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Pierre Aboulker, Nathann Cohen, Frédéric Havet, William Lochet, Phablo Moura, Stéphan Thomassé

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Abstract

In 1985, Mader conjectured the existence of a function $f$ such that every digraph with minimum out-degree at least $f(k)$ contains a subdivision of the transitive tournament of order $k$. This conjecture is still completely open, as the existence of $f(5)$ remains unknown. In this paper, we show that if $D$ is an oriented path, or an in-arborescence (i.e., a tree with all edges oriented towards the root) or the union of two directed paths from $x$ to $y$ and a directed path from $y$ to $x$, then every digraph with minimum out-degree large enough contains a subdivision of $D$. Additionally, we study Mader’s conjecture considering another graph parameter. The dichromatic number of a digraph $D$ is the smallest integer $k$ such that $D$ can be partitioned into $k$ acyclic subdigraphs. We show that any digraph with dichromatic number greater than $4^m(n-1)$ contains every digraph with $n$ vertices and $m$ arcs as a subdivision.

1 Introduction

Mader [19] established the following.

**Theorem 1** (Mader [19]). There exists an integer $g(k)$ such that every graph with minimum degree at least $g(k)$ contains a subdivision of $K_k$.

For $k \leq 4$, we have $g(k) = k - 1$ as first proved by Dirac [11]; for $k = 5$, we have the estimate $6 \leq g(5) \leq 7$ by Thomassen [26,29]. In general, the order of growth of $g(k)$ is $k^2$ as shown in [5] and [17].

Similarly, it would be interesting to find analogous results for digraphs. However, the obvious analogue that a digraph with sufficiently large minimum in- and out-degree contains a subdivision of the complete digraph of order $n$ is false as shown by Mader [20].

Let $\gamma$ be a digraph parameter. A digraph $F$ is $\gamma$-maderian if there exists a least integer $\text{mader}\_\gamma(F)$ such that every digraph $D$ with $\gamma(D) \geq \text{mader}\_\gamma(F)$ contains a subdivision of $F$.

For a digraph $D$, $\delta^+(D)$ (resp. $\delta^-(D)$) denote the minimum out-degree (resp. in-degree) and $\delta^0(D) = \min\{\delta^+(D), \delta^-(D)\}$. A natural question is to ask which digraphs $F$ are $\delta^+\text{-maderian}$ (resp. $\delta^0\text{-maderian}$). Observe that every $\delta^+\text{-maderian}$ digraph is also $\delta^0\text{-maderian}$ and that $\text{mader}\_\gamma\_\delta^+ \geq \text{mader}\_\gamma\_\delta^0$.

For each positive integer $k$, we denote by $[k]$ the subset of the natural numbers $\{1, \ldots, k\}$.

On the positive side, Mader conjectured that every acyclic digraphs is $\delta^+\text{-maderian}$. Since every acyclic digraph is the subdigraph of the transitive tournament on the same order, it is enough to prove that transitive tournaments are $\delta^+\text{-maderian}$.

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Subdivisions in digraphs of large out-degree or large dichromatic number

Pierre Aboulker¹, Nathann Cohen², Frédéric Havet¹, William Lochet¹,³, Phablo F. S. Moura¹,³,⁴, and Stéphan Thomassé³

¹Université Côte d’Azur, CNRS, Inria, I3S, France
²CNRS, Université Paris Sud, France
³LIP, ENS de Lyon, CNRS, Université de Lyon, France
⁴Instituto de Matemática e Estatística, Universidade de São Paulo, Brazil

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Conjecture 2 (Mader [20]). There exists a least integer \( mader_{\delta^+} (TT_k) \) such that every digraph \( D \) with \( \delta^+(D) \geq mader_{\delta^+} (TT_k) \) contains a subdivision of \( TT_k \).

Mader proved that \( mader_{\delta^+} (TT_1) = 3 \), but even the existence of \( mader_{\delta^+} (TT_2) \) is still open.

This conjecture implies directly that transitive tournaments (and thus all acyclic digraphs) are \( \delta^0 \)-maderian.

Conjecture 3. There exists a least integer \( mader_{\delta^0} (TT_k) \) such that every digraph \( D \) with \( \delta^0(D) \geq mader_{\delta^0} (TT_k) \) contains a subdivision of \( TT_k \).

