

## PATH DECOMPOSITIONS OF CHAINS AND CIRCUITS

E.J. FARRELL

Department of Mathematics  
The University of the West Indies  
St. Augustine, Trinidad  
West Indies

(Received June 28, 1982 and in revised form January 25, 1983)

**ABSTRACT.** Expressions for the path polynomials (see Farrell [1]) of chains and circuits are derived. These polynomials are then used to deduce results about node disjoint path decompositions of chains and circuits. Some results are also given for decompositions in which specific paths must be used.

**KEY WORDS AND PHRASES.** Path polynomial, path decomposition, incorporated graph, restricted decomposition.

1980 MATHEMATICS SUBJECT CLASSIFICATION CODES. 05C38, 05A15.

### 1. INTRODUCTION.

The graphs considered here will be finite, undirected and without loops or multiple edges. Let  $G$  be such a graph. With every path  $\alpha$  in  $G$ , let us associate the weight  $w_\alpha$ . With every spanning subgraph  $C$  of  $G$  consisting of paths  $\alpha_1, \alpha_2, \dots, \alpha_k$ , let us associate the monomial

$$w(C) = \prod_{i=1}^k w_{\alpha_i}.$$

The path polynomial of  $G$  is

$$P(G; \underline{w}) = \sum w(C),$$

where the summation is taken over all the path covers (spanning subgraphs consisting of paths only) of  $G$ . The vector  $\underline{w}$  is called the general weight vector. In this paper we will assign weights to paths according to the number of nodes which they contain. Therefore, we will have  $\underline{w} = (w_1, w_2, \dots, w_k, \dots)$ , and  $P(G; \underline{w})$  will be a polynomial in the indeterminates  $w_1, w_2$ , etc. If we put  $w_i = w$ , for all  $i$ , then the resulting polynomial  $P(G; w)$  will be called the simple path polynomial of  $G$ . The path polynomial is a special  $F$ -polynomial (see [1]).

By path incorporating an edge  $x$  in  $G$  we will mean that  $x$  is distinguished in some manner and required to belong to every path cover of  $G$  that we consider. An incorporated graph will be a graph whose edges are all incorporated. A graph containing an incorporated subgraph will be called a restricted graph. Sometimes it will be conven-

ient to shrink an incorporated subgraph to a "node". We will call such a "node" a compound node. A graph  $G$  containing an incorporated subgraph or a compound node i.e. a restricted graph, will normally be denoted by  $G^*$ .

A tree with nodes of valencies 1 and 2 only will be called a chain. The chain with  $n$  nodes will be denoted by  $P_n$ . By attaching a chain  $P_n$  to a nonempty graph  $G$  we will mean that a terminal node of  $P_n$  is identified with a node of  $G$ , so as to form a connected component in which  $G$  and  $P_n$  are subgraphs with exactly one node in common. By adding a chain  $P_n$  to a graph  $G$ , we will mean that the two terminal nodes of  $P_n$  are attached to different nodes of  $G$  (N.B. In this case,  $G$  must have at least two nodes). We refer the reader to Harary [2] for definitions of the standard terms used in graph theory.

Upper limits of summations will be infinity unless otherwise specified. A node disjoint path decomposition of  $G$  is another name for a path cover of  $G$ . The name island decomposition was used by Goodman and Hedetniemi [3], who derived an efficient algorithm for finding  $hc(T)$  - the minimum number of edges needed to be added to a tree  $T$  in order to make it Hamiltonian.  $hc(G)$  is called the Hamiltonian completion number of  $G$ . It will be denoted by  $\zeta(G)$ . Some results on  $\zeta(G)$  were obtained by Boesch, Chen, and McHugh [4]. Some results for trees were obtained by Slater [5].

In this paper we will use some of the basic results on path polynomials in order to derive the path polynomials of chains and circuits. From these polynomials, we will deduce results about node disjoint path decompositions of the graphs. Throughout the paper "decomposition" will mean "node disjoint path decomposition" and "cover" will mean "path cover".

## 2. BASIC PRELIMINARY RESULTS.

By putting the covers of  $G$  into classes according to whether or not they contain a specified edge, we obtain the following theorem, called the fundamental theorem for path polynomials.

**THEOREM 1.** Let  $G$  be a graph and  $e$  an (unincorporated) edge of  $G$ . Let  $G'$  be the graph obtained from  $G$  by deleting  $e$  and  $G^*$ , the graph obtained from  $G$  by path incorporating  $e$ . Then

$$P(G; \underline{w}) = P(G'; \underline{w}) + P(G^*; \underline{w}).$$

(N.B. Throughout this paper, we will refer to graphs obtained by deleting edges as  $G'$  and graphs obtained by incorporating edges as  $G^*$ , whenever Theorem 1 is applied.)

The fundamental algorithm for path polynomials consists of repeated applications of Theorem 1, until graphs  $G_i$  are obtained for which  $P(G_i; \underline{w})$  are known. The following lemmas imply some useful simplifications to the fundamental algorithm (also called the reduction process).

