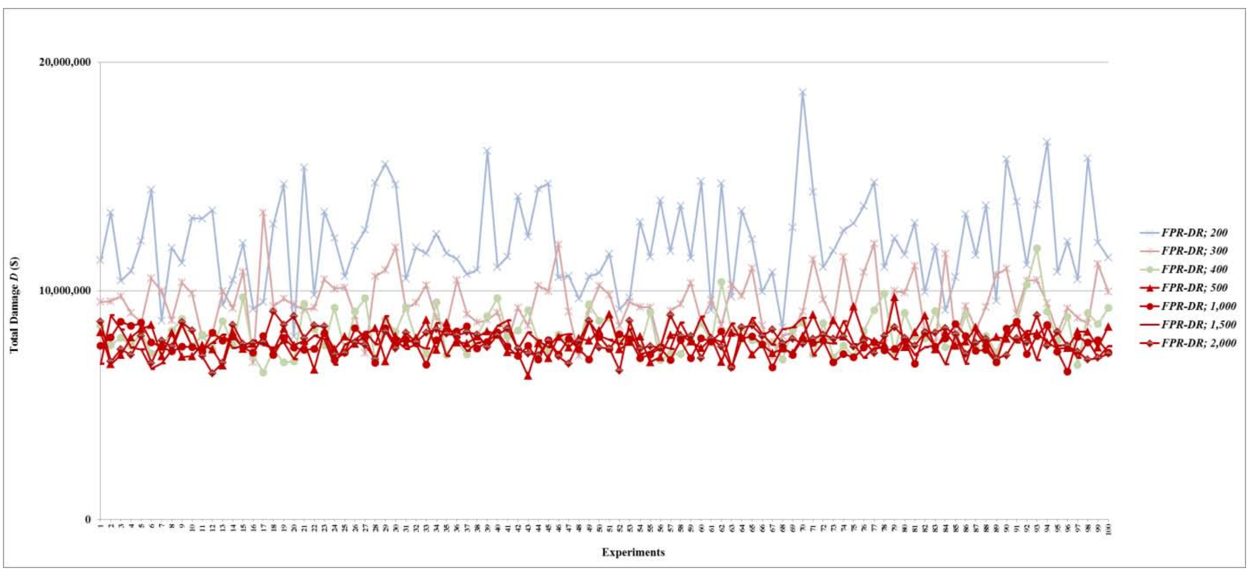

Figure 29: Total damage D of fault networks with cascading failures and backup capacity using the *FPR-DR* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

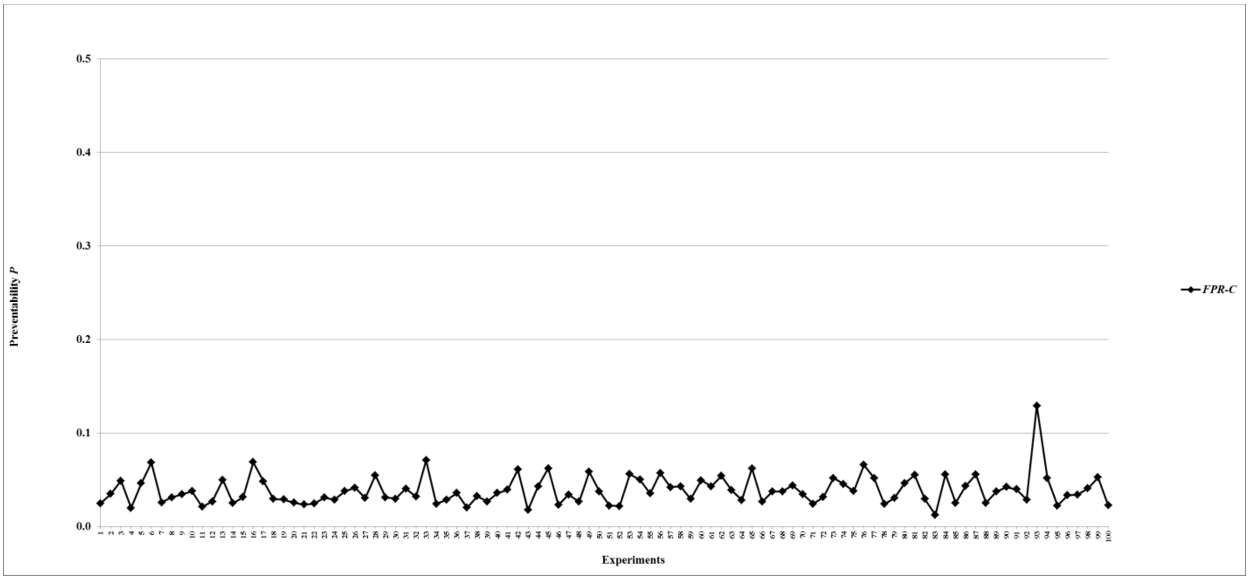

Figure 30: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-C*

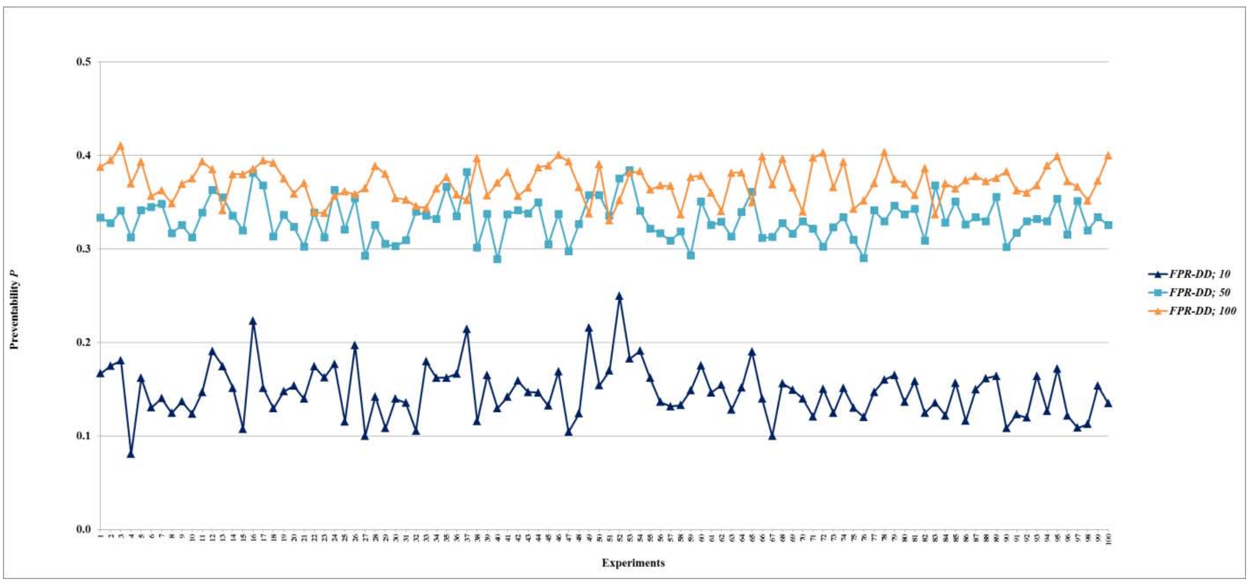

Figure 31: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DD* with resources 10, 50, and 100 units

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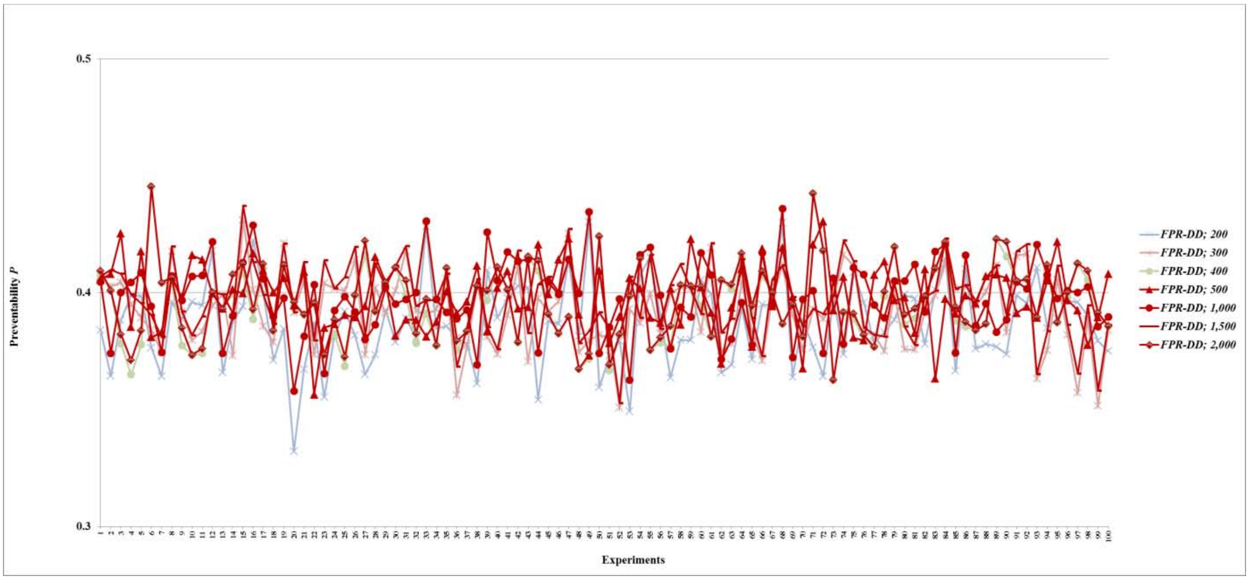

Figure 32: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DD* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

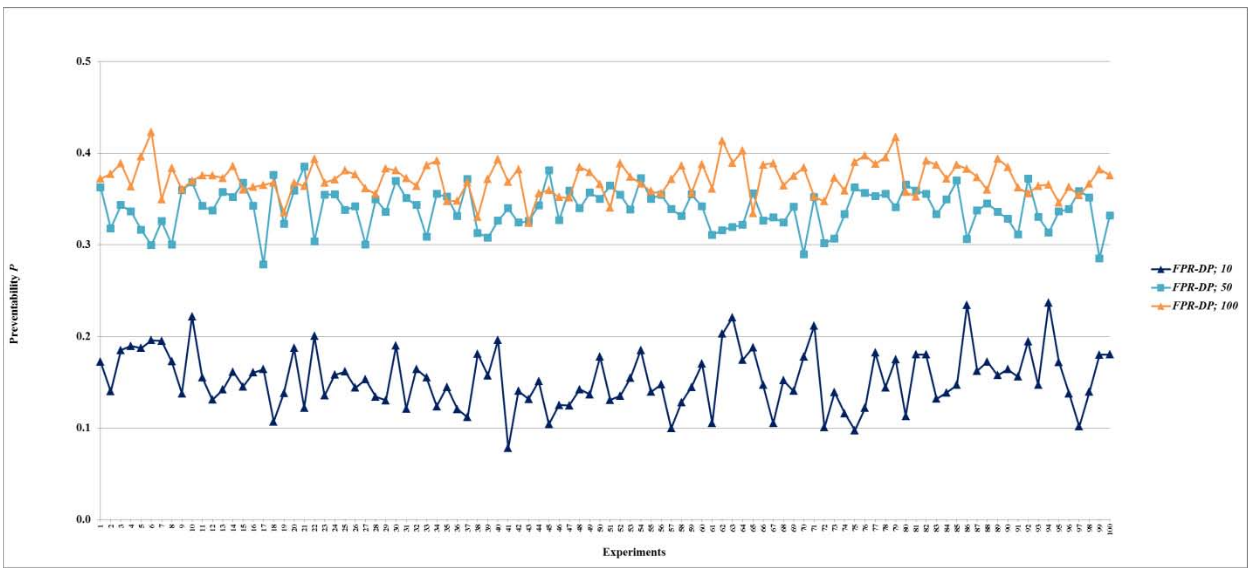

Figure 33: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DP* with resources 10, 50, and 100 units

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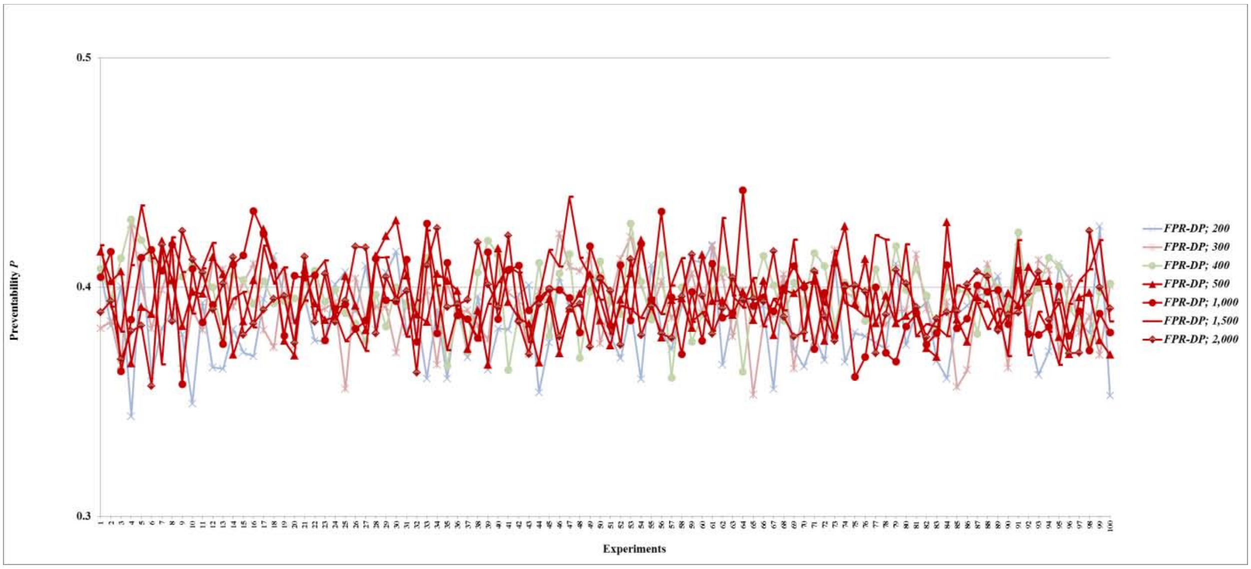