In fact, Conjecture 3 is equivalent to Conjecture 2 because if transitive tournaments are \( \delta^0 \)-maderian, then \( mader_{\delta^+} (TT_k) \leq mader_{\delta^0} (TT_k) \) for all \( k \). Indeed, let \( D \) be a digraph with minimum out-degree \( mader_{\delta^0} (TT_k) \), and let \( D' \) be the digraph obtained from disjoint copies of \( D \) and its converse (the digraph obtained by reversing all arcs) \( \overrightarrow{D} \) by adding all arcs from \( \overrightarrow{D} \) to \( D \). Clearly, \( \delta^0(D') \geq mader_{\delta^0} (TT_k) \). Therefore \( D' \) contains a subdivision of \( TT_k \). Hence, either \( D \) or \( \overrightarrow{D} \) (and so \( D \)) contains a subdivision of \( TT_k \).

Both conjectures are equivalent, but the above reasoning does not prove that a \( \delta^0 \)-maderian digraph is also \( \delta^+ \)-maderian. The case of oriented trees (i.e. orientations of undirected trees) is typical. Using a simple greedy procedure, one can easily find every oriented tree of order \( k \) in every digraph with minimum in- and out-degree \( k \) (so \( mader_{\delta^0} (T) = |T| - 1 \) for any oriented tree \( T \)). On the other hand, it is still open whether oriented trees are \( \delta^+ \)-maderian and a natural important step towards Conjecture 2 would be to prove the following weaker one.

Conjecture 4. Every oriented tree is \( \delta^+ \)-maderian.

We give evidences to this conjecture. First, in Subsection 2.1, we prove that every oriented path (i.e. orientation of an undirected path) \( P \) is \( \delta^+ \)-maderian and that \( mader_{\delta^+} (P) = |V(P)| - 1 \). Next, in Subsection 2.2, we consider arborescences. An out-arborescence (resp. in-arborescence) is an oriented tree in which all arcs are directed away from (resp. towards) a vertex called the root. Trivially, the simple greedy procedure shows that \( mader_{\delta^+} (T) = |T| - 1 \) for every out-arborescence. In contrast, the fact that in-arborescences are \( \delta^+ \)-maderian is not obvious since we have no control on the in-degree of each vertex in a digraph of out-degree at least \( k \). We show in Theorem 23 that the in-arborescences are \( \delta^+ \)-maderian.

In [21], Mader gave another partial result towards Conjecture 2. We proved the existence of a function \( f(k) \) such that every digraph \( D \) with \( \delta^+(D) \geq f(k) \) contains a pair of vertices \( u \) and \( v \) with \( k \) disjoint directed paths between \( u \) and \( v \). It is however not known if we can insist on these paths to be arbitrarily long. In Theorem 24, we do the first step toward this question by proving it in the case \( k = 2 \).

Conjecture 2 states that the acyclic digraphs are \( \delta^+ \)-maderian. However, they are not the only ones. For example, it is folklore that every digraph with minimum out-degree at least 1 contains a directed cycle, which is a subdivision of \( \overrightarrow{C}_2 \), the directed 2-cycle. More generally, one can easily show, by considering a directed path of maximum length, that every digraph with minimum out-degree at least \( k - 1 \) contains a directed cycle of length at least \( k \). In other words, \( mader_{\delta^+} (\overrightarrow{C}_k) = k - 1 \), where \( \overrightarrow{C}_k \) denotes the directed \( k \)-cycle. Furthermore Alon [3] showed that every digraph with minimum out-degree at least \( 64k \) contains \( k \) disjoint directed cycles, which forms a subdivision of the disjoint union of \( k \) copies of \( \overrightarrow{C}_2 \). A celebrated conjecture of Bermond and Thomassen [4] states that the bound \( 64k \) can be decreased to \( 2k - 1 \).

Conjecture 5 (Bermond and Thomassen [4]). For every positive integer \( k \), every digraph with minimum out-degree at least \( 2k - 1 \) contains \( k \) disjoint directed cycles.

In [3], Alon also conjectured the following.

Conjecture 6 (Alon [3]). There exists a function \( h \) such that every digraph with minimum out-degree \( h(k) \) has a partition \( (V_1, V_2) \) such that, for \( i = 1, 2 \), \( D(V_i) \) has minimum out-degree \( k \).