**LEMMA 1.** (i) If an incorporated edge creates an incorporated circuit in  $G^*$ , then

$$P(G^*; \underline{w}) = 0.$$

(ii) If an incorporated edge creates a node of valency 3 in  $G^*$ , then

$$P(G^*; \underline{w}) = 0.$$

In any practical application of the reduction process, we could incorporate an edge  $e$ , by identifying the nodes at the ends of  $e$  as described in Read [6] for chromatic polynomials. However, we must keep track of the number of nodes in the incorporated subgraph associated with the new node formed by identification.

Lemma 1 suggests that we can delete from  $G^*$ , all edges which will finally complete circuits with incorporated edges. Also, if two edges have been incorporated at node  $x$ , then all unincorporated edges at  $x$  can be deleted.

The following result is called the Component Theorem. It is also given in [1] for general F-polynomials. It can be easily proved.

THEOREM 2. Let  $G$  be a graph consisting of  $n$  components  $H_1, H_2, \dots, H_n$ . Then

$$P(G; \underline{w}) = \prod_{i=1}^n P(H_i; \underline{w}).$$

3. PATH POLYNOMIALS OF CHAINS.

The notation  $G^*[n]$  will be used for a restricted graph containing an incorporated chain with  $n$  edges. The following theorem gives a recurrence relation for the path polynomial of chains.

THEOREM 3.

$$P(P_n; \underline{w}) = \sum_{i=1}^n w_i P(P_{n-1}; \underline{w}).$$

PROOF. Apply the reduction process to  $P_n$  by deleting a terminal edge. Then  $G'$  will be a graph containing two components, an isolated node and  $P_{n-1}$ .  $G^*$  will be  $P_n^*[1]$ . Apply the process to  $P_n^*[1]$  by deleting the terminal edge adjacent to the incorporated edge. In this case, the graph  $G'$  will be a graph with two components, an incorporated edge, having a weight  $w_2$  and  $P_{n-2}$ .  $G^*$  will be  $P_n^*[2]$ . Continue the reduction process in this manner to subsequent graphs  $P_n^*[k]$  ( $k > 2$ ), until the entire chain is incorporated. The result then follows by adding the contributions of the graphs  $G'$  formed during the process and the final incorporated graph  $P_n^*[n-1]$ , having a weight  $w_n$ .

For brevity, we will write  $P(n)$  for  $P(P_n; \underline{w})$ , when it would lead to no confusion. Conventionally, we write  $P(0) = 1$ . The following table gives values of  $P(n)$  for  $n = 1, 2, 3, 4, 5$  and  $6$ . Observe that the sum of the coefficients of the polynomial in the  $n^{\text{th}}$  row is  $2^{n-1}$ .

The following theorem gives a generating function  $P(P_n; \underline{w}, t)$  for  $P(n)$ .

THEOREM 4.

$$P(P_n; \underline{w}, t) = [1 - (w_1 t + w_2 t^2 + w_3 t^3 + \dots)]^{-1}.$$

PROOF.

$$\begin{aligned} P(n) &= \sum_{i=1}^n w_i P(n-i) \\ &= \text{coefficient of } t^n \text{ in } \sum_{s=1}^{\infty} w_s t^s \cdot \sum_{k=0}^{\infty} P(k) t^k. \\ \text{Put } w(t) &= \sum_{s=1}^{\infty} w_s t^s \text{ and } P(t) = \sum_{k=0}^{\infty} P(k) t^k. \end{aligned}$$

Table 1  
Path Polynomials of Chains

n	P(n)
1	$w_1$
2	$w_1^2 + w_2$
3	$w_1^3 + 2w_1w_2 + w_3$
4	$w_1^4 + 3w_1^2w_2 + 2w_1w_3 + w_2^2 + w_4$
5	$w_1^5 + 4w_1^3w_2 + 3w_1^2w_3 + 3w_1w_2^2 + 2w_1w_4 + 2w_2w_3 + w_5$
6	$w_1^6 + 5w_1^4w_2 + 4w_1^3w_3 + 6w_1^2w_2^2 + 3w_1^2w_4 + 6w_1w_2w_3 + 2w_1w_5$ $+ w_2^3 + 2w_2w_4 + w_3^2 + w_6$

Then

$$\sum_{n=1} P(n)t^n = w(t) P(t) .$$

⇒

$$P(t) - P(0) = w(t) P(t).$$

The result therefore follows.

We will now consider chains containing incorporated subchains. The covers of these restricted chains will be covers in which a particular path must appear. When the incorporated subchain contains r edges and contains a node of valency 1 of the restricted chain, the graph will be denoted by  $P_n^*[r]$ , where n is the number of nodes in the nodes in the unincorporated subchain (including the node common to both subchains). The path polynomial of  $P_n^*[r]$  is given in the following theorem.

