A THEOREM CONCERNING CYCLIC DIRECTED GRAPHS WITH APPLICATIONS

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N00014-75-C-0781
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WITH APPLICATIONS TO NETWORK RELIABILITY

by
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DECEMBER 1978

This research has been partially supported by the Office of Naval Research under Contract N00014-75-C-0781 and the Department of Energy under Contract EC-77-S-01-5105 with the University of California. Reproduction in whole or in part is permitted for any purpose of the United States Government.
**Title:** A THEOREM CONCERNING CYCLIC DIRECTED GRAPHS WITH APPLICATIONS TO NETWORK RELIABILITY

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**Type of Report:** Research Report

**Performing Organization Name and Address:**
Operations Research Center
University of California
Berkeley, California 94720

**Controlling Office Name and Address:**
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

**Monitoring Agency Name and Address:**

**DISTRIBUTION STATEMENT (of this Report):**
Approved for public release; distribution unlimited.

**DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):**

**SUPPLEMENTARY NOTES:**
Also supported by the Department of Energy under Contract EC-77-S-01-5105.

**KEY WORDS:**
Network
Reliability
Topological Formula

**ABSTRACT:**
(SEE ABSTRACT)
ACKNOWLEDGEMENT

I am grateful to Professor Richard Barlow of University of California, Berkeley for bringing Reference [1] to my attention and helping me to understand some of the finer points of that paper. The concise proof of Lemma 1 was suggested by Ms. Jane Hagstrom of the Department of Industrial Engineering and Operations Research, University of California, Berkeley. Finally, Professor Richard Karp, also of University of California, Berkeley, provided several valuable suggestions regarding the proof of Lemma 2.
ABSTRACT

In a recent paper, Satyanarayana and Prabhaker have presented a new topological formula for evaluating exact reliability of terminal-pair directed networks. Terms in the formula are associated in a one-to-one fashion with certain acyclic subgraphs of the network, cyclic subgraphs being of no importance. In their paper, however, the proof that cyclic subgraphs may be ignored seems to be incomplete. We consider an alternate proof of this fact.
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In a recent incisive and original paper, Satyanarayana and Prabhaker [1] have suggested a new and efficient method for calculating exact system reliability for two terminal networks. The method applies to a directed graph $G$ with a single source vertex $s$ and a sink vertex $t$ and with distinct initial and terminal vertices for each edge. Any edge $e$ may be working or failed, with probabilities $p_e$ and $1 - p_e$, and the system is assumed to be working if and only if edges which have not failed constitute at least one path from $s$ to $t$. By path, we mean a simple path; that is, a chain of edges directed from $s$ to $t$ that involves no cycle; in the reliability literature such a path is usually called a minimal path. (For simplicity, let us assume graph vertices are not subject to failure, though the concepts stated here apply equally well to graphs where vertices also are "imperfect." In this case the system would be considered working if and only if there were at least one simple path from $s$ to $t$ all of whose edges and vertices were working.)

A central point of Reference [1] is that if the inclusion-exclusion formula is utilized to determine the probability of all edges working in at least one $s$-$t$ path, terms in the formula may be associated with particular subgraphs of $G$. More specifically, a term is the probability that all edges are working in some set of paths, and these edges determine a subgraph of $G$. Other terms may refer to the same group of edges and hence to the same subgraph. The idea is to collect terms common to each subgraph and express the probability of the system working as
where the sum ranges over all subgraphs \( H \) having edge sets that can be expressed as a union of \( s - t \) paths of \( G \). \( \Pr \{ H \} \) is simply the probability that all edges of \( H \) are working. The coefficient \( d_H \) is an integer, which is easily shown to be the difference between the number of ways of representing the edge set of \( H \) as the union of an odd number of \( s - t \) paths of \( G \), and the number of ways of representing this set as a union of an even number of paths.