The difficulty of this question is remarkable, as the existence of \( h(2) \) still remains open. If true, this conjecture implies the following one.

Conjecture 7. If \( F_1 \) and \( F_2 \) are \( \delta^+ \)-maderian, then the disjoint union of \( F_1 \) and \( F_2 \) is also \( \delta^+ \)-maderian.
Proof. Let δ digraph with k smallest integer k of δ. Theorem 8. If no subdivision of F, Conjecture 11. If and so mader ⃗χD is still open. Since every digraph D of order k (Burr [7]) Conjecture 10 made the following conjecture. An oriented cycle, all subdivisions of which have the same number of blocks. Theorem 9. Every digraph D such that all its subdivisions have a directed cycle of even length. In particular, ⃗K3, the complete digraph on three vertices, belongs to this class. All digraphs in this class have been characterized by Seymour and Thomassen [25]. Moreover, Devos et al. [10] showed the existence of digraphs with large minimum out-degree and in-degree such that there exists no pair of vertices u and v with four internally disjoint directed paths between them, two from u to v and two from v to u. In Theorem 28, we show that if the minimum out-degree is large enough then we can find two vertices u and v with three internally disjoint directed paths between them, one from u to v and two from v to u.

Note that every graph with chromatic number at least p has a subgraph with minimum degree at least p − 1. This implies, by Theorem 1, that every graph with chromatic number at least g(k) + 1 contains a subdivision of ⃗Kk. In the context of digraphs, there exist two natural analogues of the chromatic number. Given a digraph D, the chromatic number of D, denoted by χ(D), is simply the chromatic number of its underlying graph. The dichromatic number of D, denoted by ⃗χ(D), is the smallest integer k such that D admits a k-dicolouring. A k-dicolouring is a k-partition {V1, . . . , Vk} of V(D) such that D(Vi) is cyclic for every i ∈ [k]. Hence, it is natural to ask which digraphs are χ-maderian and which ones are ⃗χ-maderian. Burr [7] proved that every (k − 1)2-chromatic digraph contains every oriented forest of order k. Later on, Addario-Berry et al. [1] slightly improved this value to k2/2 − k/2 + 1. This implies that every forest is χ-maderian. Cohen et al. [9] showed that for any positive integer b, there are digraphs of arbitrarily high chromatic number that contain no oriented cycles with less than b blocks. This directly implies that if a digraph is not an oriented forest, then it is not χ-maderian because it contains an oriented cycle, all subdivisions of which have the same number of blocks.

Theorem 9. A digraph is χ-maderian if and only if it is an oriented forest.

The χ-maderian digraphs are known but determining maderχ for such digraphs is still open. Burr [7] made the following conjecture.

Conjecture 10 (Burr [7]). Every digraph with chromatic number 2k − 2 contains every oriented tree of order k as a subdigraph.

An interesting step towards Burr’s conjecture is to prove the following consequence of it.

Conjecture 11. If T is an oriented tree of order k, then maderχ(T) ≤ 2k − 2.

In Section 3, we prove that every digraph is ⃗χ-maderian. Again determining mader⃗χ for every digraph is still open. Since every digraph D of order n is a subdigraph of ⃗Kn, the complete digraph of order n, and so mader⃗χ(D) ≤ mader⃗χ( ⃗Kn), it is natural to focus on ⃗Kn.
Problem 12. What is $\text{mader}_\chi(K_n)$?

In Subsection 3.1, we show $\text{mader}_\chi(K_n) \leq 4n^2-2n+1(n-1)+1$ and more generally that if $F$ is a digraph with $n$ vertices, $m$ arcs and $c$ connected components, then $\text{mader}_\chi(F) \leq 4^m-n+\varepsilon(n-1)+1$ (Corollary 36). We also give better upper bounds on $\text{mader}_\chi$ for some particular digraphs.