THEOREM 5.

$$P(P_n^*[r]; \underline{w}) = \sum_{i=1}^n w_{r+i} P(n-i).$$

PROOF. Apply the reduction process to  $P_n^*[r]$  by always deleting the edge which links the restricted edges to the unrestricted ones. The result then follows.

When the incorporated subchain does not include a node of valency 1 of the restricted chain, the graph will be denoted by  $P_{n_1+n_2}^*[r]$  where  $n_1$  and  $n_2$  ( $n_1, n_2 > 1$ ) are the number of nodes in the unrestricted subchains. The path polynomial of this graph is given in the following result.

THEOREM 6.

$$P(P_{n_1+n_2}^*[r]; \underline{w}) = \sum_{s=1}^{n_1} \sum_{t=1}^{n_2} w_{r+s+t-1} P(n_1-s) P(n_2-t) \quad (n_1, n_2 > 1).$$

PROOF. Apply the reduction process to the graph, by deleting the edge of the subchain  $P_{n_1}$ , which is adjacent to an incorporated edge. The graph  $G_1'$  will consist of two components  $P_{n_1-1}$  and  $P_{n_2}^*[r]$ .  $G_1'^*$  will be  $P_{(n_1-1)+n_2}^*[r+1]$ . Apply the reduction

process to  $G_1^*$ , and to subsequent  $G_i^*$ 's by deleting the edge of the unrestricted sub-chain of  $P_{n_1}$  which is adjacent to an incorporated edge. By adding the contributions of the  $G_i^*$ 's and the final restricted graph  $P_{n_2}^*[n_1 - 1 + r]$  we get

$$P(P_{n_1+n_2}^{**}[r]; \underline{w}) = \sum_{s=1}^{n_1} P(n_1 - s) P(P_{n_2}^*[r+s-1]; \underline{w}).$$

The result follows by using Theorem 5.

When the incorporated chain is attached to a node of valency 2 of the chain, the graph will be denoted by  $P_{n_1, n_2}^*[r]$ , where  $n_1$  and  $n_2$  ( $n_1, n_2 > 1$ ) are the number of nodes in the subchains separated by the node of valency 3. The result for this graph is given in the following theorem.

THEOREM 7.

$$P(P_{n_1, n_2}^*[r]; \underline{w}) = P(n_1 - 1) \sum_{i=1}^{n_2} w_{r+i} P(n_2 - i) + P(n_2 - 1) \sum_{i=1}^{n_1 - 1} w_{r+j+1} P(n_1 - j - 1) \quad (n_1 n_2 > 1).$$

PROOF. Let  $x$  be the node of valency 3 and  $y$  and  $z$  the nodes of the subchains  $P_{n_1}$  and  $P_{n_2}$  respectively, which are adjacent to  $x$ . Apply the reduction process by deleting the edge  $xy$ .  $G$  will be the graph consisting of components  $P_{n_1-1}$  and  $P_{n_2}^*[r]$ .  $G^*$  will consist of components  $P_{n_2-1}$  and  $P_{n_1-1}^*[r+1]$ . Hence we get

$$P(P_{n_1, n_2}^*[r]; \underline{w}) = P(n_1 - 1) P(P_{n_2}^*[r]; \underline{w}) + P(n_2 - 1) P(P_{n_1-1}^*[r+1]; \underline{w}).$$

The result then follows by using Theorem 5.

4. SIMPLE PATH POLYNOMIALS OF CHAINS.

The factor  $(1+w)$  appears quite frequently in the simple path polynomials of chains and circuits. We will therefore replace it by  $z$ . Let us assume that

$$P(G; w) = \sum_{i=1} A_i z^i,$$

where the  $A_i$ 's are constants. By putting  $w = 0$ , we get  $\sum_{i=1} A_i = 0$ , since  $P(G; w)$  can have no constant term. Also, the number of Hamiltonian paths in  $G$  (denoted by  $H(G)$ ) will be the coefficient of  $w$  in  $P(G; w)$ , which is  $\sum_{i=1} i A_i$ . Hence we have

LEMMA 2. Let  $P(G; w) = \sum_{i=1} A_i z^i$ , where  $z = 1 + w$ . Then

(i)  $\sum_{i=1} A_i = 0$

and

(ii)  $H(G) = \sum_{i=1} i A_i$ .

We can obtain the simple path polynomial of  $P_n$  from Theorem 4 by putting  $w_i = w$  for all  $i$ , then equating coefficients of  $t^n$ . However, the result can be more easily obtained by a straightforward combinatorial argument. A cover of  $P_n$  with cardinality  $k$  can be obtained by deleting  $k-1$  edges for any  $0 < k \leq n$ . Hence, we have

THEOREM 8.

$$P(P_n; w) = w(1+w)^{n-1} = z^n - z^{n-1}.$$

The following corollaries are immediate from Theorems 5 and 6. They can also be independently proved, by recognizing that in the case of the simple path polynomial of restricted chains, we can "shrink" the incorporated subchains to a node.