The ingenuity of the approach is due mainly to the fact that the coefficients \( d_H \) are either \(-1\), \(-1\), or \(0\). Satyanarayana and Prabhaker show that \( d_H \) is \(-1\) or \(-1\) for \( H \) an acyclic subgraph and give an algorithm for finding each of these subgraphs and its \( d_H \) value. They also offer a proof that \( d_H = 0 \) for \( H \) a cyclic subgraph, so cyclic subgraphs may be ignored.

The proof that \( d_H = 0 \) for the cyclic subgraphs seems to involve some technical points that require further clarification. In the present discussion, we establish this fact by a somewhat different argument, an argument that will hopefully be of some interest to the reader in its own right.

Most of the terminology used here is the same as that of Reference [1]. The subgraphs of \( G \) that are of interest are p-graphs; a p-graph is a directed graph with source \( s \) and sink \( t \) in which every edge is in at least one \( s - t \) path. Given a set \( P \) of paths with initial vertex \( s \) and terminal vertex \( t \), let \( Gr ( P ) \) be the graph consisting precisely of the vertices and edges of paths in \( P \). \( Gr ( P ) \) is then a p-graph, and the set \( P \) is then called a formation of \( Gr ( P ) \). \( P \) is an odd formation.
of \( \text{Gr}(P) \) if the set \( P \) contains an odd number of paths and an even
formation if \( P \) contains an even number of paths.

If \( H \) is a \( p \)-graph, then \( d_H = 0 \) in formula (1) when the number of
odd formations of \( H \) is equal to the number of even formations. Our
argument that these numbers are equal for a cyclic \( p \)-graph involves two
lemmas and a theorem. Lemma 2 and the theorem give the main ideas;
Lemma 1 provides a technical fact used in proving Lemma 2. A number of
eamples are included to illustrate the various concepts.

**Lemma 1:**

Let \( G \) be a directed graph and \( P_{wz} \) be the set of all paths from
vertex \( w \) to vertex \( z \) in \( G \). If \( E \) is the set of edges common to
every path in \( P_{wz} \) and if \( P_{wz} \) contains at least two paths, then there
are at least two paths in \( P_{wz} \) whose only common edges are those in \( E \).

**Examples:**

(a)

(b)

**FIGURE 1**

In Figure 1 (a), \( E = \emptyset \) and paths \{ab\} and \{cd\} are edge disjoint.
In Figure 1 (b), \( E = \{b\} \) and paths \{abc\} and \{dbc\} have only edge
b in common.
Proof:

If \( P_{wz} \) has at least two paths, it is not difficult to see that no path in \( P_{wz} \) can consist only of edges in \( E \). Now consider the graph \( G_r(P_{wz}) \) as a flow network with source \( w \) and sink \( z \). Let all edges in the set \( E \) have flow capacity 2 and all other edges of \( G_r(P_{wz}) \) have capacity 1. Every \( w - z \) cut for the network has capacity at least 2, since no edges other than those in \( E \) are common to all paths. However, removal from \( G_r(P_{wz}) \) of any edge in \( E \) interrupts all paths from \( w \) to \( z \), so the minimal \( w - z \) cut has capacity 2. Thus, there exists an integer max flow having value 2. (See Reference [2].) No path in \( P_{wz} \) consists only of edges in \( E \), so this flow may be decomposed into two flows, each having value 1 along a distinct path in \( P_{wz} \).

Because edges of these paths which are not in \( E \) have capacity 1, these two paths are edge disjoint except for edges in \( E \).