Figure 34: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DP* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

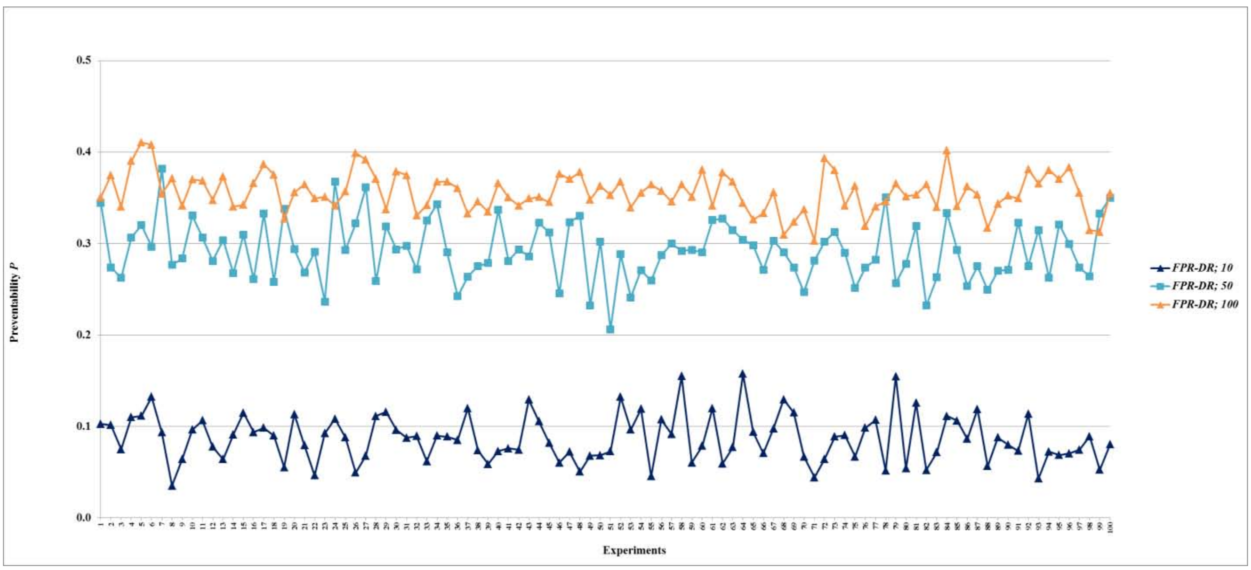

Figure 35: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DR* with resources 10, 50, and 100 units

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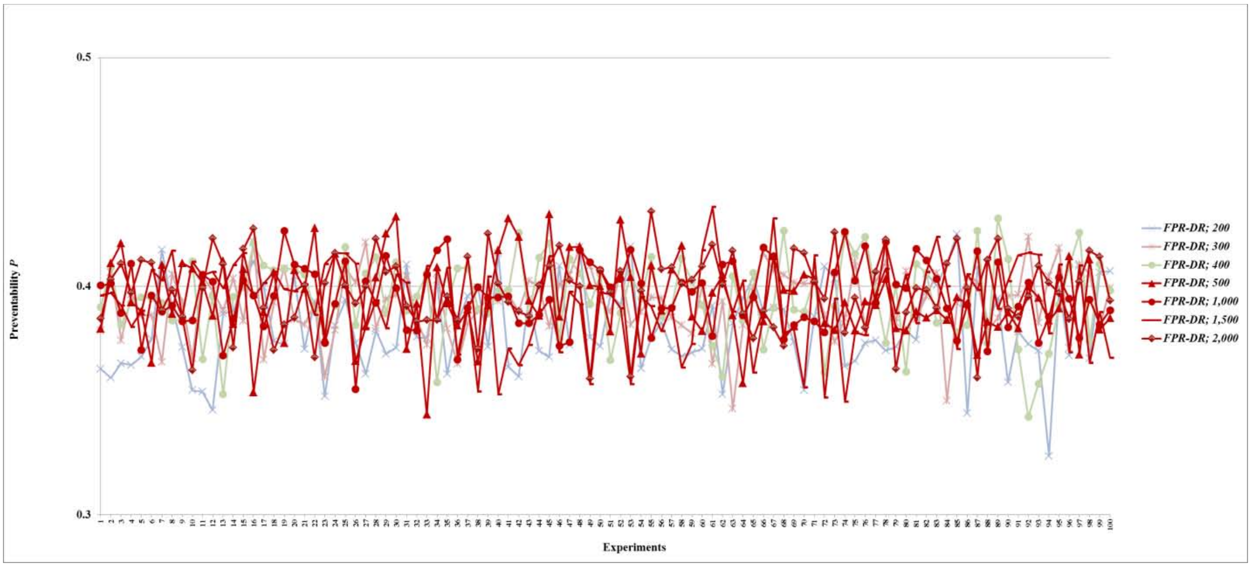

Figure 36: Preventability P of fault networks with cascading failures and backup capacity using the *FPR-DR* with resources 200, 300, 400, 500, 1,000, 1,500, and 2,000 units

Table 5: Total Damage and Preventability of Fault Networks with Cascading Failures and Backup Capacity

FPR Sequencer; Total Available Repair Resources	Total Damage D		Preventability P	
	Mean	Standard Deviation	Mean	Standard Deviation
FPR-C	148373001	9288272	0.03851	0.01589
FPR-DD; 10	105108343	11885502	0.14739	0.02841
FPR-DD; 50	30052458	5563336	0.33118	0.02094
FPR-DD; 100	17128898	2613894	0.37075	0.01843
FPR-DD; 200	11367503	1570235	0.38669	0.01775
FPR-DD; 300	9349344	1117094	0.39201	0.01617
FPR-DD; 400	8254510	924284	0.39495	0.01617
FPR-DD; 500	7799390	604234	0.39781	0.01431
FPR-DD; 1,000	7636528	545318	0.39766	0.01628
FPR-DD; 1,500	7689905	485015	0.39747	0.01575
FPR-DD; 2,000	7773727	560613	0.39660	0.01593
FPR-DP; 10	105705485	13271770	0.15372	0.03176
FPR-DP; 50	29992620	6110029	0.33925	0.02223
FPR-DP; 100	17395991	2966890	0.37180	0.01803
FPR-DP; 200	11310111	1369366	0.38602	0.01781
FPR-DP; 300	9461647	1230181	0.39217	0.01589
FPR-DP; 400	8065408	855075	0.39730	0.01407
FPR-DP; 500	7832061	657541	0.39407	0.01496
FPR-DP; 1,000	7696657	505783	0.39449	0.01668
FPR-DP; 1,500	7686924	512478	0.39678	0.01608
FPR-DP; 2,000	7830611	567063	0.39358	0.01438
FPR-DR; 10	127750386	11732134	0.08709	0.02602
FPR-DR; 50	42927586	8660819	0.29236	0.03252
FPR-DR; 100	21324304	4451081	0.35635	0.02123
FPR-DR; 200	12129522	2007120	0.38216	0.01887
FPR-DR; 300	9478993	1190272	0.39280	0.01448
FPR-DR; 400	8176260	924508	0.39493	0.01764
FPR-DR; 500	7824465	570546	0.39449	0.01706
FPR-DR; 1,000	7650762	487693	0.39555	0.01413
FPR-DR; 1,500	7761738	534957	0.39275	0.01824
FPR-DR; 2,000	7789133	565894	0.39807	0.30072

VI. Discussion

The experiments results show that applying the *FPR-DD* and *FPR-DP* results in almost the same total damage and preventability, although the *FPR-DD* aims to minimize total damage and the *FPR-DP* aims to maximize preventability. The *FPR-DD* is developed based on *LEMMA 1,* which assumes that any fault has at most one root cause. The *FPR-DP* is developed based on *LEMMA 2,* which assumes that a root cause only causes at most one faulty leaf node. In real-world complex systems, these two assumptions are hardly accurate. A root cause may cause multiple faulty leaf nodes, whereas a faulty leaf node may be caused by multiple root causes. This many-to-many relationship is a reason why the *FPR-DD* and *FPR-DP* perform almost the same. On the other hand, both perform better than the *FPR-C* and *FPR-DR;* the latter is also a decentralized FPR sequencer that randomly selects root nodes for repairs. This finding suggests that parallelism (simultaneous repairs of multiple root nodes) and FPR sequencers that take advantage of the structure of a fault network help improve the performance of FPR sequencers.

Total repair resources significantly affect the performance of FPR sequencers up to a point. Increasing repair resources improves the performance of FPR sequencers until the amount reaches a threshold. To maximize preventability requires less resource than minimizing total damage. This observation provides an important insight for managing faults in complex systems. For instance, in a transportation system with ongoing traffic problems in certain areas, a primary objective is to prevent congestion in other regions. To resolve each traffic problem as they occur may reduce damage but may not be necessary to prevent congestions elsewhere. As long as repair resources are sufficient to resolve a certain percentage of all traffic problems (69.93% if it is a cascading failure and 3.32% if traffic problems are random failures and mostly independent), any of the three decentralized FPR sequencers can prevent the maximum number of congestions from occurring.

Another important insight regarding random failures is that only a small fraction of the MRT, 6.63% based on the simulation experiments, is needed to minimize total damage and maximize preventability. A cascading failure may be catastrophic, but it may happen relatively rarely. Most complex systems routinely experience random failures that occur sporadically over a long period of time. The simulation experiments indicate that their long-term damage is higher than that of cascading failures, although the latter attract much more attention to the public for their broad impacts. It is not true that more repair resources always reduce damage caused by faults and prevent more faults from occurring. Random failures may be effectively and efficiently managed using the *FPR-DD* or *FPR-DP* with a relatively small amount of repair resources.

VII. Future Research

The simulation experiments use the electrical power grid of the Western United States to obtain the thresholds for repair resources. Additional experiments may be conducted in the future to fine-tune the thresholds with more input from the system. Other complex systems may have different threshold values and may also be studied in the future. The simulation results also suggest that parallelism and FPR sequencers that take advantage of the structure of a fault network help improve the performance of FPR sequencers. Future research may develop other FPR sequencers and experiment with additional complex systems to further identify how different FPR sequencers perform in different systems.

VIII. Conclusions

Four fault prevention and repair sequencers, including a centralized sequencer, *FPR-C,* and three decentralized sequencers, *FPR-DD, FPR-DP,* and *FPR-DR,* are developed to sequence the prevention and repair of three different types of faults in a complex system, including random failures, cascading failures, and cascading failures with backup capacity. The *FPR-DD* aims to minimize total damage caused by faults. The *FPR-DP* aims to maximize preventability, the percentage of faults prevented from occurring. The *FPR-DR* randomly selects faults for simultaneous repairs. All four FPR sequencers are implemented in a software program to generate FPR sequences and compare and validate their performance. The electrical power grid of the Western United States is studied in total 10,500 experiments to examine the performance of the four FPR sequencers. Results show that either the *FPR-DD* or *FPR-DP* should be used to prevent and repair faults in complex systems; both sequencers minimize total damage and maximize preventability.

Total repair resources affect the performance of three decentralized FPR sequencers. Total repair resources have different thresholds for different types of failures and performance metrics. Below a threshold, increasing total repair resources improves the performance of an FPR sequencer. Above the threshold, increasing total repair resources does not further improve the performance of the FPR sequencer. The threshold of repair resources is measured as a percentage of repair resources sufficient to simultaneously repair all root nodes, which are root causes and must be repaired directly using repair resources. Below is a summary of thresholds for three types of failures:

(a) Random failures: 6.63% for total damage and 3.32% for preventability;
(b) Cascading failures: 100% for total damage. No threshold for preventability since faults are not prevented once a cascading failure begins; and
(c) Cascading failures with backup capacity: 100% for total damage and 69.93% for preventability.

In summary, to manage a cascading failure, increasing repair resources reduces total damage caused by faults until repair resources are sufficient to repair all root causes of the cascading failure. Without backup capacity for nodes to continue operating, e.g., backup power in a smart grid, faults in a cascading failure cannot be prevented since the cascading failure happens quickly before any repair may be completed. When there is backup capacity, increasing repair resources up to 69.93% of the MRT help prevent more faults from occurring. For random failures, only 6.63% of the MRT are necessary to minimize total damage and 3.32% of those are needed to maximize preventability.

Availability of Data and Material

All data used are available in this article or publicly available.

Conflict of Interests

None.

Funding

None.

Authors' Contributions

The author contributed 100% of this article.

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Fail Fast, Fix Faster: Risk-Based Testing for Agile Product Teams

By Kiran K. Kalyanaraman

Abstract- Efficient and effective testing strategies are critical within agile product development. Traditional testing approaches often fall short in fast-paced agile environments, leading to delayed feedback and increased time-to-market. A proposed methodology, Risk-Based Testing (RBT) tailored for agile teams, prioritizes testing efforts based on the likelihood and impact of potential risks. By integrating RBT into the agile workflow, the feedback loop is accelerated, enabling teams to "fail fast" and "fix faster." The efficacy of this approach is demonstrated through case studies and simulated agile sprints, showcasing a significant reduction in critical defects and improved release velocity. Practical implications of implementing RBT are discussed, highlighting its potential to enhance product quality and accelerate development cycles. Results indicate a substantial improvement in agile testing practices, paving the way for more responsive and resilient product development. A novel perspective on agile testing is offered by providing a structured framework for prioritizing testing efforts based on risk assessments, thereby improving overall product quality and release speed.