COROLLARY 5.1. For all  $r$ ,

$$P(P_n^*[r];w) = P(P_n;w) = z^n - z^{n-1}.$$

COROLLARY 6.1. For all  $r$ ,

$$P(P_{n_1+n_2}^{**}[r];w) = P(P_{n_1+n_2-1};w) = z^{n_1+n_2-1} - z^{n_1+n_2-2}.$$

We can obtain the simple path polynomial of  $P_{n_1, n_2}^*[r]$  by direct substitution into Theorem 7; however, this will be a bit tedious. It is better to obtain the result independently by using the reduction process. The result is given in the following corollary, for which an independent proof is given.

COROLLARY 7.1.

$$P(P_{n_1, n_2}^*[r];w) = z^{n_1+n_2-4} (z-1)^2 (z+1).$$

PROOF. Apply the reduction process to the graph, just as we did in the proof of Theorem 7.  $G$  will consist of components  $P_{n_1-1}$  and  $P_{n_2}^*[r]$ . But from Corollary 5.1,

$$P(P_{n_2}^*[r];w) = P(P_{n_2};w).$$

$G^*$  will consist of components  $P_{n_2-1}$  and  $P_{n_1-1}^*[r+1]$ . But

$$P(P_{n_1-1}^*[r+1];w) = P(P_{n_1-1};w).$$

Hence we get

$$\begin{aligned} P(P_{n_1, n_2}^*[r];w) &= P(P_{n_1} - 1) P(n_2) + P(n_2 - 1) P(n_1 - 1) \\ &= (z^{n_1-1} - z^{n_1-2})(z^{n_2} - z^{n_2-1}) + (z^{n_2-1} - z^{n_2-2})(z^{n_1-1} - z^{n_1-2}) \end{aligned}$$

The result then follows after simplification.

Let us denote by  $P_n^{k*}$ , the restricted chain formed by attaching to a chain  $P_n$ ,  $k$  incorporated paths ( $k < \lfloor n/2 \rfloor$ ) such that no two are attached to adjacent nodes of  $P_n$ . We will also assume that none of the end-nodes of  $P_n$  are used, for if it is, then it can be treated as an ordinary node, as implied by Corollary 5.1. The simple path polynomial of  $P_n^{k*}$  is given in the following theorem.

THEOREM 9.

$$P(P_n^{k*};w) = z^{n-2k-1} (z-1)^{k+1} (z+1)^k.$$

PROOF BY INDUCTION ON  $k$ . Corollary 7.1 verifies the case for  $k=1$ . Let us assume that the statement holds for  $k=r$ . Then

$$P(P_n^{r*};w) = z^{n-2r-1} (z-1)^{r+1} (z+1)^r.$$

We can apply the reduction process to  $P_n^{(r+1)*}$  by deleting the edge which is adjacent

to "last" incorporated path from the end of the restricted chain, such that  $G$  would consist of (i) a restricted chain containing  $r$  incorporated paths, and (ii) a restricted chain with one end-node attached to an incorporated path. Thus the components of  $G$  will be  $P_s^{r*}$  and  $P_t^*$ , with  $s+t = n$ . Since the incorporated path is attached to an end-node of  $P_t^*$ ,  $P(P_t^*;w) = P(P_t;w)$ . Hence

$$\begin{aligned} P(G;w) &= z^{s-2r-1} (z-1)^{r+1} (z+1)^r z^{t-1} (z-1) \\ &= z^{n-2r-2} (z-1)^{r+2} (z+1)^r. \end{aligned}$$

The graph  $G^*$  will contain two components  $P_{s-1}^{r*}$  and  $P_t^*$ . Hence

$$\begin{aligned} P(G^*;w) &= z^{s-2r-2} (z-1)^{r+1} (z+1)^r z^{t-1} (z-1) \\ &= z^{n-2r-3} (z-1)^{r+2} (z+1)^r. \end{aligned}$$

It follows that

$$P(P_n^{(r+1)*};w) = z^{n-2r-2} (z-1)^{r+2} (z+1)^r + z^{n-2r-3} (z-1)^{r+2} (z+1)^r.$$

On simplification, we get

$$P(P_n^{(r+1)*};w) = z^{n-2r-3} (z-1)^{r+2} (z+1)^{r+1}.$$

Hence the statement holds for  $k = r+1$ , when it is assumed for  $k = r$ . By the Principle of Induction, it holds for all  $r$ .

5. PATH DECOMPOSITION OF CHAINS.

Let  $\pi = (n_1^{k_1}, n_2^{k_2}, \dots, n_r^{k_r})$  be a partition of  $n$ . We will denote by  $N_G(\pi)$ , the number of decompositions of the graph  $G$  into  $k_i$  paths with  $n_i$  nodes, for  $i = 1, 2, \dots, r$ .  $N_G$  will denote the total number of decompositions of  $G$  into paths. It is clear that  $N_G(\pi)$  is the coefficient of  $w_{n_1}^{k_1} w_{n_2}^{k_2} \dots w_{n_r}^{k_r}$  in  $P(G;w)$ .