Given a cyclic \( p \)-graph \( G \) and a simple cycle \( C \) in \( G \), let \( M^C \) be a minimal set of paths in \( G \), such that the \( p \)-subgraph \( G_r(M^C) \) of \( G \) contains all edges of \( C \). Let us call \( M^C \) a minimal cover for \( C \). Evidently, there may be more than one minimal cover for \( C \), so let \( \{M_i^C, i = 1, \ldots, k\} \) be the family of all minimal covers for \( C \). By the minimality requirement, it is clear that \( M_i^C \not\subseteq M_j^C \) for \( i \neq j \).
Example:

\[ \text{FIGURE 2} \]

The cycle \( C = \{bdfe\} \) has but one minimal cover, \( M^C = \{(abdfh),\{gfebc\}\} \). Note that paths \( \{abc\} \) and \( \{gfh\} \) each contain an edge of the cycle but are not in \( M^C \).

**Lemma 2:**

Let \( G \) be a cyclic p-graph. Then \( G \) contains a simple cycle \( C \) and an \( s-t \) path \( P^C \) such that \( P^C \) is not in any minimal cover for \( C \).

(The statement of the lemma is trivial when there is a path in \( G \) which contains no edge of some cycle. However, as the previous example illustrates, for some cyclic p-graphs, every path might intersect every cycle.)

**Proof:**

We might as well assume every \( s-t \) path of \( G \) has an edge in common with every cycle of \( G \). Suppose \( P \) is an \( s-t \) path and let \( w \) be the first vertex along \( P \) which is contained in some (simple) cycle, say \( C' \), and let \( w \) be the edge of \( C' \) entering node \( w \). Note that \( w \neq s \), since otherwise edge \( w \) enters the source, which is not valid for \( G \) a p-graph. Thus there is a subpath \( P_{sw} \) of \( P \) directed from vertex \( s \) to vertex \( w \). The p-graph property leads us to conclude also that \( w \neq t \), so the set \( P_{wt} \) of all subpaths from vertex \( w \) to the sink \( t \) is not empty. But no path in \( P_{wt} \) can involve a vertex of
the path $P_{sw}$ other than $w$, since otherwise $w$ would not then be the first cycle vertex in the original path $P$. Each combination of $P_{sw}$ with a subpath in $P_{wt}$ is thus a simple $s-t$ path. Figure 3 roughly illustrates the situation.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{Figure 3}
\end{figure}

Under the initial assumption that every $s-t$ path of $G$ has an edge in common with every cycle of $G$, it turns out that $P_{wt}$ must contain at least two paths. The validity of the lemma does not depend on this fact, but our proof may be simplified by ignoring the case when $P_{wt}$ contains a single path. That $P_{wt}$ contains at least two paths is not difficult to show, though we do not show it here.

Let $E$ be the set of edges common to every path in $P_{wt}$. By Lemma 1 above, there are at least two paths $P'_{wt}$ and $P''_{wt}$ whose only common edges are those in $E$. Since we have assumed that every $s-t$ path in $G$ contains an edge of the cycle $C'$, every path in $P_{wt}$ must pass through a vertex of $C'$. Let $x$ be the last vertex along $C'$ from vertex $w$, such that $x$ is a vertex along path $P'_{wt}$ or $P''_{wt}$. Without loss of generality, suppose path $P'_{wt}$ passes through vertex $x$. 


Consider the cycle $C$, formed from cycle $C'$ by replacing the cycle path from vertex $w$ to vertex $x$ in $C'$ with the subpath of $P'_{wt}$ from $w$ to $x$. The cycle $C$ passes through each of its vertices but once, so $C$ is, in fact, a simple cycle. ($C$ could be the same as $C'$.) For convenience (or maybe inconvenience), Figure 4 attempts to illustrate the situation.