Keywords: agile testing, risk-based testing, agile product development, test prioritization, defect management, continuous integration, continuous delivery.

GJRE-G Classification: LCC Code: QA76.76.T48

FAILFASTFIXFASTERRISKBASEDTESTINGFORAGILEPRODUCTTEAMS

Strictly as per the compliance and regulations of:

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I. Introduction

Agile methodologies have revolutionized software development by emphasizing iterative development, rapid feedback, and adaptability. However, maintaining high product quality within these fast-paced environments presents a significant challenge. Traditional testing approaches, often sequential and exhaustive, struggle to keep pace with the rapid release cycles of agile teams. The need for a more dynamic and responsive testing strategy is evident (Davis, 2020).

Specifically, the challenge of testing in agile is compounded by the continuous integration and continuous delivery (CI/CD) pipelines. These environments demand rapid feedback on code changes to prevent the accumulation of defects. Traditional testing often leads to bottlenecks, delaying releases and hindering the "fail fast" principle central to agile (Martinez, 2023).

The limitations of traditional testing in agile stem from their inability to prioritize testing efforts based on risk. For instance, testing every feature with equal intensity can lead to wasted effort on low-risk areas while neglecting critical functionalities. This results in delayed detection of high-impact defects and increased time-to-market (Anderson, 2023).

Risk-Based Testing (RBT) tailored for agile product teams is proposed to address these limitations. This approach leverages risk assessment techniques to prioritize testing efforts, focusing on areas with the highest potential impact and likelihood of defects. By integrating RBT into the agile workflow, we aim to accelerate the feedback loop and enable teams to "fail fast, fix faster" (Clark, 2021).

The novelty of this approach lies in its ability to dynamically adapt testing priorities based on evolving risks. This allows agile teams to focus on the most critical areas at each stage of development, ensuring that high-impact defects are detected and addressed early. We believe that this methodology offers a significant improvement over traditional testing approaches in agile environments (Bennett, 2022).

II. Problem Statement

The core problem addressed in this paper is the inefficiency of traditional testing approaches within the context of rapid agile product development. This issue is particularly relevant due to the constant pressure to deliver high-quality software at an accelerated pace. Existing testing methods often fail to align with the dynamic nature of agile sprints (Johnson, 2020).

Specifically, the problem of delayed feedback in agile testing is exacerbated by the lack of risk prioritization. Testing teams often spend equal time on low-risk and high-risk features, leading to inefficient resource allocation. For instance, a minor UI change may receive the same level of scrutiny as a critical backend algorithm, wasting valuable testing time (Hernandez, 2022).

Furthermore, the scalability of traditional testing is a significant concern in agile environments. As the complexity of products increases and the frequency of releases accelerates, traditional testing methods struggle to keep pace. This leads to testing bottlenecks and delayed releases, hindering the agile workflow (Garcia, 2023). The limitations of current testing approaches are also evident in their reactive nature. Many teams rely on post-development testing, leading to late detection of defects. This reactive approach increases the cost and effort required to fix defects, as they are discovered later in the development cycle.

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Therefore, there is a clear need for a proactive and risk-driven testing strategy that aligns with the principles of agile product development. Such a strategy should be able to prioritize testing efforts, adapt to changing requirements, and provide rapid feedback to development teams.

III. Solution

To address the challenges outlined in the problem statement, we propose a Risk-Based Testing (RBT) methodology tailored for agile product teams. This approach leverages risk assessment techniques to prioritize testing efforts, focusing on areas with the highest potential impact and likelihood of defects. The core idea is to shift from a reactive to a proactive testing approach (Rodriguez, 2018).

Specifically, our solution incorporates a risk assessment framework that identifies and prioritizes potential risks based on their impact and likelihood. For instance, we use a risk matrix, where the axes represent "likelihood" and "impact," to categorize risks as high, medium, or low, guiding testing efforts accordingly. This allows us to focus on the most critical areas (Patel, 2020). The risk assessment is conducted collaboratively, involving developers, testers, and product owners, to ensure a comprehensive understanding of potential issues. The key innovation of our approach lies in its integration with the agile workflow. We propose incorporating risk assessment and prioritization into sprint planning and daily stand-ups. This ensures that testing efforts are aligned with the evolving priorities of the sprint (Nguyen, 2022).

Furthermore, our solution emphasizes continuous risk assessment and adaptation. As requirements and risks evolve, testing priorities are dynamically adjusted. We employ techniques such as risk burndown charts to track and manage risks throughout the sprint. These charts visually represent the reduction of risks over time, allowing teams to monitor progress and identify areas requiring attention. Automated test selection is also integrated, using risk-based criteria to select and execute the most relevant tests. This reduces redundancy and ensures that critical functionalities are thoroughly tested. The effectiveness of our approach is demonstrated through case studies and simulated agile sprints. The results show that RBT significantly reduces the number of critical defects and improves release velocity. This highlights the potential of our proposed methodology for enhancing agile testing practices (Martinez, 2023).

IV. Uses

The proposed Risk-Based Testing methodology has a wide range of practical applications in agile product development. One key application is in sprint planning, where risk assessments can be used to prioritize testing tasks and allocate resources effectively (Taylor, 2022). For example, if a high-risk feature is identified, the team can allocate more testing resources and time to that area. Another important application is in continuous integration and continuous delivery (CI/CD) pipelines.

By integrating RBT into CI/CD, teams can ensure that high-risk code changes are tested thoroughly before being deployed to production (Smith, 2023). This can involve automated test selection based on risk criteria, ensuring that critical functionalities are tested with each build. Furthermore, our solution can be applied to regression testing, where risk-based test selection can reduce the number of tests required while maintaining high coverage of critical functionalities. This means that instead of running all regression tests, only those covering high-risk areas are executed, saving time and resources. RBT can also be used in exploratory testing, where testers focus on high-risk areas based on the risk assessments, allowing for more targeted and efficient exploration.

V. Impact

The proposed RBT methodology has the potential to make a significant impact on agile product development by improving product quality and accelerating release cycles. By focusing on high-risk areas, teams can reduce the number of critical defects and deliver more reliable software (Williams, 2023). Specifically, our approach can contribute to a reduction in time-to-market by enabling teams to "fail fast, fix faster." Early detection of defects reduces the cost and effort required for remediation, leading to faster releases. RBT can also improve team collaboration and communication by providing a shared understanding of risks and testing priorities. This promotes a more proactive and risk-aware culture within the team. The methodology also has the potential to enhance customer satisfaction by ensuring that high-impact features are thoroughly tested, leading to a more stable and reliable product. Moreover, the adoption of RBT can lead to better resource allocation by focusing testing efforts on the most critical areas, reducing waste and improving efficiency. The overall impact of RBT is to create a more efficient, reliable, and responsive agile development process.

VI. Scope

The scope of this paper focuses on the application of Risk-Based Testing (RBT) within agile product development teams, particularly emphasizing its integration into the daily workflows of these teams. This includes the implementation of risk assessment techniques during sprint planning (Smith, 2023), daily stand-ups, and continuous integration/continuous delivery (CI/CD) pipelines (Taylor, 2022). We

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concentrate on the practical application of RBT to prioritize testing efforts based on the potential impact and likelihood of defects, aiming to improve the efficiency and effectiveness of agile testing (Rodriguez, 2018).

The case studies and simulated agile sprints used to evaluate the methodology primarily involve software development projects, though the principles can be adapted to other product development contexts. The paper explores the use of risk matrices, risk burndown charts (Patel, 2020), and automated test selection, utilizing risk assessment frameworks (Nguyen, 2022), as key components of the RBT framework, providing practical guidance for their implementation. We limit our analysis to the impact of RBT on product quality, release velocity, and team collaboration, focusing on measurable outcomes that demonstrate the benefits of this approach. The scope also considers the adaptability of RBT to various agile methodologies, including Scrum and Kanban, highlighting its flexibility in different agile environments.

VII. Conclusion

In conclusion, this paper has presented a Risk-Based Testing (RBT) methodology tailored for agile product teams, addressing the limitations of traditional testing approaches in fast-paced development environments. By prioritizing testing efforts based on risk assessments, RBT enables teams to "fail fast, fix faster," leading to improved product quality and accelerated release cycles. The integration of RBT into the agile workflow, including sprint planning (Smith, 2023) and CI/CD pipelines (Taylor, 2022), facilitates continuous risk assessment and adaptation, ensuring that testing priorities remain aligned with evolving requirements and risks. The case studies and simulated agile sprints demonstrate the efficacy of RBT, showcasing a significant reduction in critical defects and improved release velocity (Rodriguez, 2018).

The practical applications of RBT, including its use in sprint planning, regression testing, and exploratory testing, highlight its versatility and adaptability to various agile projects. The impact of RBT extends beyond improved product quality and release velocity, encompassing enhanced team collaboration, better resource allocation, and increased customer satisfaction. The adoption of RBT represents a paradigm shift from reactive to proactive testing, fostering a risk-aware culture within agile teams and ultimately leading to more reliable and responsive product development. Risk burndown charts (Patel, 2020), and utilizing risk assessment frameworks (Nguyen, 2022) are key components of the methodology. Integrating Risk-Based Testing into Agile Workflows (O'Brien, 2021) is a crucial part of the process.

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Adopting Manufacturing Flexibility to Achieve Competitive Advantage in a Global Economy

By Chinedu James Ujam

Abstract- Considering the requirements of the market and the effects of globalization, this research investigates the concept of manufacturing flexibility and underlines its potential to enhance competitive advantage. To explore its various aspects and its effects on operational efficiency, customer satisfaction, and adaptability to market fluctuations, the research adopts a mixed-methods approach that integrates literature review and case analyses of global manufacturing companies. The results suggest that manufacturing flexibility significantly enhances operational efficiency and the ability to adapt to uncertain market conditions. Additionally, the research adopts a multidisciplinary perspective to analyze current shifts in corporate organizational strategies and their effects on employment and industrial structures. It develops a model based on competencies that combines internal management practices with external relationships into a cohesive analytical framework. This model demonstrates how companies adapt to new competitive challenges by effectively managing their capabilities.

Keywords: manufacturing flexibility, competitive advantage, global economy, flexible manufacturing systems (FMS), operational agility.

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ADOPTINGMANUFACTURINGFLEXIBILITYTOACHIEVECOMPETITIVEADVANTAGEINAGLOBALECONOMY

Strictly as per the compliance and regulations of:

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Abstract- Considering the requirements of the market and the effects of globalization, this research investigates the concept of manufacturing flexibility and underlines its potential to enhance competitive advantage. To explore its various aspects and its effects on operational efficiency, customer satisfaction, and adaptability to market fluctuations, the research adopts a mixed-methods approach that integrates literature review and case analyses of global manufacturing companies. The results suggest that manufacturing flexibility significantly enhances operational efficiency and the ability to adapt to uncertain market conditions. Additionally, the research adopts a multidisciplinary perspective to analyze current shifts in corporate organizational strategies and their effects on employment and industrial structures. It develops a model based on competencies that combines internal management practices with external relationships into a cohesive analytical framework. This model demonstrates how companies adapt to new competitive challenges by effectively managing their capabilities. The study also discusses the evolution of global production networks, focusing on crucial elements such as geography, activity, and power dynamics. From the lens of labor market segmentation theory, it evaluates the employment outcomes associated with network-based organizational forms and competency-centric strategies, highlighting the emergence of new patterns of employment segmentation within and among firms. The research points out the most common global network organizational frameworks that alter the creation and distribution of value in international industries. The conclusion of the study emphasizes the critical need for innovative policies to strike a balance between competitive pressures from one firm to another and within firms, alongside the challenges and obstacles in achieving this aim.

Keywords: manufacturing flexibility, competitive advantage, global economy, flexible manufacturing systems (FMS), operational agility.

I. Introduction

Technological transformations, evolving consumer preferences, and intense rivalry characterize the worldwide economy. Manufacturers encounter challenges such as reduced product lifespan, the need for personalization, and fluctuations in the supply chain. Traditional manufacturing techniques often struggle to keep pace with these changes. Manufacturing flexibility, defined as the capacity to adjust production methods to varying circumstances efficiently and economically, has become a key strategic necessity. This research delves into how manufacturing flexibility provides organizations with a competitive advantage in the global market. It emphasizes the role of flexibility in enabling companies to respond to shifting market dynamics, manage risks, and enhance customer satisfaction. Globally, manufacturers are experiencing a profound shift due to changes in external markets and advancements in technology. The aim now extends beyond simply "producing superior products" to "enhancing production processes," which encompasses aspects such as management, engineering, service planning, and implementation. A few critical market transformations drive this dual focus on refining products and processes. The primary trends disrupting the traditional framework of the global manufacturing industry are economic adjustments triggered by downturns in developed nations and the rise of rapidly expanding emerging markets. Furthermore, the sector faces challenges from technological evolution related to Big Data, the Internet of Things, mobile and social computing, along with cloud-based technologies. Issues involving talent shortages, complex partner and supplier networks, intensified global competition, and increased regulations.