The following corollary is immediate from Theorem 8. It confirms the observation made about the sum of the coefficients of the polynomials in Table 1 above.

COROLLARY 8.1.

$$N_P = 2^{n-1}.$$

It can be observed from Table 1, that all partitions of the integer  $n$  appear as subscripts of  $w$ . [ $w_i^k = w_1 w_1 \dots$  ( $k$  times)]. This suggests the following theorem which is otherwise obvious.

THEOREM 10. For every partition  $\pi = (d_1, d_2, \dots, d_k)$  of  $n$ , a decomposition of  $P_n$  into paths containing  $d_i$  nodes ( $i = 1, 2, \dots, k$ ).

The following corollary of Theorem 3 gives a recurrence which is useful for finding the number of decompositions of a chain into paths with specified lengths.

COROLLARY 3.1.

$$N_P(n_1^{k_1}, n_2^{k_2}, \dots, n_r^{k_r}) = \sum_{i=1}^r N_P(n-n_i) (n_1^{k_1}, n_2^{k_2}, \dots, n_{i-1}^{k_{i-1}}, n_i^{k_i-1}, n_{i+1}^{k_{i+1}}, \dots, n_r^{k_r}).$$

PROOF. From Theorem 3, we have

$$P(n) = w_1 P(n-1) + w_2 P(n-2) + \dots + w_n.$$

$N_{P_n}(n_1^{k_1}, n_2^{k_2}, \dots, n_r^{k_r})$  is the coefficient of  $w_{n_1}^{k_1} w_{n_2}^{k_2} \dots w_{n_r}^{k_r}$  in  $P(n)$ . The only terms on the R.H.S. which contribute to this coefficient are  $w_{n_1}^{P(n-n_1)}$ ,  $w_{n_2}^{P(n-n_2)}$ , ... and  $w_{n_r}^{P(n-n_r)}$ . The result therefore follows.

Corollary 3.1 suggests an algorithm for finding the number  $N_{P_n}(n_1^{k_1}, n_2^{k_2}, \dots, n_r^{k_r})$ . The following lemma is quite useful when applying Corollary 3.1. Its proof is straightforward.

LEMMA 3.

- (i)  $N_{P_n}(1^{n-2}, 2) = n - 1$ .
- (ii)  $N_{P_n}(1^{n-3}, 3) = n - 2$ .
- (iii)  $N_{P_n}(1, n-1) = 2$ .
- (iv)  $N_{P_n}((n/k)^k) = 1$ , where  $k$  divides  $n$ .

ILLUSTRATION.

$$\begin{aligned} N_{P_6}(1^2, 2^2) &= N_{P_5}(1, 2^2) + N_{P_4}(1^2, 2) \\ &= N_{P_4}(2^2) + N_{P_3}(1, 2) + N_{P_3}(1, 2) + N_{P_2}(1^2) \\ &= 1 + 2 + 2 + 1 \\ &= 6, \text{ in agreement with Table 1.} \end{aligned}$$

By a restricted decomposition of a graph  $G$ , we mean a decomposition in which particular paths must be included. Clearly, the decompositions of restricted graphs will be restricted.

The following corollaries can be easily deduced from the results given in Section 4 by putting  $w = 1$ .

COROLLARY 5.2. The number of restricted decompositions of the chain  $P_{n+k}$  in which a particular terminal subchain  $P_k$  is always included, is  $2^{n-1}$ .

COROLLARY 6.2. The number of restricted decompositions of  $P_{n_1+n_2+n_3}(n_1, n_2, n_3 > 1)$  in which a particular subchain  $P_{n_3}$  (which does not include a terminal edge) is always included, is  $2^{n_1+n_2-2}$ , where  $n_1$  and  $n_2$  are the numbers of nodes in the subchains separated by  $P_{n_3}$ .

COROLLARY 7.2. Let  $G$  be a graph consisting of 3 chains  $P_{n_1}, P_{n_2}$  and  $P_{n_3}$  ( $n_1, n_2, n_3 > 1$ ) attached to a single node. The number of restricted decompositions of  $G$ , in which the chain  $P_{n_3}$  is always included, is  $3 \cdot 2^{n_1+n_2-4}$ .

COROLLARY 9.1. Let  $G$  be the graph formed by attaching  $k$  chains to non-adjacent nodes of valency 2 in  $P_n$ . The number of restricted decompositions of  $G$ , in which the  $k$  chains are always included, is  $3^k \cdot 2^{n-2k-1}$ .

By extracting the coefficient of  $w^s$  in the expression given for  $P(P_{n_1, n_2}^* [r]; w)$  in Corollary 7.1 and the expression for  $P(P_n^{k*}; w)$  given in Theorem 9, we obtain the following results.