To prove Theorem 1, Mader showed a stronger result about the average degree. Recall that the average degree of a graph $G$ is $\bar{d}(G) = 2|E(G)|/|V(G)|$. He proved that there exists a function $g(k)$ such that every graph $G$ with at least $\bar{d}(G) \geq g(k)$ contains a subdivision of $K_k$. The average out-degree of a digraph $D$ is $\bar{d}^+(D) = |A(D)|/|V(D)|$. (Note that this is equal to the average in-degree and half the average degree.) A digraph is $\overrightarrow{P}_3$-free if it does not contain $\overrightarrow{P}_3$ as a subdigraph, where $\overrightarrow{P}_3$ is the dipath on three vertices. There are bipartite graphs with arbitrarily large degree and arbitrarily large girth (recall that the girth of a graph is the length of a smallest cycle or $+\infty$ if it is a forest). Orienting edges of such graphs from one part to the other result in $\overrightarrow{P}_3$-free digraphs with arbitrarily large average out-degree and arbitrarily large girth (the girth of a digraph is the girth of its underlying graph). Consequently, a digraph is $\overrightarrow{d}^*$-maderian only if it is an antidirected forest, that is, an oriented forest containing no $\overrightarrow{P}_3$ as a subdigraph. This simple necessary condition is also sufficient. Burr [8] showed that all antidirected forests are $\overrightarrow{d}^*$-maderian: for every antidirected forest $F$, $\text{mader}_x(F) \leq 4|V(F)| - 4$.

Theorem 13. A digraph is $\overrightarrow{d}^*$-maderian if and only if it is an antidirected forest.

Addario-Berry et al. [1] conjectured that the bound $4|V(F)| - 4$ in Burr’s result is not tight.

Conjecture 14 (Addario-Berry et al. [1]). Let $D$ be a digraph. If $|A(D)| > (k-2)|V(D)|$, then $D$ contains every antidirected tree of order $k$ as a subdigraph.

The value $k-2$ in this conjecture would be best possible, since the oriented star $S^+_k$, consisting of a vertex dominating $k-1$ others, is not contained in any digraph in which every vertex has out-degree $k-2$. It is also tight because the complete digraph $\overrightarrow{K}_{k-1}$ has $(k-2)(k-1)$ arcs but trivially does not contain any oriented tree of order $k$.

As observed in [1], Conjecture 14 for oriented graphs implies Burr’s conjecture (Conjecture 10) for antidirected trees and Conjecture 14 for symmetric digraphs is equivalent to the well-known Erdős-Sós conjecture.

Conjecture 15 (Erdős and Sós [12]). Let $G$ be a graph. If $|E(G)| > \frac{1}{2}(k-2)|V(G)|$, then $G$ contains every tree of order $k$.

Their conjecture has attracted a fair amount of attention over the last decades. Partial solutions are given in [6, 15, 24]. In the early 1990’s, Ajtai, Komlós, Simonovits and Szemerédi announced a proof of this result for sufficiently large $m$.

Since $k$-connected and $k$-edge-connected graphs have minimum degree at least $k$, Theorem 1 implies that every graph $G$ with connectivity (resp. edge-connectivity) at least $g(k)$ contains a subdivision of $K_k$. Let $\kappa(D), \kappa'(D)$, be respectively the strong connectivity and the strong arc-connectivity of $D$.

Problem 16. Are all digraphs $\kappa$-maderian? $\kappa'$-maderian?

The following conjecture due to Thomassen [28] implies that all digraphs are $\kappa$-maderian.

Conjecture 17 (Thomassen [28]). There exists $f_1(k)$ such that if $\kappa(D) \geq f_1(k)$, and $x_1, \ldots, x_k$ and $y_1, \ldots, y_k$ are distinct vertices of $D$, then $D$ contains $k$ disjoint dipaths $P_1, \ldots, P_k$ such that $P_i$ goes from $x_i$ to $y_i$ for all $i \in [k]$.

This conjecture would also imply the following one due to Lovász [18].

Conjecture 18. There exists a integer $p$ such that every $p$-strongly connected digraph has an even directed cycle.
2 Subdivision in digraphs with large minimum out-degree

2.1 Subdivisions of oriented paths

Let \( P = (x_1, x_2, \ldots, x_n) \) be an oriented path. We say that \( P \) is an \((x_1, x_n)\)-path. The vertex \( x_1 \) is the initial vertex of \( P \) and \( x_n \) its terminal vertex. \( P \) is a directed path or simply a dipath, if \( x_i \to x_{i+1} \) for all \( i \in [n-1] \).