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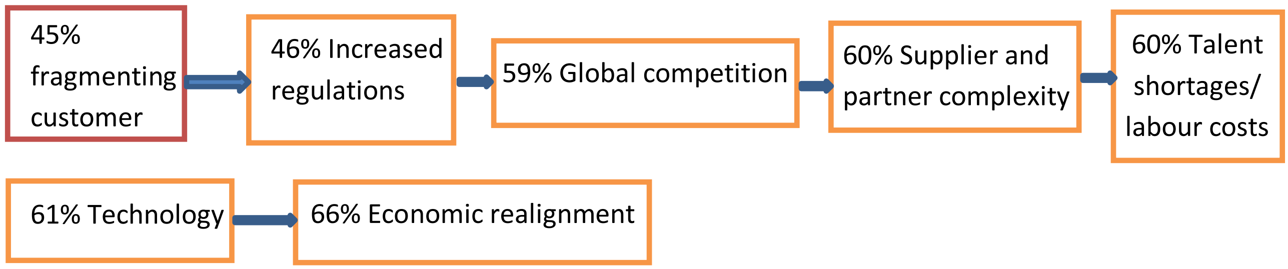

Fig. 1: External market shifts are remaking the landscape for manufacturers

The influence of these modifications is viewed in different ways by executive functions and varies in strength according to the organization's size, sector, and geographical area. For example, firms in the industrial equipment field are more preoccupied with economic adjustments compared to others (74% of respondents). The shift in technology is particularly significant in Asia's rapidly expanding markets (75%), where companies can quickly embrace the latest tools due to their minimal reliance on outdated systems. Nonetheless, 69% of top executives in the manufacturing industry highlight labor expenses and workforce shortages as significant issues. Moreover, C-level leaders also identify increasing regulatory pressures as another vital concern (52%), forming the context in which all these transformations are occurring.

In response to these influences, manufacturing firms are implementing various approaches to modify their operations and identify innovative ways to distinguish themselves. One important strategy involves merging new services with current product lines to enhance value during both the sales process and the lifespan of the product. Other tactics focus on internationalizing product development and streamlining planning and engineering processes to create nearly limitless product variations based on fundamental platforms. This analysis explores how manufacturers are adapting their operations to flourish in the existing global landscape. The report highlights three key themes that underpin successful transformation efforts:

The service imperative, which transforms repair and maintenance into a vital differentiator and a significant profit source; reimagining strategy and planning to become the primary source of competitive edge rather than solely operational efficiency; and pervasive innovation, which extends beyond conventional product research and development to include all components of the enterprise ecosystem.

These three approaches establish a framework for turning change into tangible business achievements. By prioritizing these elements, manufacturers can realize substantial reductions in costs and growth in revenue.

Definitions used in the study:

Strategy and planning encompass the choices made by a company regarding the design, sourcing, production, and servicing of its goods, along with the coordination of these activities.

Service pertains to the methods a company employs to maintain its products, provide its services, and manage these operations.

Manufacturing operations involve the implementation of production processes, which include procurement, logistics, manufacturing, scheduling, and oversight.

II. Manufacturing Flexibility

Manufacturing flexibility has been a significant focus in operations management, with researchers exploring its various aspects and advantages. The main aspects consist of:

1. *Volume Flexibility:* The capacity to modify production levels according to changing demand. Slack (1987) stated that volume flexibility is essential for handling seasonal variations and uncertainty in the market.
2. *Product Flexibility:* The ability to efficiently transition between multiple products or variations. This is crucial in sectors that require high customization, like electronics and automotive (Gerwin, 1993).
3. *Process Flexibility:* The capability of manufacturing processes to adjust to alterations in product design or production methods. This fosters innovation and minimizes downtime during changes (Upton, 1994).
4. *Supply Chain Flexibility:* The responsiveness of supply chains to disturbances, ensuring ongoing operations and resilience (Christopher & Towill, 2001).

Theoretical Foundations: According to the Resource-Based View (RBV), manufacturing flexibility is a critical, unique, and hard-to-replicate asset that offers a lasting competitive edge. Research done by Hayes and Wheelwright (1984) highlights the importance of flexible manufacturing systems (FMS) in achieving alignment with market needs.

Empirical Evidence: Studies indicate that companies exhibiting greater manufacturing flexibility perform better than their counterparts regarding operational efficiency, customer satisfaction, and adaptability in the market (Sethi & Sethi, 1990).

III. Waves of Change

As market dynamics and technological advancements disrupt many long-established beliefs regarding manufacturing, a strategic shift is essential. It is anticipated that over two-thirds (68%) of manufacturing companies will undertake significant transformations in their business processes within the next three years. In terms of geography, a larger percentage of firms in Europe (74%) are likely to revise their fundamental operating frameworks compared to those in North America (64%) and Asia (67%). In light of these changes, innovative approaches are required to bring about meaningful transformation. Major focus areas for this manufacturing change include revising strategies and planning, emphasizing service, and fostering innovation widely. How manufacturers approach these areas can greatly influence their revenues and expenses.

Reassessing strategy and planning According to our research, the main factors contributing to business success are strategy and planning for products (43% of participants), services (37%), and manufacturing (31%). In all sectors, strategy and planning are more critical than operational execution as a competitive factor.

The growing focus on strategy and planning can be attributed to the diminishing effectiveness of traditional methods for enhancing profitability. More than half (52%) of those surveyed stated that they have exhausted almost all potential cost savings in their manufacturing processes. While this statistic suggests that there is still progress to be made, 65% of executives surveyed feel that optimizing operations has shifted from being a differentiator to merely the baseline requirement for the industry. This proportion is expected to increase to 71% within three years.

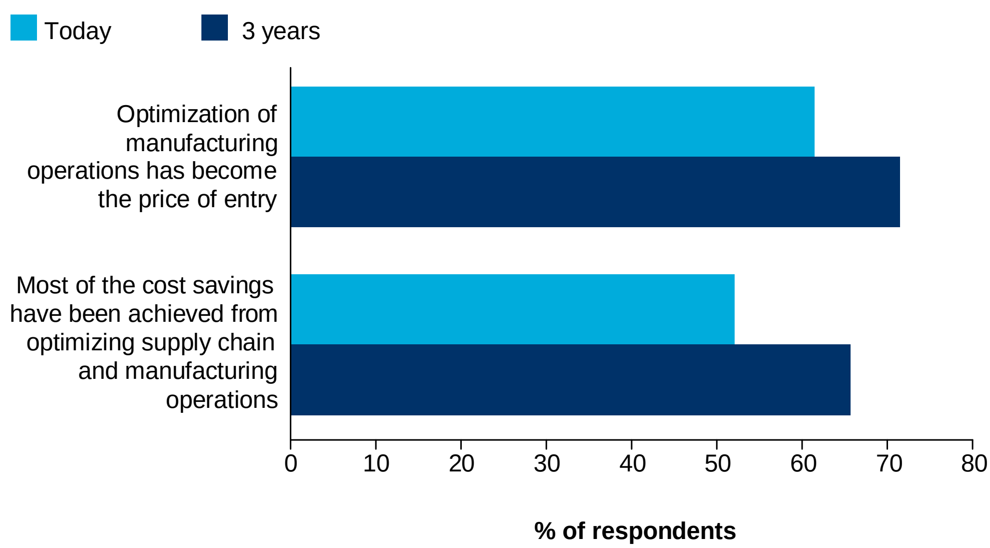

Fig. 2: Optimization of manufacturing operations becomes routine

Another factor contributing to the increased focus on planning and strategy is customer fragmentation, which poses a significant challenge for manufacturers. This trend of customer fragmentation is especially evident in Asia (57%), where there is a wide range of customer requirements and financial capacities, capturing the attention of C-level leaders (57%). In light of this growing fragmentation, over two-thirds of those surveyed intend to implement Voice of the Customer strategies, with industries such as aerospace (72%), high technology (75%), and large corporations (79%) taking the lead in gaining deeper insights into their customers. More than half of the executives participating in the survey aim to create networked or "smart" products that establish a feedback mechanism utilizing customer information, particularly high tech (71%) and large companies (60%) at the forefront. Approximately 43% of manufacturers are considering moving more production closer to their customers, especially in the medical device (54%) and automotive (50%) sectors. However, manufacturers are not merely responding to challenges like the diminished role of operations as a competitive advantage and increasing customer fragmentation. One proactive approach being adopted is enhancing the alignment of strategy and planning between engineering and service departments, expected to grow from 54% currently to 73% in three years, as revealed by the survey. Improved synergy between engineering and service teams aligns with a stronger commitment from executives to utilize feedback from service delivery (currently at 52%) to influence decision-making and facilitate advancements in product development and quality (projected to be 65% in three years).

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IV. Policy Challenge

Addressing the social and environmental issues of today effectively requires communities, nations, and regions around the globe to generate economic prosperity in ways that align with the principles of sustainable development. This, in turn, relies on their capacity to devise developmental strategies that leverage suitable forms of economic competitive advantage amidst increasingly competitive global markets. This challenge is exemplified by the objective set at the Lisbon Summit in March 2000, where the European Community aimed to become "the most competitive knowledge-based economy in the world" by 2010, capable of sustaining economic growth while creating better jobs and promoting social cohesion. A recent communication from the European Commission on 'corporate social responsibility' (CSR) aims to clarify how CSR can help achieve this objective. The Commission appropriately situates CSR within the broader framework of globalization and the evolving discourse on the role of businesses in society. The communication mainly concentrates on how to promote voluntary business actions and their outcomes within a setting of stakeholder dialogue. Consequently, it underscores the necessity to enhance micro-level management abilities, tools, and standards.

The prospect of a considerable macro-level change in the function of businesses in society has not been thoroughly investigated, including its implications for policy. There has been little to no examination thus far regarding whether CSR could alter the foundation of a nation's economic competitive advantage. Practitioners and analysts of CSR have generally remained disconnected from and unaware of the operation of the larger competitive landscape. The rationale behind CSR has stayed largely a concern at the micro level. Likewise, mainstream analysts and those designing the frameworks for international competition largely overlook the potential for a nation's economic competitive edge to be rooted in the social and environmental performance aspects of the business sector itself. The Copenhagen Centre has taken steps to bridge this gap by beginning to investigate how changes in the role of businesses in society might support new forms of international economic competitive advantage. At this juncture, the goal has been to spark essential discussions by outlining various issues, challenges, and dilemmas facing policymakers from government agencies, the business sector, and civil society organizations. Preliminary findings indicate that:

- The societal gains from shifts in the business role in society will remain restricted unless these changes align with economic competitiveness strategies and outcomes at local, national, and regional levels.
- Such strategies and results can and should be cultivated, being most effective when grounded in collaborations between the business sector, civil society, and public organizations.
- Public policy has the potential to enhance the connections between these partnerships and the competitive advantages of nations.

V. Competitive Paradoxes

The effects of globalization on social and environmental aspects generate a spectrum of divergent opinions. While some emphasize the apparent benefits of global investments and commerce, others stress the obvious drawbacks. Similarly, the connection between economic advancement and social as well as environmental results has been a subject of intense debate. The most pressing concerns revolve around the destinies of over a billion individuals, primarily in less economically developed countries, who survive on less than one US dollar daily. Yet, the contradictions regarding economic growth are just as, if not more, evident in so-called advanced nations. Economies traditionally classified as 'Anglo-Saxon' are not only among the most competitive globally but also stand out in the developed world for their significant levels of income disparity among citizens. Across Europe, the remarkable economic progress of recent decades has been paralleled by a rise in inequalities stemming from uneven access to employment opportunities. In fact, the concept of access to work is evolving, as remote work, part-time positions, and flexible job arrangements become increasingly prevalent. By the mid-1990s, for instance, a quarter of all jobs in the UK were part-time.

Increasing demands are being made on public institutions at the national, regional, and international levels to transform public policies to implement the necessary checks and balances that oversee how economic activities lead to social and environmental results. The Lisbon declaration serves as a prominent instance where the European Community has recognized its duties and reiterated its dedication to becoming the leading competitive knowledge economy globally while also fostering and maintaining social unity. The South African Government has articulated, though in different terms, strategies and guidelines intended to prepare the economy for global competition while simultaneously promoting a defined agenda of black economic empowerment throughout the country's labor and financial sectors. These national and regional strategies reflect both deep-seated tensions and coherent planning efforts. Every facet of publicly funded social welfare spending across Europe faces scrutiny due to an apparent push for more streamlined economies. This occurs even though a knowledge-driven economy can certainly lead to disparities in a context where at least 15% of adults possess only basic

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literacy skills in 14 out of 20 OECD nations, or in the UK, where it is estimated that about 25% of the populace cannot read or comprehend simple government documents. Initiatives aimed at black empowerment from the South African Government face criticism from various quarters, with detractors claiming they compromise the nation's economic competitiveness and thus the foundation upon which black economic empowerment could be realized. Such criticisms persist despite a widespread acknowledgement that social unrest stemming from unequal development acts as a significant deterrent to potential foreign investment. These conflicting policies evoke discussions from the 1990s regarding the degree to which developing nations needed to 'catch up' to developed countries prior to tackling escalating environmental issues. Opponents of direct measures to elevate environmental standards often pointed to the Environmental Kuznets Curve, which is an inverted U-shaped model suggesting that pollution levels decline only after a certain level of economic affluence is achieved that allows governments to invest in environmental conservation (see Figure 1). For instance, economist Francis Cairncross posited that as impoverished nations become wealthier, and with trade acting as a substantial source of riches, their environmental criteria will improve.