COROLLARY 7.3. Let  $G$  be a graph consisting of 3 chains  $P_{n_1}$ ,  $P_{n_2}$  and  $P_{n_3}$  ( $n_1, n_2, n_3 > 1$ ) attached to a node. The number of restricted decompositions of  $G$ , with cardinality  $s (s > 1)$ , in which the chain  $P_{n_3}$  is always included, is

$$\begin{bmatrix} N-3 \\ s-2 \end{bmatrix} + \begin{bmatrix} N-4 \\ s-2 \end{bmatrix}$$

where  $N = n_1 + n_2$ .

COROLLARY 9.2. Let  $G$  be a graph formed by attaching  $k$  chains to non-adjacent nodes of valency 2 of a chain  $P_n$ . The number of restricted decompositions of  $G$ , with cardinality  $s (s > k)$ , in which the  $k$  chains are always included is

$$\sum_{r=0}^s \begin{bmatrix} k \\ r \end{bmatrix} \begin{bmatrix} n-2k-1 \\ s-k-r-1 \end{bmatrix} 2^{k-r}.$$

6. PATH POLYNOMIALS OF CIRCUITS.

The notation  $C_n$  will be used for a circuit with  $n$  nodes. The following theorem gives an expression for the path polynomial of  $C_n$ .

THEOREM 11.

$$P(C_n; w) = \sum_{r=1}^n r w_r P(n-r).$$

PROOF. Apply the reduction process to  $C_n$  by deleting an edge. The graph  $G^{\sim}$  will be  $P_n$ .  $G^*$  will be  $C_n^*[1]$ . Continue to apply the reduction process to the restricted graphs formed, by always deleting an edge which is adjacent to an incorporated edge. The graphs  $G^{\sim}$  will be restricted chains. The graph formed by incorporating the final edge of  $C_n$  cannot contribute to  $P(C_n; w)$  since it contains an incorporated circuit.

By adding the contributions of the graphs  $G^{\sim}$  formed during the process, we get

$$P(C_n; w) = \sum_{r=0}^{n-1} P(P_{n-r}^* [r]; w) \quad (\text{with } P_n^*[0] \equiv P_n).$$

By using Theorem 5, we get

$$\begin{aligned} P(C_n; w) &= \sum_{r=0}^{n-1} \sum_{i=1}^{n-r} w_{r+i} P(n-r-i) \\ &= \sum_{r=1}^n r w_r P(n-r), \text{ as required.} \end{aligned}$$

The following table gives values of  $C(n)$  ( $\equiv P(C_n; w)$ ) for  $n = 1, 2, 3, 4, 5$ , and 6. Observe that the sum of the coefficients of the polynomial in the  $n^{\text{th}}$  row is  $2^n - 1$ .

Table 2  
Path Polynomials of Circuits

n	C(n)
1	$w_1$
2	$w_1^2 + 2w_2$
3	$w_1^3 + 3w_1w_2 + 3w_3$
4	$w_1^4 + 4w_1^2w_2 + 4w_1w_3 + 2w_2^2 + 4w_4$
5	$w_1^5 + 5w_1^3w_2 + 5w_1^2w_3 + 5w_1w_2^2 + 5w_2w_3 + 5w_5$
6	$w_1^6 + 6w_1^4w_2 + 6w_1^3w_3 + 9w_1^2w_2^2 + 6w_1^2w_4 + 12w_1w_2w_3 + 6w_1w_5$ $+ 2w_2^3 + 6w_2w_4 + 3w_3^2 + 6w_6$

A generating function for  $P(C_n; \underline{w})$  can be obtained by using a technique similar to that used in the proof of Theorem 4. It is given in the following theorem.

THEOREM 12.

$$P(C_n; \underline{w}, t) = \frac{w_1 t + 2w_2 t^2 + 3w_3 t^3 + \dots}{1 - (w_1 t + w_2 t^2 + w_3 t^3 + \dots)} = \frac{t P'(t)}{P(t)},$$

where  $P(t) \equiv P(P_n; \underline{w}, t)$ .

Let  $C_{n+r-1}^*[r]$  be a restricted circuit consisting of an incorporated path with  $r$  edges and a path with  $n$  nodes. Let us apply the reduction process to  $C_{n+r-1}^*[r]$  as we did in the proof of Theorem 11 for the restricted circuits. This will yield

$$P(C_{n+r-1}^*[r]; \underline{w}) = \sum_{i=0}^{n-1} P(P_{n-i}^*[r+i]; \underline{w}).$$

By applying Theorem 5, we get the following result.

THEOREM 13.

$$P(C_{n+r-1}^*[r]; \underline{w}) = \sum_{i=0}^{n-1} \sum_{j=1}^{n-i} w_{r+i+j} P(n-i-j).$$

Consider now the case in which the incorporated chain  $P_r^*$  is attached to  $C_n$ . We will denote this graph by  $C_n^{**}[r-1]$ . If we apply the reduction process to this graph, by deleting an unincorporated edge which is adjacent to an incorporated edge, the graph  $G'$  will be  $P_{q+r-1}^*[r-1]$  and  $G^*$  will be  $P_{q+r-1}^*[r]$ . Hence we obtain the following result by using Theorem 5.