Let \( k_l \) be nonnegative integer and \( k_2, \ldots, k_l \) be positive integers. We denote by \( P(k_1, k_2, \ldots, k_l) \) the path obtained from an undirected path \((v_1 v_2 \ldots v_{l+1})\) by replacing, for every \( i \in [\ell] \), the edge \((v_i, v_{i+1})\) by a directed path of length \( k_l \) from \( v_i \) to \( v_{i+1} \) if \( i \) is odd, and from \( v_{i+1} \) to \( v_i \) if \( i \) is even. (If \( k_1 = 0 \), then \( v_1 = v_{2p} \).

**Theorem 19.** Let \( P(k_1, k_2, \ldots, k_l) \) be a path, and let \( D \) be a digraph with \( \delta^+(D) \geq \sum_{i=1}^{\ell} k_i \). For every \( v \in V(D) \), \( D \) contains a path \( P(k'_1, k'_2, \ldots, k'_\ell) \) with initial vertex \( v \) such that \( k'_i \geq k_i \) if \( i \) is odd, and \( k'_i = k_i \) otherwise.

**Proof.** By induction on \( \ell \). If \( \ell = 1 \), then the result holds trivially. Assume now \( \ell \geq 2 \), and suppose that, for every path \( P(x_1, x_2, \ldots, x_t) \) with \( t < \ell \) and every digraph \( G \) with \( \delta^+(G) \geq \sum_{i=1}^{\ell} x_i \), \( G \) contains a path \( P(x'_1, x'_2, \ldots, x'_\ell) \) starting at any vertex of \( G \) such that \( x'_i \geq x_i \) if \( i \) is odd, and \( x'_i = x_i \) otherwise.

Let \( v \) be a vertex of \( D \). Since \( \delta^+(D) \geq \sum_{i=1}^{\ell} k_i \), there exists a \((v, u)\)-dipath \( P_{v,u} \) in \( D \) of length exactly \( k_1 \), for some vertex \( u \in V(D) \). Let \( D' = D - (P_{v,u} - u) \), let \( C \) be the connected component of \( D' \) containing \( u \), and let \( H \) be a sink strong component of \( C \) (i.e. a strong component without arcs leaving it) that is reachable by a directed path in \( C \) starting at \( u \). We denote by \( P_{u,x} \) a \((u, x)\)-dipath in \( C \) such that \( V(P_{u,x}) \cap V(H) = \{x\} \).

Note that no vertex of \( H \) dominates a vertex in \( V(P_{u,x}) \setminus \{x\} \) since \( H \) is a sink strong component. Thus, \( \delta^+(H) \geq \delta^+(D) - k_1 \geq k_2 \). As a consequence, \( H \) contains a directed cycle of length at least \( k_2 \). Using this and the fact that \( H \) is strongly connected, we conclude that there exists a dipath \( P_{y,x} \) in \( H \) from a vertex \( y \in V(H) \setminus \{x\} \) to \( x \) of length exactly \( k_2 \). Let \( G = H - (P_{y,x} - y) \). One may easily verify that \( \delta^+(G) \) is at least \( \delta^+(D) - k_1 - k_2 \). For \( \ell \geq 3 \), the induction hypothesis, \( G \) contains a path \( W_y := P(k'_2, \ldots, k'_\ell) \) with initial vertex \( y \) such that \( k'_i \geq k_i \) if \( i \) is odd, and \( k'_i = k_i \) otherwise. Therefore, \( Q_{v,y} W_y \) is the desired path \( P(k'_1, k'_2, \ldots, k'_\ell) \) with initial vertex \( v \).

Since \( \sum_{i=1}^{\ell} k_i = |V(P(k_1, k_2, \ldots, k_l))| - 1 \), and that the complete digraph \( \tilde{K}_k \) on \( k \) vertices has minimum out-degree \( k - 1 \) and contains no path on more than \( k \) vertices, we obtain the following corollary.

**Corollary 20.** \( \text{mader}_{\delta^+}(P) = |V(P)| - 1 \) for every oriented path \( P \).

2.2 Subdivision of in-arborescences

The aim of this subsection is to prove that the in-arborescences are \( \delta^+ \)-maderian. We need some preliminary results. The first one is the vertex and directed version of the celebrated Menger’s theorem [22]. (See also [14] for a short proof.)

**Theorem 21** (Menger’s theorem). Let \( D \) be a digraph, and let \( S, T \subseteq V(D) \). The maximum number of vertex-disjoint \((S, T)\)-dipaths is equal to the minimum size of an \((S, T)\)-vertex-cut.