![Figure 4](image_url)

Finally, let $P^C = P_{sw} P'_{sw}$, the $s-t$ path formed by joining subpaths $P_{sw}$ and $P'_{sw}$ at vertex $w$. We maintain that $P^C$ is not in any minimal cover $M^C_1$ for cycle $C$. To see this, let $M^C_1$ be any minimal cover of $C$ and suppose $P^\omega$ is a path in $M^C_1$ that contains edge $\omega$. If $v$ is the initial vertex of $\omega$, $P^\omega$ may be expressed as $P_{sv} P_{\omega w} P_{vt}$, where $P_{sv}$ is some path from $s$ to $v$ and $P_{\omega w} \in P_{wt}$. Now note that the set of cycle $C$ edges in $P'_{sw}$ is a subset of the set $E$ of edges common to all paths in $P_{wt}$. $P_{wt}$ thus contains at least the edges of cycle $C$ in $P'_{sw}$. Hence, $P^C$ cannot be in $M^C_1$, since $P^\omega$ contains at least one more edge of $C$ than $P^C$ (namely, $\omega$). Since $M^C_1$ was an arbitrary cover of $C$, the lemma follows. ||
To further clarify the construction of Lemma 2, let us consider the following example:

Take $P_{sw}$ to consist of edge $a$, and $\{ebdf\}$ to be the cycle $C'$. The edge entering vertex $w$ is then $\omega = e$. The set of paths $P_{wt}$ is $\{\{bc\}, \{bdfh\}, \{bifh\}\}$. We can let $P''_{wt} = \{bc\}$ and $P'_{wt}$ be either $\{bdfh\}$ or $\{bifh\}$. Suppose $P'_{wt} = \{bifh\}$. In this case, vertex $x$ is the initial vertex of edge $\omega$, i.e., $x = v$ in the vertex labeling of the proof. The new cycle $C$ will then be $\{ebif\}$. There is only a single minimal cover of $C$, namely, $\mathcal{M}^C = \{\{abifh\}, \{gfebc\}\}$. The path $P^C_{sw}P''_{wt} = \{abc\}$ contains only the cycle $C$ edge $b$; whereas, $P^\omega_{wt} = \{gfebc\}$ contains not only cycle edge $b$, but also edge $e$.

Let $\mathcal{F}_G$ be the family of all formations of a p-graph $G$ and let $P$ be any $s-t$ path in $G$. We partition the formations of $\mathcal{F}_G$ into families $\mathcal{R}(P)$ and $\{\mathcal{D}_H(P) \mid H \text{ a proper p-subgraph of } G\}$ as follows: A particular formation $P \in \mathcal{F}_G$ is assigned to $\mathcal{R}(P)$ if either (1) $P$ does not contain path $P$, or (2) $P$ contains path $P$ but $P - \{P\}$ is also a formation of $G$. If $P$ cannot be assigned to $\mathcal{R}(P)$
then \( H = Gr(\{P - \{P\}\}) \) is a proper subgraph of \( G \) and \( P \) is assigned to \( D_H(P) \). Note that the number of odd formations in \( R(P) \) equals the number of even formations. As a rule, most of the families \( \{D_H(P) \mid H \text{ a proper } p\text{-subgraph of } G \} \) will be empty. In some cases, \( R(P) \) may be empty.

If \( D_H(P) \) is nonempty, let \( P_H = \{P - \{P\} \mid P \in D_H(P)\} \). \( P_H \) consists of all formations of the \( p \)-graph \( H \), since if \( Q \) is any formation of \( H \), \( Q \cup \{P\} \) must be a formation of \( G \); hence, \( Q \cup \{P\} \in D_H(P) \) and \( Q \in P_H \).

As an example of this partition, consider the graph of Figure 6.

![Diagram](image)

**FIGURE 6**

The paths are:

- \( p^1 = \{ag\} \)
- \( p^4 = \{bd fh\} \)
- \( p^2 = \{afh\} \)
- \( p^5 = \{c ed g\} \)
- \( p^3 = \{bd g\} \)
- \( p^6 = \{ch\} \).