THEOREM 14.

$$P(C_n^{**}[r-1]; \underline{w}) = \sum_{i=1}^{n+r-1} (w_{r+i} + w_{r+i-1}) P(n+r-1-i).$$

7. SIMPLE PATH POLYNOMIALS OF CIRCUITS.

The simple path polynomial of  $C_n$  can be easily deduced from Theorems 8 and 11,

or by elementary combinatorial argument. It is given in the following theorem.

THEOREM 15.

$$P(C_n; w) = (1 + w)^n - 1 = z^n - 1.$$

The restricted graph  $C_{n+r-1}^*[r]$  can be treated as  $C_{n-1}$  by "shrinking" the incorporated path to a node. Thus we have

COROLLARY 13.1.  $P(C_{n+r-1}^*[r]; w) = P(C_{n-1}; w) = z^{n-1} - 1.$

Instead of deriving results for  $C_n^{**}[r-1]$ , we would solve the general problem in which  $k$  incorporated chains are attached to non-adjacent nodes of  $C_n$  ( $k \leq [\frac{n}{2}]$ ). Let us denote this graph by  $C_n^{k*}$ .

We will consider 2 cases: (1)  $C_n^{k*}$  contains a pair of consecutive incorporated chains which are separated by a path of length greater than 2, and (2)  $C_n^{k*}$  has no such pair of incorporated chains. In case (1), we can apply the reduction process to  $C_n^{k*}$ , by deleting an edge which is adjacent to an incorporated chain and which belongs to a separating path of length greater than 2.  $G'$  will be  $P_n^{(k+1)*}$ , since the end-node to which an incorporated chain is attached, can be treated as an ordinary node.  $G^*$  will be  $P_{n-1}^{(k-1)*}$ . Hence from Theorem 9, we get

$$\begin{aligned} P(C_n^{k*}; w) &= z^{n-2k-1} (z-1)^k (z+1)^{k-1} + z^{n-2k} (z-1)^k (z+1)^{k-1} \\ &= z^{n-2k} (z^2 - 1)^k. \end{aligned}$$

In case (2),  $G'$  will be  $P_{n-1}^{(k-1)*}$  and  $G^*$  will be  $P_{n-1}^{(k-2)*}$ . It follows that

$$\begin{aligned} P(C_n^{k*}; w) &= z^{n-2k-1} (z-1)^k (z+1)^{k-1} + z^{n-2k+2} (z-1)^{k-1} (z+1)^{k-2} \\ &= z^{n-2k-1} (z-1)^{k-1} (z+1)^{k-2} (z^3 + z^2 - 1). \end{aligned}$$

Hence we have the following theorem.

THEOREM 16. If  $C_n^{k*}$  contains a pair of consecutive incorporated chains, separated by a path in  $C_n$  of length greater than 2, (or if  $k = 1$ ) then

$$P(C_n^{k*}; w) = z^{n-2k} (z^2 - 1)^k;$$

otherwise,

$$P(C_n^{k*}; w) = z^{n-2k-1} (z-1)^{k-1} (z+1)^{k-2} (z^3 + z^2 - 1).$$

8. PATH DECOMPOSITIONS OF CIRCUITS.

The covers of  $P_n$  will also be covers of  $C_n$ . Therefore, it is expected that the results similar to those given in Section 5 will also hold for circuits.

The following is an immediate corollary of Theorem 15. It confirms our observation of the sum of the coefficients of the polynomials in Table 2.

COROLLARY 11.1.  $N_{C_n} = 2^n - 1.$

Since the covers of  $P_n$  will also be covers of  $C_n$ , we have from Theorem 10, the following corollary.

COROLLARY 10.1. For every partition  $\pi = (d_1, d_2, d_3, \dots, d_k)$  of  $n$ ,  $\exists$  a decomposition of  $C_n$  into paths containing  $d_i$  nodes ( $i = 1, 2, \dots, k$ ).

The following corollary of Theorem 11 is analogous to Corollary 3.1. Its proof is similar.

COROLLARY 11.1.

$$N_{C_n}(n_1^{k_1}, n_2^{k_2}, \dots, n_r^{k_r}) = \sum_{i=1}^r n_i N_{P_{n-n_i}}(n_1^{k_1}, n_2^{k_2}, \dots, n_{i-1}^{k_{i-1}}, n_i^{k_i-1}, n_{i+1}^{k_{i+1}}, \dots, n_r^{k_r}).$$

The following lemma is analogous to Lemma 3. It will be useful for practical applications of Corollary 11.2.

LEMMA 4. (i)  $N_{C_n}(1^{n-2}, 2) = N_{C_n}(1, n-3, 3) = N_{C_n}(1, n-1) = N_{C_n}(n) = n$ .

(ii)  $N_{C_n}((n/k)^k) = n/k$ , where  $k$  divides  $n$ .

The following corollaries are immediate from Corollary 13.1.

COROLLARY 13.2. The number of restricted decompositions of  $C_{n+k}$  in which a particular subchain  $P_{k+2}$  is always included is  $2^{n-1} - 1$ .