VI. Traditional View on Economic Competitiveness

The economic competitiveness among countries is typically assessed through a range of metrics related to productive elements that reflect flexibility in the market, innovation, as well as technological and organizational progressiveness, along with social and political stability. There exists a multitude of competitiveness indexes. While each varies in focus, they generally cover similar areas. For instance, the IMD, which is a prominent European business institution, employs 314 criteria to formulate its economic competitiveness rankings for 49 nations. These criteria are categorized into four main domains: economic performance, efficiency of government and business, and infrastructure. The IMD's assessment does not incorporate corporate responsibility. Nevertheless, many principles of corporate responsibility are represented in how the IMD approaches so-called 'soft' matters, including 'values-in-society' and perspectives on gender and various forms of discrimination. It is noteworthy that most of these topics fall under the IMD's final category, 'infrastructure', indicating that the IMD perceives them as not directly contributing to business productivity. In fact, they are typically regarded as not even indirectly impacting business efficacy or overall productivity since these criteria are mostly articulated negatively, meaning they only score favorably toward economic competitiveness if they do not impede market flexibility or productivity. At times, this may verge on redundancy. For instance, the criterion concerning 'environmental regulations' is interpreted to imply "Environmental regulations and compliance do not obstruct the competitiveness of enterprises." In essence, there is hardly any evidence in the IMD framework to suggest that responsible conduct may enhance competitive edge, such as through fostering greater motivation among the workforce, sparking innovation, or improving brand awareness. The World Economic Forum (WEF) has also weighed in on the evaluation of economic competitiveness. The competitiveness index put forth by the WEF is computed based on five sets of criteria and associated data: the GDP per capita of the country as of 1992; the Economic Creativity Index; the Finance Index; the International Index; and the Economic Crises Index. While framed differently, the majority of the fundamental criteria included in these five categories are largely akin to those utilized by IMD. Consequently, it is not surprising that its Global Competitiveness Report yields a country competitiveness ranking that closely resembles that of the IMD.

In summary, the traditional perspective regarding economic competitiveness deals with social concerns in one or more of the following manners:

- Considered inputs for businesses (usually developed and provided from outside), rather than integral parts of business strategies and results;
- Facilitating economic competitiveness when they enhance human capital or other inputs at a low cost;
- Seen as neutral (at best) if they do not damage market flexibility and the overall dynamics of the social economy.

VII. Corporate Responsibility

The impact of businesses on society is currently a significant issue among lawmakers, non-governmental organizations, labor unions, and the business sector itself. An increasing number of companies are showing a desire to tackle the 'triple bottom line' within their approaches, plans, and operations. This expanding sector has largely been championed by international corporations with high-end brands. Lately, more previously less prominent companies have also begun to participate, often due to the negative effects of growing public interest and frustration. The evolving function of businesses in society has various interpretations. Terms such as corporate sustainability, corporate social responsibility, and corporate citizenship have emerged to characterize this era of challenge and transformation. However, there is a rising agreement that the scope of this challenge goes beyond mere charitable contributions and legal obligations, extending to aspects like labor conditions in supplier factories, access to essential medications for those in poverty,

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and transparency regarding how management decisions are made. These represent key areas of corporate responsibility: • Human rights • Working environments • Equality and diversity • Safeguards for consumers • Environmental and health repercussions • Economic growth • Ethical business conduct • Lobbying and political engagement • The role of businesses in areas of conflict.

How is Corporate Responsibility Connected to Market Flexibility?

Advocates of free markets have long maintained that the most effective method to alleviate poverty is by deregulating markets, thereby harnessing the energy of capital effectively managed by profit-driven entrepreneurs. From this perspective has arisen a notable criticism of corporate responsibility, notably articulated by former OECD Chief Economist, David Henderson. Henderson contends that societal issues are most effectively tackled within liberal markets where businesses focus on profit-making and the government's role is to redistribute wealth through tax collection and public service provision. He asserts that when businesses voluntarily accept accountability for broader social and environmental impacts, they incur substantial costs, which ultimately hinder market efficiency and diminish the potential for wealth generation that could otherwise address poverty and social inequality. Illustrating the various business arguments for corporate responsibility helps counter this claim to some extent. However, the majority of these business arguments are still based on initial, short-term advantages related to reputation and financial gain. It remains conceivable that a company might find it beneficial in the short term to adopt certain corporate responsibility measures, while still facing long-term detriments due to diminished competitiveness. Some might argue, for instance, that the decline of Ben & Jerry's and the disappointing financial results of The Body Shop were closely linked to their perceived misguided focus on corporate responsibility, which gradually weakened their competitive edge. There is no denying that efforts made by companies like Nike to enhance labor standards in their global supply chains incur real expenses that are not necessarily recouped through higher sales and profits. Fully addressing labor standards does not guarantee immediate benefits. Although reduced reputational risks are tangible, they do little to equalize the competitive landscape with what John Elkington refers to as 'stealth companies'—organizations that operate below the public's radar while contributing little or nothing to meaningful change.

The concept of market flexibility has become so ideologically charged that some proponents of progressive corporate behavior outright dismiss it as a legitimate challenge. This viewpoint is flawed and could be detrimental. Economic competitiveness requires a vibrant and innovative business community. This environment is fostered and facilitated primarily by markets that promote and reward innovation, reduce unnecessary expenses, and enable companies to concentrate on achieving stability and success. The aspiration for corporate responsibility must align with the necessity for suitably flexible markets. There is, therefore, an evident challenge in ensuring that corporate responsibility initiatives do not stifle the vitality of the wider economy by becoming, for example, excessively bureaucratic.

Corporate Responsibility Clusters as Factors of Competitive Edge?

The early findings from Accountability and The Copenhagen Centre indicate that the evolving, relational features of corporate responsibility initiatives might be crucial in understanding its connections to a country's economic competitiveness and its capacity to effectively contribute to public policy goals. This connects with the concept of 'clustering,' a framework for examining economic phenomena that has gained significant traction among economists and business executives since it was introduced by Michael Porter from Harvard University. The term cluster describes groups of organizations that are intertwined not only through transactions but also through a wider range of interactions. These ties enable a collaborative yet self-organizing evolution within the business sector.

Regarding corporate responsibility, various shared challenges such as workforce inclusion, social investment approaches, continuous learning opportunities, diversity in gender and ethnicity, and involvement in decision-making are relevant across all industries to differing extents. These sectors often share similar stakeholder groups, and by collaborating with these groups, businesses can collectively tackle urgent issues affecting local and regional communities, as well as broader societal interest groups. Likewise, concerning environmental accountability, groups of companies likely draw from the same limited resources and face equivalent pressures to exhibit responsible practices, alongside similar regulations, tax obligations, and public policy contexts. The concept of 'corporate responsibility clustering' elevates the idea of cooperation among competing firms to a new, largely uncharted dimension. For instance, firms operating in nations with notably active NGO environments, like the UK, may become more adept at engaging with civil societies, managing global NGO relationships, enhancing their reputational management, and discovering innovative product and process opportunities linked to social and environmental performance. Companies that have collaborated with NGOs, labor unions, and government entities on issues ranging from 'conflict diamonds' to corruption to labor standards are likely to be better at identifying and establishing lucrative business partnerships. Service providers, including auditors and public relations consultants, will cultivate specialized expertise and networks in corporate responsibility, potentially opening avenues for international business prospects in the future. Public entities that adapt well to environments where corporate responsibility practices are more prominent and discussed may develop more fruitful relationships with the business sector. Furthermore, governments that are active on the global platform will likely advocate for corporate responsibility in international markets, thereby establishing a stronger basis for these practices to enhance the competitive edge of their local business communities.

'Corporate responsibility clustering' encompasses various elements. It transcends just the business realm and can involve many types of connections, including collaborations and legal disputes. The primary competitive edge offered by such clustering stems from numerous potential learning methods and activities, which can range from viral approaches (such as NGO initiatives spreading across different sectors) to preventive approaches (for instance, companies investing in knowledge and adaptation to avert future issues). Viewed this way, NGOs can serve as an incredibly economical consultancy for businesses, enhancing their capacity to learn, raising awareness of emerging concerns, and fostering organizational cultures that are more adaptable and responsive. If corporate responsibility is to promote social inclusion at both national and regional scopes, it must move beyond isolated actions and individual business cases. The factors highlighted earlier spark consideration and offer some guidance for the essential exploration of the underlying realities.

a) *The Importance of Trust and Shared Values*

Trust and shared values are seen as key factors for coordinating and controlling work within a flexible organization. From the standpoint of organizational theory, when tasks are intricate and continuously evolving, "direct supervision" becomes excessively costly, and "bureaucratic control" based on standardizing work is impractical.

Organizations need to depend on "unobtrusive control," or "the regulation of the cognitive foundations behind actions" (Perrow, 1986, p. 129).

This type of internal control promotes trust among colleagues and management, facilitating collaboration within the organization. Firms can choose to hire individuals who possess suitable values or cultivate those values within new employees through the interactive processes that occur within the organization. In contract theory, trust is viewed as an alternative to market mechanisms and bureaucracy for managing transactions. In situations of significant uncertainty and complexity, firms cannot manage transactions through market prices or bureaucratic regulations, instead relying on socialization as the main mechanism of mediation or control (Ouchi, 1980). Macneil (1980) further details the difference between market-oriented and trust-centered transactions, contributing significantly with his classification of "discrete" versus "relational" contracts. Discrete contracts are precisely specified in terms of duration and content, focusing solely on the exchange of goods, with a clearly defined allocation of costs, benefits, and obligations between the parties involved.

In contrast, relational agreements mainly focus on individuals rather than items, making them distinct and non-transferable. The value, terms, and length of exchanges are defined loosely, with transactions adapting based on common norms and beliefs shared among people. Consequently, trust plays a crucial role in both organization and contract theories as a means of coordination and control. Although more intricate and challenging to implement compared to other methods, control grounded in shared norms and values seems to be the most effective option when dealing with complex and ever-changing activities or transactions.

b) *The Strategic Function of Human Resource Management*

The significance of human resource management (HRM) in fostering a company's competitive edge has gained increased attention over the last ten years, leading to various lines of research. The strategic human resource management (SHRM) viewpoint considers HRM to be influenced by the company's surroundings, competitive strategy, and organizational structure (refer to Lawler, 1995, for a summary). When competitive strategies focus on innovation and adaptability within a complex and evolving environment, the pertinent HRM practices are similar to those found in the Japanese model (Aoki, 1990, 1994; Cole, 1994; Koike, 1994) as well as the participative management approach in the U.S. (Beer et al., 1990; Kochan and Osterman, 1994; Pfeffer, 1994). In these different frameworks, the main objectives of HRM include encouraging employee commitment to organizational tasks, nurturing employee initiative and creativity, and ensuring the availability of a skilled workforce. To achieve these objectives, a coherent set of HRM practices is essential, encompassing the hiring, development, evaluation, and motivation of personnel. Firstly, scholars stress the higher selectivity of firms involved in competency development strategies. Selection standards may be objective for technical abilities but often appear broad and subjective when assessing work attitudes and values or the ability of individuals to effectively function within the organization. Secondly, human resource development can be characterized as "a series of experiences that stretch individuals to learn new knowledge, attitudes, and

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behavior" (Beer et al., 1990). It primarily relies on job-related experiences, especially on-the-job training, which is best suited for cultivating experiential knowledge. Thirdly, individual performance evaluation is based on a mix of objective and subjective standards. Objective criteria can assess outcomes, while subjective criteria evaluate work attitudes and behaviors, which best demonstrate how individuals can contribute to the organization. Motivation techniques for the workforce can vary significantly by country. In the Japanese model, employees are encouraged to pursue continuous learning and problem-solving since these activities are included in performance assessments, influencing promotion prospects.

Changing forms of industrial organization: The rise of global production networks. As previously noted, organizational strategies based on competencies necessitate a reevaluation of the functions of firms and their connections with others engaged in complementary operations. By means of externalization and quasi-internalization, companies are creating intricate networks of inter-firm connections, which lead to a reconfiguration of production processes within their sector through the development of organized networks. These networks have been analyzed from various theoretical standpoints, among which the "strategic network" and "global commodity chain" models can be effectively merged for our examination. On one side, both focus on the arrangement of complementary tasks within the value chain, as well as the shifting power dynamics of firms within their respective markets. Conversely, each highlights different and supportive facets of production mechanisms. The strategic viewpoint on inter-firm networks primarily addresses the competitiveness of firms. It characterizes a strategic network as a "long-term, intentional collaboration among separate but related profit-driven entities that permits those involved to attain or maintain a competitive edge over outside rivals" (Jarillo, 1988, p. 32). Grounded in management theory, this strategic standpoint underscores the critical need for governance and coordination within inter-firm networks to serve as a robust source of competitive leverage. Consequently, a strategic network is driven by a central organization that facilitates the interactions among firms specializing at different levels of the value chain (Jarillo, 1988; Sydow, 1992; Miles and Snow, 1994). This perspective enables a connection between firms' organizational strategies and the dynamics of inter-firm relationships, by shifting the analytical focus from the individual firm to the network, while maintaining a coherent understanding of competitiveness and its organizational demands. Nevertheless, the strategic network framework provides limited insight into the broader social, institutional, and geographical contexts influencing firms' operations, which are often neglected in management and strategic studies.

c) The Competitive Environment

While it is crucial for all managers to understand how external factors impact their organization, they should also reflect on ways to manage and potentially influence these environmental forces to benefit their organization. This is generally less feasible for small enterprises, as they tend to have less power. Nonetheless, small businesses should analyze their surroundings for potential opportunities and challenges to identify where they might achieve a competitive edge and where their resources could be most effectively utilized.

Thinking strategically necessitates an understanding of alternate strategic aims and goals, as well as the capability to identify significantly different contexts. Furthermore, it involves diagnosing an organization based on various vital attributes and being able to modify those attributes to align the organization effectively with its surroundings in order to fulfill its strategic aims and goals.

Forecasting in a complex, ever-changing modern setting is inherently challenging; the uncertainties involved can lead to unpredictability and possible chaos. Managers gain their awareness of the environment and strategy through their experiences and insights, and by reflecting on what they observe. It is essential to evaluate the importance of events and observable occurrences. Nevertheless, when contemplating future strategic adjustments, additional considerations will include suppliers, clients, rivals, demand, technology, governmental regulations, and other factors. Encouraging managers to think about forthcoming changes, ask questions, and challenge assumptions will enhance their understanding and awareness, which should aid in decision-making.