The set \( F_G \) of formations of \( G \) is
\[
\begin{align*}
    p^1 &= \{p^2p^3p^5\} & p^5 &= \{p^4p^2p^4p^5\} \\
    p^2 &= \{p^1p^2p^3p^5\} & p^6 &= \{p^1p^3p^4p^5\} \\
    p^3 &= \{p^1p^4p^5\} & p^7 &= \{p^2p^3p^4p^5\} \\
    p^4 &= \{p^2p^4p^5\} & p^8 &= \{p^1p^2p^3p^4p^5\} \\
    p^9 &= \{p^2p^3p^5p^6\} & p^{13} &= \{p^1p^2p^4p^5p^6\} \\
    p^{10} &= \{p^1p^2p^3p^5p^6\} & p^{14} &= \{p^1p^3p^4p^5p^6\} \\
    p^{11} &= \{p^1p^4p^5p^6\} & p^{15} &= \{p^2p^3p^4p^5p^6\} \\
    p^{12} &= \{p^2p^4p^5p^6\} & p^{16} &= \{p^1p^2p^3p^4p^5p^6\} \\
\end{align*}
\]

Let us choose \( p^3 \) and partition according to this path:

\[
\mathcal{R}(p^3) = \left\{ p^3, p^4, p^5, p^{11}, p^{12}, p^{13}, p^6, p^7, p^8, p^{14}, p^{15}, p^{16} \right\}.
\]

Note the first 8 formations in \( \mathcal{R}(p^3) \) do not contain \( p^3 \), but the last 8 do. Finally, the only proper \( p \)-subgraph \( H \) for which \( \mathcal{D}_H(p^3) \) is nonempty is that of Figure 7; for this subgraph, \( \mathcal{D}_H(p^3) = \{p^1, p^2, p^9, p^{10}\} \).

\[\text{FIGURE 7}\]
Theorem:

Let $G$ be a cyclic $p$-graph. The number of odd formations of $G$ is equal to the number of even formations.

Proof:

We will use induction on the number of paths of $G$.

It is easy to verify that there are no cyclic $p$-graphs having less than 4 paths, so let $G$ have $n = 4$ paths. By Lemma 2, $G$ has a cycle $C$ and a path $P^C$ that is contained in no minimal cover $M^C_1$ for that cycle. Partition the family $P_G$ of formations as indicated above, using the path $P^C$. We maintain that $D_H(P^C)$ is empty for every $p$-subgraph $H$ of $G$. To see this, note that if $P \in D_H(P^C)$, there is at least one minimal cover $M^C_1$ in $P - \{P^C\}$, since $P^C$ is in no $M^C_1$. But then $H = Gr(P - \{P^C\})$ is cyclic, which is not possible because $H$ has 3 or less paths. Thus $P_G = R(P^C)$, and since the number of even formations of $G$ in $R(P^C)$ is equal to the number of odd formations, the theorem is true when $G$ has 4 paths.

Now suppose the theorem is true for all cyclic $p$-graphs having $m$ paths, $4 \leq m \leq n - 1$. Let $G$ be a cyclic $p$-graph having $n$ paths. By Lemma 2 again, $G$ has a cycle $C$ and a path $P^C$ that is in no minimal cover for $C$. Partitioning the family $P_G$ of all formations of $G$, we get families $R(P^C)$ and $\{D_H(P^C) \mid H$ a proper $p$-subgraph of $G\}$. If $D_H(P^C)$ is empty for all $p$-subgraphs $H$ of $G$, then $P_G = R(P^C)$ as above, and the number of even formations of $G$ equals the number of odd formations. Hence, suppose $D_H(P^C)$ is nonempty for some $H$. Since $P^C$ is contained in no $M^C_1$, $H$ must be cyclic and $H$ contains $n - 1$ or less paths. By the induction assumption, the family $P_H$ of all
formations of $H$ has the same number of even as odd formations. Each formation of $G$ in $D_H(P^C)$ can be produced by appending $P^C$ to one of the formations in $P_H$. Hence, for every nonempty family $D_H(P^C)$, the number of even formations in $D_H(P^C)$ equals the number of odd formations. Thus, each family in the partition of $P_G$ is either empty or contains the same number of even as odd formations, and the theorem follows.||
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