COROLLARY 13.3. The number of restricted decompositions with cardinality  $s$ , of  $C_{n+k}$ , in which a particular subchain  $P_{k+2}$  is always included is  $\binom{n-1}{s}$ .

From Theorem 16, we obtain the following corollaries.

COROLLARY 16.1. Let  $G$  be a graph consisting of a circuit with  $k$  chains attached to it. If  $G$  contains a pair of consecutive attached chains which are separated by a path of length greater than 2, then the number of restricted decompositions of  $G$  in which all  $k$  chains are included is  $3^k \cdot 2^{n-2k}$ . Otherwise, the number of such restricted decompositions is  $11 \cdot 3^{k-2} \cdot 2^{n-2k-1}$ .

COROLLARY 16.2. The number of restricted decompositions with cardinality  $s (s > k)$  of the graph  $G$  of Corollary 16.1 is

$$\sum_{r=0}^k \binom{k}{r} \binom{n-2k}{s-k-r} 2^{k-r},$$

when  $G$  contains a pair of consecutive attached chains, separated by a path of length greater than 2. Otherwise, the number of such decompositions is

$$\sum_{i=0}^{k-2} \binom{k-2}{i} 2^{k-2-i} [ \binom{N}{m-2} + 3 \binom{N+1}{m} + \binom{N+2}{m+1} ],$$

where  $N = n - 2k - 1$  and  $m = s - i - k$ .

REFERENCES

1. FARRELL, E.J. On a general class of graph polynomials, J. Comb. Theory B 26 (1979), 111-122.
2. HARARY, F. Graph Theory, Addison-Wesley, Reading, Mass., 1969.

3. GOODMAN, S.E. and HEDETNIEMI, S.T. On the Hamiltonian completion problem, in: R.A. Buri and F. Harary, eds., Graphs and Combinations (Springer-Verlag, Berlin, 1974), 262-272.
4. BOESCH, F.T., CHEN, S. and McHUGH, J.A.M. On covering the points of a graph with disjoint paths in: R.A. Buri and F. Harary, eds., Graphs and Combinations (Springer-Verlag, Berlin, 1974), 201-212.
5. SLATER, P.L. Path coverings of the vertices of a tree, Discrete Math. 25 (1979), 65-74.
6. READ, R.C. Introduction to chromatic polynomials, J. Comb. Theory 4 (1968), 52-71.

## Special Issue on Decision Support for Intermodal Transport

### Call for Papers

Intermodal transport refers to the movement of goods in a single loading unit which uses successive various modes of transport (road, rail, water) without handling the goods during mode transfers. Intermodal transport has become an important policy issue, mainly because it is considered to be one of the means to lower the congestion caused by single-mode road transport and to be more environmentally friendly than the single-mode road transport. Both considerations have been followed by an increase in attention toward intermodal freight transportation research.

Various intermodal freight transport decision problems are in demand of mathematical models of supporting them. As the intermodal transport system is more complex than a single-mode system, this fact offers interesting and challenging opportunities to modelers in applied mathematics. This special issue aims to fill in some gaps in the research agenda of decision-making in intermodal transport.

The mathematical models may be of the optimization type or of the evaluation type to gain an insight in intermodal operations. The mathematical models aim to support decisions on the strategic, tactical, and operational levels. The decision-makers belong to the various players in the intermodal transport world, namely, drayage operators, terminal operators, network operators, or intermodal operators.

Topics of relevance to this type of decision-making both in time horizon as in terms of operators are:

- Intermodal terminal design
- Infrastructure network configuration
- Location of terminals
- Cooperation between drayage companies
- Allocation of shippers/receivers to a terminal
- Pricing strategies
- Capacity levels of equipment and labour
- Operational routines and lay-out structure
- Redistribution of load units, railcars, barges, and so forth
- Scheduling of trips or jobs
- Allocation of capacity to jobs
- Loading orders
- Selection of routing and service

Before submission authors should carefully read over the journal's Author Guidelines, which are located at <http://www.hindawi.com/journals/jamds/guidelines.html>. Prospective authors should submit an electronic copy of their complete manuscript through the journal Manuscript Tracking System at <http://mts.hindawi.com/>, according to the following timetable:

Manuscript Due	June 1, 2009
First Round of Reviews	September 1, 2009
Publication Date	December 1, 2009

### Lead Guest Editor

**Gerrit K. Janssens**, Transportation Research Institute (IMOB), Hasselt University, Agoralaan, Building D, 3590 Diepenbeek (Hasselt), Belgium; [Gerrit.Janssens@uhasselt.be](mailto:Gerrit.Janssens@uhasselt.be)

### Guest Editor

**Cathy Macharis**, Department of Mathematics, Operational Research, Statistics and Information for Systems (MOSI), Transport and Logistics Research Group, Management School, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium; [Cathy.Macharis@vub.ac.be](mailto:Cathy.Macharis@vub.ac.be)