Successful strategic management encompasses more than a mere set of straightforward steps. It demands that managers engage in strategic thinking, cultivate the capability to see transitioning conditions, and interpret an unclear and uncertain future by recognizing the interconnections between essential elements. This skill goes beyond a superficial understanding of major social, political, legal, economic, and technological trends.

Managers who engage in strategic thought can picture their organizations within the framework of global trends and occurrences, as well as identify crucial interconnections. They concentrate on how their organization ought to respond to new opportunities and challenges.

For any organization, specific environmental factors will exert substantial influence over decision-making. For some manufacturing and service organizations, customers may be the most influential factor; for others, it might be competition.

As outlined by Ansoff, the degree to which the environment is volatile or dynamic relies on six elements: the variability of the market landscape, the speed of transformation, the level of competition, the potential of technology, customer discrimination, and the pressures imposed by government and influence groups. He posits that in a more turbulent environment, firms must adopt bolder competitive strategies and a proactive stance toward innovation or change to thrive.

The competitive landscape is shaped by market structure and profitability, the intensity of competition, the degree of product differentiation, market expansion, the life cycle stage of products or services, the frequency of new product introductions, capital requirements, and economies of scale. It is crucial for managers to understand where the most significant opportunities and threats exist at any given moment and to concentrate on those aspects that currently impact the organization and warrant strategic focus.

d) Strategic Approach

Strategy is primarily about thinking and action rather than mere planning. It represents a method of managing the business based on strategic insight and viewpoint. Strategic management focuses on recognizing, selecting, and executing the strategy that an organization adopts. Managers must understand the challenges that need to be addressed for effective formulation and execution of strategic changes. Furthermore, they should comprehend the managerial and behavioral dynamics occurring within organizations to grasp how changes are actually implemented.

Strategic management is a continuous process that guarantees an advantageous alignment between the organization and its constantly evolving surroundings. This type of management defines the organization's purpose, examines the surrounding environment to identify opportunities, and integrates this examination with an assessment of the organization's strengths and weaknesses to pinpoint a viable niche where the organization can hold a competitive edge. Implementation also forms a crucial part of this process. The most effective strategy may fail if leadership does not convert that strategy into actionable plans, organizational structures, motivation and communication systems, control mechanisms, and other essential means for execution.

Strategic management entails an understanding of how robust the organization and its strategies are, potential improvements to their effectiveness, and awareness of changing conditions.

The key factors include:

- The organization's capability to create value in significant ways, which
- Utilizes resources effectively to achieve synergy while also
- Addressing the needs of the organization's primary stakeholders, especially customers and owners.

The formulation of a new strategy must consider these criteria.

Research into small manufacturing companies across various industries indicates that gathering insights on diverse aspects of special environmental areas (such as customers, competitors, suppliers) helps align certain competitive strategies with their environments (specifically, stages in the industry lifecycle), while the frequency of environmental scanning does not influence these alignments.

Environmental scanning is typically regarded as essential for developing effective strategies. Furthermore, thorough scanning of the environment is deemed necessary for successfully aligning competitive strategies with external demands and attaining exceptional performance.

Environmental scanning is seen as a critical step in linking strategy development. By analyzing both the task and general environment, a firm can identify opportunities it can leverage and recognize threats to its performance or viability, therefore allowing the firm to craft a competitive strategy that aligns with essential environmental factors.

Organizations must grasp the intricacies and trends of a shifting environment. Some changes will stem from external influences, while others will result from the organization's own actions. Through this understanding, organizations should be capable of effectively managing change, including technological advancements, processes, and structures, to sustain a successful alignment with their environment. This, in turn, should lead to favorable and advantageous competitive results.

Thus, strategic management in smaller enterprises should encompass the following aspects:

- A thorough understanding of external factors and how they are evolving
- Recognition of possible future risks and opportunities
- Choices regarding suitable goods and services for well-defined target markets
- The proficient handling of resources necessary to develop and deliver these products to the market – ensuring quality, pricing, and timing are on point.

Strategic management is most effective when the resources align with the expectations and requirements of stakeholders and adapt to maintain relevance in a fluctuating environment. The external surroundings include suppliers, distributors, and customers, as well as financial institutions and business owners. To achieve success and, in many instances, profitability, organizations must fulfill the demands and expectations of their stakeholders. The various demands dictate what a company needs to excel at.

Therefore, for organizations to meet the expectations of their stakeholders, particularly their customers, while surpassing their competition, their competitive offerings should include:

- The capacity to address the recognized essential success factors for the specific industry or market
- Unique strengths and skills that provide a competitive edge
- The readiness and capability to leverage these strengths to meet the unique demands of individual customers, which can often justify a higher price.

Strategic achievement necessitates a solid comprehension of market demands and the ability to meet the needs of targeted customers more effectively and profitably than competitors do.

e) Competitive Advantage

True competitive advantage indicates that companies can fulfill customer needs more proficiently than their rivals. It is attained when genuine value is created for customers. To thrive, a business must create value. The critical components of creating value include:

- Being knowledgeable and connected to customers, particularly in grasping their value perceptions
- A dedication to quality
- An overall high standard of service
- Quick responses to opportunities and threats from competition

Small enterprises that understand their customers can establish competitive advantages and benefit from increased prices and customer loyalty. Enhanced capacity utilization can subsequently aid in cost reduction.

While it is essential to utilize resources effectively and appropriately, it is also vital to maximize the potential value of outputs by ensuring they adequately fulfill the needs of their intended customers. An organization accomplishes this by aligning its goals with those of its customers, allowing them to add more value or ensuring that, in the case of end consumers, they feel they are receiving true value for their expenditure.

f) Business Strategy within an Organization

The essence of business strategy lies in gaining a competitive edge. Typically, strategy focuses on achieving success over the long haul. It prioritizes growth of assets over immediate earnings. Therefore, companies require a strategy to maximize resource allocation efficiency. This becomes especially crucial for significant resource distribution decisions.

The role of strategy is not merely about its effect on profit margins. Instead, it can be understood in practical terms, guiding a business's trajectory and fostering consistent and concentrated efforts. This approach helps prevent erratic shifts from one temporary opportunity to another, enabling the development of business expertise and leadership. Ultimately, strategy must also promote an understanding of when changes are needed, ensuring adaptability.

Business strategy aims to ensure that a specific enterprise can endure, expand, and remain profitable in the long run.

Key factors to consider include:

- Attracting customers
- Pinpointing suitable market segments where competition is minimal
- Recognizing customer needs and determining the best ways to meet them
- Leveraging technology and planning for its future enhancements or alternatives
- Analyzing competitors to find ways to circumvent direct rivalry
- Inspiring individuals to channel their efforts and passion towards the strategic goals of the organization.

Henry Mintzberg suggests that business strategy can adopt one of three styles: planning, entrepreneurial, and adaptive. He states that selecting the appropriate style depends on various situational factors, such as the organization's size, age, and the influence of key decision-makers.

The planning style is a method that encompasses a well-defined set of goals, a comprehensive evaluation of the organization and its environment, along with a strategic action plan to achieve these goals. Managers should embrace the planning style when the organization is established, resources are sufficient for opportunity assessment, senior leaders are aligned on the organization's goals, and there's minimal environmental uncertainty. Different situations may prefer alternative approaches.

The adaptive style is a method where both the organization's goals and the means to reach them are perpetually evolving. The organization progresses cautiously through a series of small, disconnected actions. This adaptive strategy is most effective in scenarios where environmental uncertainty is significantly high, directing management's focus on immediate outcomes, and where internal conflicts hinder consensus among senior leaders about the organization's direction.

The entrepreneurial approach offers a strategic way in which a decisive leader, often the founder of the organization, utilizes personal insights and experiences to create a gut feeling about where the organization should head. This tactic is marked by daring choices, alternating between moments of reflection and quick action. The entrepreneurial approach tends to be more successful when the organization is relatively new and small, particularly when a singular, influential leader possesses a deep understanding of the business, or in times of crisis.

Small enterprises typically offer a limited range of products or services. Their assets and skills are constrained. Their strategic choices are generally straightforward and tightly focused. Such scenarios do not necessitate the complexity found in the planning mode. In small businesses, strategic planning approaches have been observed to be disorganized, inconsistent, and lacking thoroughness. They are best characterized as informal; seldom documented and rarely conveyed beyond the inner circle of the top executive. Furthermore, the strategic focus of small businesses often spans a shorter time frame compared to larger organizations, typically addressing periods of two years or less. According to Mintzberg's evaluation, we might anticipate that the strategic planning processes in small businesses align more closely with the entrepreneurial mode than with the planning mode. This is supported by survey findings.

g) Entrepreneurship and Strategic Management

There are many instances of entrepreneurs who, due to significant early achievements, believed they could depend solely on their instincts and ultimately encountered failure. In essence, while good ideas and visions are vital, they are not enough; they must be enhanced by logical analysis. Strategic management offers a framework and mindset to assess the entrepreneurs' visions through logical evaluation and decision-making.

Thus, the primary aim of strategic management is to steer the stream of ideas and visions and to translate them into actionable business decisions.

The Strategic Entrepreneurship Concept of Strategic Management in Small and Midsized Organizations

The idea behind strategic management for small businesses should revolve around the framework of strategic entrepreneurship. This framework blends both creative intuition and logical reasoning. The process of strategy begins with the entrepreneur within the company, who shares their perspective on the firm's progress and the specific goals they envision. This leads to the creation of a vision statement that defines the desired development trajectory of the business along with the objectives to achieve within a certain timeframe. The vision statement serves as a business-oriented representation of the entrepreneur's intuitive insights.

Subsequently, a logical procedure follows, involving familiar analyses of internal and external factors, as sound business choices need to consider both internal and external contexts alongside the entrepreneur's vision. Thus, the internal and external evaluations establish criteria that assist in selecting and executing the final decision from various possibilities, including monitoring. The initial exploration of alternatives is primarily intuitive. However, the final selection is a systematic approach that relies on criteria outlined in the vision statement, particularly its measurable objectives. The choice that best meets these criteria is the one made regarding the matter at hand. This reflects how entrepreneurs arrive at their crucial decisions.

VIII. Strategic Approach and Small and Midsized Firms

Experiences from managers of small businesses regarding strategic planning and management highlight the importance of potential adjustments to this approach.

To begin with, the procedure does not have to be as intricate or time-consuming as that utilized by larger corporations. It might simply entail addressing the following queries:

- What is our current position?
- What are our goals?
- Is it achievable?
- What actions will lead us there?
- What decisions are necessary for progress?
- How do we assess our performance?

Additionally, due to the compact nature of the organization, almost all key personnel can contribute to this process. This enables the organization to leverage valuable expertise while fostering employee engagement and effective communication. Ultimately, it transforms into a beneficial learning journey for all participants.

Lastly, it is crucial for upper management, or the lead manager, to embrace strategic management actively. The manager must acknowledge that their company is evolving and expanding. There is a necessity to delegate planning responsibilities beyond one individual to cultivate shared ownership. This shift aids in facilitating the transformation of a company into a more structured organization.

A strategic method in smaller enterprises presents various distinct benefits and drawbacks.

On the upside, the modest scale of a company typically avoids the complications and intricacies encountered by strategists in larger entities. Indeed, a small enterprise might simply be viewed as a strategic business segment. Additional benefits include a restricted range of products, services, and target markets, a comparatively small amount of resources, and a limited selection of choices.

On the downside, there are also some notable challenges. First, the management team is often quite limited, sometimes consisting of just a single individual. This manager, or entrepreneur, may have consistently guided the firm based on personal intuition, finding little value in structured processes. Second, the availability of information and data necessary for internal and external evaluations may be scant, if present at all. Third, critical staff members typically acquire their expertise through practical experience instead of systematic training, potentially leading to an aversion to change. Additional issues may involve the constraints of scarce resources and questions related to ownership of the business.

a) Planning for a Competitive Edge

If an organization achieves a competitive edge, it stands a better chance of survival. A substantial edge allows the organization to flourish. According to M. Porter, businesses typically have three overarching strategic options to create a competitive advantage: a differentiation approach, a low-cost strategy, and a focus strategy, often adopted by entrepreneurs, known as a niche strategy.

Companies employing a differentiation approach compete by distinguishing themselves from their primary rivals through unique methods. A company utilizing a low-cost strategy gains a competitive advantage by offering products or services at the lowest feasible price. When entrepreneurs maintain the ability to keep costs lower than their competitors, their businesses thrive. In contrast to the broad market approaches of cost leadership and differentiation, Porter's niche strategy encourages firms to concentrate on specific market segments—targeting particular audience types, segments of the product range, or smaller geographical areas. Niche-focused competitors are specialists who cater to a specific market segment that may be local or national. Those following niche strategies develop specialized skills that align with particular markets, resulting in higher profit margins. Successful entrepreneurs recognize that both establishing and sustaining a competitive edge is a significant challenge. Without vigilant management, this advantage can be swiftly diminished.

b) The Competitive Specialization

Even though grasping the business's mission is crucial for continued existence, it alone does not guarantee exceptional performance. This is attained through maximizing competitive specialization. Competitive specialization can be leveraged in three distinct ways.

To begin with, it can be enhanced or amplified so that it is more noticeable to consumers or so that they assign it greater worth, thus being willing to pay a higher price. For instance, a focus on product quality could be elevated by further improving the quality of the item and/or effectively marketing its quality. The outcome will be a rise in both the real and perceived quality levels, as well as a decrease in the price sensitivity of the item.

Next, specialization can be expanded to accommodate a larger customer base. The most straightforward method of achieving this is through geographic expansion, but any product aimed at a narrow market segment has the potential to expand its focus and attract different segments.

Lastly, specialization can be extended to ensure that it endures through advancements in technology and shifts in consumer preferences.

Amplifying specialization should be approached cautiously and based on solid data regarding customer views. Expanding specialization carries risks as well. Broadening the focus to include more market segments might diminish its perceived value among existing clients. Likewise, maintaining the relevance of a specialization can be tricky since some specializations are tied to single products or specific markets that have limited lifespans.

IX. Results

1. *Improved Responsiveness:* Companies with advanced manufacturing flexibility experienced a 30% reduction in lead times, allowing for quicker reactions to market needs.
2. *Cost Optimization:* Flexible manufacturing systems helped firms reduce production expenses by minimizing idle time and waste. For example, an automotive manufacturer achieved a 20% decrease in production costs by utilizing process flexibility.
3. *Personalization and Customer Satisfaction:* Flexibility in product offerings enabled businesses to provide a broader selection of customized items, resulting in a 25% boost in customer satisfaction ratings.
4. *Risk Management:* Flexibility in the supply chain was vital for handling disruptions. A consumer goods company effectively addressed global supply chain issues during the COVID-19 pandemic by utilizing digital supply chain solutions and varied sourcing strategies.

Competitive Edge: Companies with exceptional manufacturing flexibility consistently reported greater market share and profitability compared to their competitors with more rigid systems.

X. Conclusion

A fresh perspective on manufacturing

A combination of outside market forces, emerging technologies, and new competitors is driving manufacturers to change their business operations. The report indicates that a successful and enduring transformation necessitates a reevaluation of strategy and planning, a strong emphasis on creating value through services, and a commitment to innovation fueled by technology that goes beyond conventional methods.

Flexibility in manufacturing serves as a key element for gaining a competitive edge in the international market. By allowing companies to respond swiftly to evolving market dynamics, it boosts responsiveness, cuts expenses, and enhances customer satisfaction. The results from this research underline the vital significance of adaptable manufacturing systems in reaching operational excellence and strategic responsiveness.

For organizations aiming to adopt manufacturing flexibility, the following guidelines are suggested:

1. *Embrace Technology:* Incorporate cutting-edge manufacturing technologies like automation, robotics, and AI to improve both process and product adaptability.
2. *Build Agile Supply Chains:* Create robust supply chains capable of adjusting to disruptions through varied sourcing, immediate data analysis, and cooperative partnerships.
3. *Educate Employees:* Provide staff with the necessary skills to effectively operate and manage flexible manufacturing systems.
4. *Foster Ongoing Improvement:* Apply lean methodologies and continuous improvement efforts to maintain flexibility and foster innovation.

As worldwide markets continue to change, the ability to adapt in manufacturing will remain vital for securing a lasting competitive edge, enabling companies to prosper in an ever more intricate and unpredictable business landscape.

With that in mind, what actions should manufacturers take in

Defining their future transformation priorities?

Identify market trends

Research indicates that manufacturers should first understand the market trends anticipated to have the most significant effect in the next three years and subsequently align these insights with their ongoing strategy and planning. Economic challenges experienced globally over the previous decade, coupled with emerging technologies, stand out as the two primary elements (reported by 66% and 61% of respondents, respectively) that have prompted a foundational shift in manufacturing competition rather than merely a cyclical one.

Points for consideration:

- Are we aware of which market trends are likely to most affect our company in the forthcoming three years?
- Do we possess an economic model that evaluates the influence of our transformation efforts and priorities on our expenses and revenue?

Evaluate the coordination of strategic and planning efforts

The next step involves manufacturers examining how they synchronize their strategic and planning efforts throughout their organizations. Leaders should inquire how their strategy and planning align engineering, service, and supply chain/manufacturing sectors. Some probable ways to achieve tighter coordination in the coming three years include initiatives in global product quality (60%), global service (57%), and global product compliance (55%). Each of these initiatives relies on effective collaboration both within the organization and across its network of partners.

Points for consideration:

- Are we cognizant of the effectiveness of coordination between strategy and planning within and among our business departments (such as engineering and supply chain) to proactively address market shifts?
- Do we have strong methods for ensuring alignment in strategy and planning throughout our organization and partner network (for example, with global product quality, global compliance, or global product development)?

Evaluate advancement towards a service-oriented business model

Service should not merely be regarded as a means to boost the value of existing products but should be seen as a unique proposition that generates revenue independently. To initiate this, manufacturers need to utilize insights gained from service delivery to guide decisions and foster enhancements in both service planning and product development and quality. Over the next three years, 77% of executives surveyed aim to utilize feedback from service execution to enhance their service value propositions, while more than half (52%) plan to leverage this data for product development and quality improvements; 56% intend to treat service as a profit center.

Points for consideration:

- Do we have a robust human resources strategy in place for attracting, training, and retaining the skilled workforce necessary for ongoing service transformation?
- Are we optimizing our utilization of remote diagnostics and other direct feedback methods to enhance customer experiences with our products and services?

Understand sources of innovation

Manufacturers must approach innovation as an enterprise-wide effort. Leading manufacturers are sourcing innovative solutions from emerging markets and bringing them to developed ones (50% of surveyed manufacturers within three years). Alongside geographic sources for new innovation, firms are expanding the use

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of smart products (over half of total respondents, 60% of very large firms, and over 70% of high tech firms within three years) to give them greater insight into customer needs and preferences.

Questions to consider:

- Do our innovation efforts extend beyond traditional R&D to encompass all parts of the enterprise ecosystem?
- Do we embrace a design, build, and service anywhere philosophy, and how do we compare to competitor capabilities and customer expectations?

Thus, there will be no shortage of work for manufacturers that keep up with the speed at which market trends evolve and stand ready with a relevant value proposition. Indeed, those who choose the right priorities now are most likely to be the ones that thrive during this important period of industry transformation.

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Career | Financial

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Career | Credibility | Reputation

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> The primary objective is to recognize the leaders in research and scientific fields of the current era with a global perspective and to create a channel between them and other researchers for better exposure and knowledge sharing. Members are most eminent scientists, engineers, and technologists from all across the world. Associate membership can later be promoted to Fellow Membership. Associates are elected for life through a peer review process on the basis of excellence in the respective domain. There is no limit on the number of new nominations made in any year. Each year, the Open Association of Research Society elect up to 12 new Associate Members.

Benefits

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Career | Credibility | Exclusive | Reputation

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Associate	Fellow	Research Group	Basic
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Certificate, LoR and Momento 2 discounted publishing/year **Gradation** of Research 10 research contacts/day **1 GB** Cloud Storage **GJ** Community Access	**Certificate,** LoR and Momento **Unlimited** discounted publishing/year **Gradation** of Research **Unlimited** research contacts/day **5 GB** Cloud Storage **Online Presense** Assistance **GJ** Community Access	**Certificates,** LoRs and Momentos **Unlimited** free publishing/year **Gradation** of Research **Unlimited** research contacts/day **Unlimited** Cloud Storage **Online Presense** Assistance **GJ** Community Access	**GJ** Community Access

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2. Drafting the paper and revising it critically regarding important academic content.
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Acknowledgments

Contributors to the research other than authors credited should be mentioned in Acknowledgments. The source of funding for the research can be included. Suppliers of resources may be mentioned along with their addresses.

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Authors can submit papers and articles in an acceptable file format: MS Word (doc, docx), LaTeX (.tex, .zip or .rar including all of your files), Adobe PDF (.pdf), rich text format (.rtf), simple text document (.txt), Open Document Text (.odt), and Apple Pages (.pages). Our professional layout editors will format the entire paper according to our official guidelines. This is one of the highlights of publishing with Global Journals—authors should not be concerned about the formatting of their paper. Global Journals accepts articles and manuscripts in every major language, be it Spanish, Chinese, Japanese, Portuguese, Russian, French, German, Dutch, Italian, Greek, or any other national language, but the title, subtitle, and abstract should be in English. This will facilitate indexing and the pre-peer review process.

The following is the official style and template developed for publication of a research paper. Authors are not required to follow this style during the submission of the paper. It is just for reference purposes.

Manuscript Style Instruction (Optional)

- Microsoft Word Document Setting Instructions.
- Font type of all text should be Swis721 Lt BT.
- Page size: 8.27" x 11'", left margin: 0.65, right margin: 0.65, bottom margin: 0.75.
- Paper title should be in one column of font size 24.
- Author name in font size of 11 in one column.
- Abstract: font size 9 with the word "Abstract" in bold italics.
- Main text: font size 10 with two justified columns.
- Two columns with equal column width of 3.38 and spacing of 0.2.
- First character must be three lines drop-capped.
- The paragraph before spacing of 1 pt and after of 0 pt.
- Line spacing of 1 pt.
- Large images must be in one column.
- The names of first main headings (Heading 1) must be in Roman font, capital letters, and font size of 10.
- The names of second main headings (Heading 2) must not include numbers and must be in italics with a font size of 10.

Structure and Format of Manuscript

The recommended size of an original research paper is under 15,000 words and review papers under 7,000 words. Research articles should be less than 10,000 words. Research papers are usually longer than review papers. Review papers are reports of significant research (typically less than 7,000 words, including tables, figures, and references)

A research paper must include:

a) A title which should be relevant to the theme of the paper.
b) A summary, known as an abstract (less than 150 words), containing the major results and conclusions.
c) Up to 10 keywords that precisely identify the paper's subject, purpose, and focus.
d) An introduction, giving fundamental background objectives.
e) Resources and techniques with sufficient complete experimental details (wherever possible by reference) to permit repetition, sources of information must be given, and numerical methods must be specified by reference.
f) Results which should be presented concisely by well-designed tables and figures.
g) Suitable statistical data should also be given.
h) All data must have been gathered with attention to numerical detail in the planning stage.

Design has been recognized to be essential to experiments for a considerable time, and the editor has decided that any paper that appears not to have adequate numerical treatments of the data will be returned unrefereed.

i) Discussion should cover implications and consequences and not just recapitulate the results; conclusions should also be summarized.
j) There should be brief acknowledgments.
k) There ought to be references in the conventional format. Global Journals recommends APA format.

Authors should carefully consider the preparation of papers to ensure that they communicate effectively. Papers are much more likely to be accepted if they are carefully designed and laid out, contain few or no errors, are summarizing, and follow instructions. They will also be published with much fewer delays than those that require much technical and editorial correction.

The Editorial Board reserves the right to make literary corrections and suggestions to improve brevity.

Format Structure

It is necessary that authors take care in submitting a manuscript that is written in simple language and adheres to published guidelines.

All manuscripts submitted to Global Journals should include:

Title

The title page must carry an informative title that reflects the content, a running title (less than 45 characters together with spaces), names of the authors and co-authors, and the place(s) where the work was carried out.

Author details

The full postal address of any related author(s) must be specified.

Abstract

The abstract is the foundation of the research paper. It should be clear and concise and must contain the objective of the paper and inferences drawn. It is advised to not include big mathematical equations or complicated jargon.

Many researchers searching for information online will use search engines such as Google, Yahoo or others. By optimizing your paper for search engines, you will amplify the chance of someone finding it. In turn, this will make it more likely to be viewed and cited in further works. Global Journals has compiled these guidelines to facilitate you to maximize the web-friendliness of the most public part of your paper.

Keywords

A major lynchpin of research work for the writing of research papers is the keyword search, which one will employ to find both library and internet resources. Up to eleven keywords or very brief phrases have to be given to help data retrieval, mining, and indexing.

One must be persistent and creative in using keywords. An effective keyword search requires a strategy: planning of a list of possible keywords and phrases to try.

Choice of the main keywords is the first tool of writing a research paper. Research paper writing is an art. Keyword search should be as strategic as possible.

One should start brainstorming lists of potential keywords before even beginning searching. Think about the most important concepts related to research work. Ask, "What words would a source have to include to be truly valuable in a research paper?" Then consider synonyms for the important words.

It may take the discovery of only one important paper to steer in the right keyword direction because, in most databases, the keywords under which a research paper is abstracted are listed with the paper.

Numerical Methods

Numerical methods used should be transparent and, where appropriate, supported by references.

Abbreviations

Authors must list all the abbreviations used in the paper at the end of the paper or in a separate table before using them.

Formulas and equations

Authors are advised to submit any mathematical equation using either MathJax, KaTeX, or LaTeX, or in a very high-quality image.

Tables, Figures, and Figure Legends

Tables: Tables should be cautiously designed, uncrowned, and include only essential data. Each must have an Arabic number, e.g., Table 4, a self-explanatory caption, and be on a separate sheet. Authors must submit tables in an editable format and not as images. References to these tables (if any) must be mentioned accurately.

Figures

Figures are supposed to be submitted as separate files. Always include a citation in the text for each figure using Arabic numbers, e.g., Fig. 4. Artwork must be submitted online in vector electronic form or by emailing it.

Preparation of Eletronic Figures for Publication

Although low-quality images are sufficient for review purposes, print publication requires high-quality images to prevent the final product being blurred or fuzzy. Submit (possibly by e-mail) EPS (line art) or TIFF (halftone/ photographs) files only. MS PowerPoint and Word Graphics are unsuitable for printed pictures. Avoid using pixel-oriented software. Scans (TIFF only) should have a resolution of at least 350 dpi (halftone) or 700 to 1100 dpi (line drawings). Please give the data for figures in black and white or submit a Color Work Agreement form. EPS files must be saved with fonts embedded (and with a TIFF preview, if possible).

For scanned images, the scanning resolution at final image size ought to be as follows to ensure good reproduction: line art: >650 dpi; halftones (including gel photographs): >350 dpi; figures containing both halftone and line images: >650 dpi.

Color charges: Authors are advised to pay the full cost for the reproduction of their color artwork. Hence, please note that if there is color artwork in your manuscript when it is accepted for publication, we would require you to complete and return a Color Work Agreement form before your paper can be published. Also, you can email your editor to remove the color fee after acceptance of the paper.

Tips for Writing a Good Quality Engineering Research Paper

Techniques for writing a good quality engineering research paper:

1. Choosing the topic: In most cases, the topic is selected by the interests of the author, but it can also be suggested by the guides. You can have several topics, and then judge which you are most comfortable with. This may be done by asking several questions of yourself, like "Will I be able to carry out a search in this area? Will I find all necessary resources to accomplish the search? Will I be able to find all information in this field area?" If the answer to this type of question is "yes," then you ought to choose that topic. In most cases, you may have to conduct surveys and visit several places. Also, you might have to do a lot of work to find all the rises and falls of the various data on that subject. Sometimes, detailed information plays a vital role, instead of short information. Evaluators are human: The first thing to remember is that evaluators are also human beings. They are not only meant for rejecting a paper. They are here to evaluate your paper. So present your best aspect.

2. Think like evaluators: If you are in confusion or getting demotivated because your paper may not be accepted by the evaluators, then think, and try to evaluate your paper like an evaluator. Try to understand what an evaluator wants in your research paper, and you will automatically have your answer. Make blueprints of paper: The outline is the plan or framework that will help you to arrange your thoughts. It will make your paper logical. But remember that all points of your outline must be related to the topic you have chosen.

3. Ask your guides: If you are having any difficulty with your research, then do not hesitate to share your difficulty with your guide (if you have one). They will surely help you out and resolve your doubts. If you can't clarify what exactly you require for your work, then ask your supervisor to help you with an alternative. He or she might also provide you with a list of essential readings.

4. Use of computer is recommended: As you are doing research in the field of research engineering then this point is quite obvious. Use right software: Always use good quality software packages. If you are not capable of judging good software, then you can lose the quality of your paper unknowingly. There are various programs available to help you which you can get through the internet.

5. Use the internet for help: An excellent start for your paper is using Google. It is a wondrous search engine, where you can have your doubts resolved. You may also read some answers for the frequent question of how to write your research paper or find a model research paper. You can download books from the internet. If you have all the required books, place importance on reading, selecting, and analyzing the specified information. Then sketch out your research paper. Use big pictures: You may use encyclopedias like Wikipedia to get pictures with the best resolution. At Global Journals, you should strictly follow here.

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7. Revise what you wrote: When you write anything, always read it, summarize it, and then finalize it.

8. Make every effort: Make every effort to mention what you are going to write in your paper. That means always have a good start. Try to mention everything in the introduction—what is the need for a particular research paper. Polish your work with good writing skills and always give an evaluator what he wants. Make backups: When you are going to do any important thing like making a research paper, you should always have backup copies of it either on your computer or on paper. This protects you from losing any portion of your important data.

9. Produce good diagrams of your own: Always try to include good charts or diagrams in your paper to improve quality. Using several unnecessary diagrams will degrade the quality of your paper by creating a hodgepodge. So always try to include diagrams which were made by you to improve the readability of your paper. Use of direct quotes: When you do research relevant to literature, history, or current affairs, then use of quotes becomes essential, but if the study is relevant to science, use of quotes is not preferable.

10. Use proper verb tense: Use proper verb tenses in your paper. Use past tense to present those events that have happened. Use present tense to indicate events that are going on. Use future tense to indicate events that will happen in the future. Use of wrong tenses will confuse the evaluator. Avoid sentences that are incomplete.

11. Pick a good study spot: Always try to pick a spot for your research which is quiet. Not every spot is good for studying.

12. Know what you know: Always try to know what you know by making objectives, otherwise you will be confused and unable to achieve your target.

13. Use good grammar: Always use good grammar and words that will have a positive impact on the evaluator; use of good vocabulary does not mean using tough words which the evaluator has to find in a dictionary. Do not fragment sentences. Eliminate one-word sentences. Do not ever use a big word when a smaller one would suffice.

Verbs have to be in agreement with their subjects. In a research paper, do not start sentences with conjunctions or finish them with prepositions. When writing formally, it is advisable to never split an infinitive because someone will (wrongly) complain. Avoid clichés like a disease. Always shun irritating alliteration. Use language which is simple and straightforward. Put together a neat summary.

14. Arrangement of information: Each section of the main body should start with an opening sentence, and there should be a changeover at the end of the section. Give only valid and powerful arguments for your topic. You may also maintain your arguments with records.

15. Never start at the last minute: Always allow enough time for research work. Leaving everything to the last minute will degrade your paper and spoil your work.

16. Multitasking in research is not good: Doing several things at the same time is a bad habit in the case of research activity. Research is an area where everything has a particular time slot. Divide your research work into parts, and do a particular part in a particular time slot.

17. Never copy others' work: Never copy others' work and give it your name because if the evaluator has seen it anywhere, you will be in trouble. Take proper rest and food: No matter how many hours you spend on your research activity, if you are not taking care of your health, then all your efforts will have been in vain. For quality research, take proper rest and food.

18. Go to seminars: Attend seminars if the topic is relevant to your research area. Utilize all your resources.

19. Refresh your mind after intervals: Try to give your mind a rest by listening to soft music or sleeping in intervals. This will also improve your memory. Acquire colleagues: Always try to acquire colleagues. No matter how sharp you are, if you acquire colleagues, they can give you ideas which will be helpful to your research.

20. Think technically: Always think technically. If anything happens, search for its reasons, benefits, and demerits. Think and then print: When you go to print your paper, check that tables are not split, headings are not detached from their descriptions, and page sequence is maintained.

21. Adding unnecessary information: Do not add unnecessary information like "I have used MS Excel to draw graphs." Irrelevant and inappropriate material is superfluous. Foreign terminology and phrases are not apropos. One should never take a broad view. Analogy is like feathers on a snake. Use words properly, regardless of how others use them. Remove quotations. Puns are for kids, not grunt readers. Never oversimplify: When adding material to your research paper, never go for oversimplification; this will definitely irritate the evaluator. Be specific. Never use rhythmic redundancies. Contractions shouldn't be used in a research paper. Comparisons are as terrible as clichés. Give up ampersands, abbreviations, and so on. Remove commas that are not necessary. Parenthetical words should be between brackets or commas. Understatement is always the best way to put forward earth-shaking thoughts. Give a detailed literary review.
22. Report concluded results: Use concluded results. From raw data, filter the results, and then conclude your studies based on measurements and observations taken. An appropriate number of decimal places should be used. Parenthetical remarks are prohibited here. Proofread carefully at the final stage. At the end, give an outline to your arguments. Spot perspectives of further study of the subject. Justify your conclusion at the bottom sufficiently, which will probably include examples.
23. Upon conclusion: Once you have concluded your research, the next most important step is to present your findings. Presentation is extremely important as it is the definite medium though which your research is going to be in print for the rest of the crowd. Care should be taken to categorize your thoughts well and present them in a logical and neat manner. A good quality research paper format is essential because it serves to highlight your research paper and bring to light all necessary aspects of your research.

Informal Guidelines of Research Paper Writing

Key points to remember:

- Submit all work in its final form.
- Write your paper in the form which is presented in the guidelines using the template.
- Please note the criteria peer reviewers will use for grading the final paper.

Final points:

One purpose of organizing a research paper is to let people interpret your efforts selectively. The journal requires the following sections, submitted in the order listed, with each section starting on a new page:

The introduction: This will be compiled from reference matter and reflect the design processes or outline of basis that directed you to make a study. As you carry out the process of study, the method and process section will be constructed like that. The results segment will show related statistics in nearly sequential order and direct reviewers to similar intellectual paths throughout the data that you gathered to carry out your study.

The discussion section:

This will provide understanding of the data and projections as to the implications of the results. The use of good quality references throughout the paper will give the effort trustworthiness by representing an alertness to prior workings.

Writing a research paper is not an easy job, no matter how trouble-free the actual research or concept. Practice, excellent preparation, and controlled record-keeping are the only means to make straightforward progression.

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Specific editorial column necessities for compliance of a manuscript will always take over from directions in these general guidelines.

To make a paper clear: Adhere to recommended page limits.

Mistakes to avoid:

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- Submitting a manuscript with pages out of sequence.
- In every section of your document, use standard writing style, including articles ("a" and "the").
- Keep paying attention to the topic of the paper.

- Use paragraphs to split each significant point (excluding the abstract).
- Align the primary line of each section.
- Present your points in sound order.
- Use present tense to report well-accepted matters.
- Use past tense to describe specific results.
- Do not use familiar wording; don't address the reviewer directly. Don't use slang or superlatives.
- Avoid use of extra pictures—include only those figures essential to presenting results.

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Choose a revealing title. It should be short and include the name(s) and address(es) of all authors. It should not have acronyms or abbreviations or exceed two printed lines.

Abstract: This summary should be two hundred words or less. It should clearly and briefly explain the key findings reported in the manuscript and must have precise statistics. It should not have acronyms or abbreviations. It should be logical in itself. Do not cite references at this point.

An abstract is a brief, distinct paragraph summary of finished work or work in development. In a minute or less, a reviewer can be taught the foundation behind the study, common approaches to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Use comprehensive sentences, and do not sacrifice readability for brevity; you can maintain it succinctly by phrasing sentences so that they provide more than a lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study with the subsequent elements in any summary. Try to limit the initial two items to no more than one line each.

Reason for writing the article—theory, overall issue, purpose.

- Fundamental goal.
- To-the-point depiction of the research.
- Consequences, including definite statistics—if the consequences are quantitative in nature, account for this; results of any numerical analysis should be reported. Significant conclusions or questions that emerge from the research.

Approach:

- o Single section and succinct.
- o An outline of the job done is always written in past tense.
- o Concentrate on shortening results—limit background information to a verdict or two.
- o Exact spelling, clarity of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else.

Introduction:

The introduction should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable of comprehending and calculating the purpose of your study without having to refer to other works. The basis for the study should be offered. Give the most important references, but avoid making a comprehensive appraisal of the topic. Describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will give no attention to your results. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here.

The following approach can create a valuable beginning:

- o Explain the value (significance) of the study.
- o Defend the model—why did you employ this particular system or method? What is its compensation? Remark upon its appropriateness from an abstract point of view as well as pointing out sensible reasons for using it.
- o Present a justification. State your particular theory(-ies) or aim(s), and describe the logic that led you to choose them.
- o Briefly explain the study's tentative purpose and how it meets the declared objectives.

Approach:

Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done. Sort out your thoughts; manufacture one key point for every section. If you make the four points listed above, you will need at least four paragraphs. Present surrounding information only when it is necessary to support a situation. The reviewer does not desire to read everything you know about a topic. Shape the theory specifically—do not take a broad view.

As always, give awareness to spelling, simplicity, and correctness of sentences and phrases.

Procedures (methods and materials):

This part is supposed to be the easiest to carve if you have good skills. A soundly written procedures segment allows a capable scientist to replicate your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order, but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt to give the least amount of information that would permit another capable scientist to replicate your outcome, but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section.

When a technique is used that has been well-described in another section, mention the specific item describing the way, but draw the basic principle while stating the situation. The purpose is to show all particular resources and broad procedures so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step-by-step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

Materials may be reported in part of a section or else they may be recognized along with your measures.

Methods:

- Report the method and not the particulars of each process that engaged the same methodology.
- Describe the method entirely.
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures.
- Simplify—detail how procedures were completed, not how they were performed on a particular day.
- If well-known procedures were used, account for the procedure by name, possibly with a reference, and that's all.

Approach:

It is embarrassing to use vigorous voice when documenting methods without using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result, when writing up the methods, most authors use third person passive voice.

Use standard style in this and every other part of the paper—avoid familiar lists, and use full sentences.

What to keep away from:

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings—save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part as entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Use statistics and tables, if suitable, to present consequences most efficiently.

You must clearly differentiate material which would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matters should not be submitted at all except if requested by the instructor.

Content:

- Sum up your conclusions in text and demonstrate them, if suitable, with figures and tables.
- In the manuscript, explain each of your consequences, and point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation of an exacting study.
- Explain results of control experiments and give remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or manuscript.

What to stay away from:

- Do not discuss or infer your outcome, report surrounding information, or try to explain anything.
- Do not include raw data or intermediate calculations in a research manuscript.
- Do not present similar data more than once.
- A manuscript should complement any figures or tables, not duplicate information.
- Never confuse figures with tables—there is a difference.

Approach:

As always, use past tense when you submit your results, and put the whole thing in a reasonable order.

Put figures and tables, appropriately numbered, in order at the end of the report.

If you desire, you may place your figures and tables properly within the text of your results section.

Figures and tables:

If you put figures and tables at the end of some details, make certain that they are visibly distinguished from any attached appendix materials, such as raw facts. Whatever the position, each table must be titled, numbered one after the other, and include a heading. All figures and tables must be divided from the text.

Discussion:

The discussion is expected to be the trickiest segment to write. A lot of papers submitted to the journal are discarded based on problems with the discussion. There is no rule for how long an argument should be.

Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implications of the study. The purpose here is to offer an understanding of your results and support all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of results should be fully described.

Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact, you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved the prospect, and let it drop at that. Make a decision as to whether each premise is supported or discarded or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."

Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work.

- You may propose future guidelines, such as how an experiment might be personalized to accomplish a new idea.
- Give details of all of your remarks as much as possible, focusing on mechanisms.
- Make a decision as to whether the tentative design sufficiently addressed the theory and whether or not it was correctly restricted. Try to present substitute explanations if they are sensible alternatives.
- One piece of research will not counter an overall question, so maintain the large picture in mind. Where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

When you refer to information, differentiate data generated by your own studies from other available information. Present work done by specific persons (including you) in past tense.

Describe generally acknowledged facts and main beliefs in present tense.

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	A-B	**C-D**	**E-F**
Abstract	Clear and concise with appropriate content, Correct format. 200 words or below	Unclear summary and no specific data, Incorrect form Above 200 words	No specific data with ambiguous information Above 250 words
Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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