**Lemma 22.** Let \( D \) be a digraph, let \( S \subseteq V(D) \) be a nonempty subset of vertices of in-degree 0 in \( D \), and let \( T \subseteq V(D) \) such that \( T \cap S = \emptyset \). If \( \delta^+(v) \geq \Delta^-(D) \) for all \( v \in V(D) \setminus T \), then there exist \( |S| \) vertex-disjoint \((S, T)\)-dipaths in \( D \).

**Proof.** Suppose to the contrary that there do not exist \( |S| \) vertex-disjoint \((S, T)\)-dipaths in \( D \). By Menger’s theorem, there exists a set of vertices \( X \subseteq V(D) \) with cardinality \( |X| < |S| \) which is an \((S, T)\)-vertex-cut. Let \( C \) be the set of vertices in \( D - X \) that are reachable in \( D \) by a dipath with initial vertex in \( S \setminus X \). Set \( k = |X \cap S| \). Observe that \( k < |S| \).
Let us count the number \( a(C, X) \) of arcs with tail in \( C \) and head in \( X \). Since the vertices in \( S \) have in-degree 0 and every vertex in \( C \) has out-degree at least \( \Delta^-(D) \),

\[
a(C, X) \geq |C| \cdot \Delta^-(D) - |C| - (|S| - k) \cdot \Delta^-(D) = (|S| - k) \cdot \Delta^-(D).
\]

Moreover, \( a(C, X) \) is at most the number of arcs with head in \( X \) which is at most \((|X| - k) \cdot \Delta^-(D)\), because the vertices in \( S \cap X \) have in-degree 0. Hence \((|S| - k) \cdot \Delta^-(D) \leq a(C, X) \leq (|X| - k) \cdot \Delta^-(D)\).

This is a contradiction to \(|X| < |S|\). 

Let \( k \) and \( \ell \) be positive integers. The \( \ell \)-branching in-arborescence of depth \( k \), denoted by \( B(k, \ell) \), is defined by induction as follows.

- \( B(0, \ell) \) is the in-arborescence with a single vertex, which is the root and the leaf of \( B(0, \ell) \).
- \( B(k, \ell) \) is obtained from \( B(k-1, \ell) \) by taking each leaf of \( B(k-1, \ell) \) in turn and adding \( \ell \) new vertices dominating this leaf. The root of \( B(k, \ell) \) is the one of \( B(k-1, \ell) \), and the leaves of \( B(k, \ell) \) are the newly added vertices, that is, those not in \( V(B(k-1, \ell)) \).

The number of vertices of \( B(k, \ell) \) is denoted by \( b(k, \ell) \); so \( b(k, \ell) = \sum_{i=0}^{k} \ell^i = \frac{\ell^{k+1} - 1}{\ell - 1} \).

Observe that every in-arborescence \( T \) is a subdigraph of \( B(k, \ell) \) with \( k = \Delta^-(T) \) and \( \ell \) the maximum length of a dipath in \( T \). Therefore to prove that in-arborescences are \( \delta^+ \)-maderian, it suffices to show that \( B(k, \ell) \) is \( \delta^+ \)-maderian for all \( k \) and \( \ell \).

We define a recursive function \( f : \mathbb{N} \to \mathbb{N} \) as follows. For all positive integers \( k \) and \( \ell \) such that \( \ell \geq 2 \), \( f(1, \ell) = \ell \) and, for \( k \geq 2 \), we define

\[
f(k, \ell) = t(k, \ell) \cdot (\ell - 1) \cdot k + t(k, \ell),
\]

where \( t(k, \ell) := f(k-1, b(k-1, \ell) \cdot (\ell - 1) + 1) \cdot b(k-1, \ell) \).

If \( \mathcal{D} \) is a family of digraphs, a packing of elements of \( \mathcal{D} \) is the disjoint union of copies of elements of \( \mathcal{D} \).

**Theorem 23.** Let \( k \) and \( \ell \geq 2 \) be positive integers, and let \( D \) be a digraph with \( \delta^+(D) \geq f(k, \ell) \). Then \( D \) contains a subdivision of \( B(k, \ell) \).

**Proof.** We prove the result by induction on \( k \) and \( \ell \). If \( k = 1 \), then \( \delta^+(D) \geq \ell \). Thus, \( \Delta^-(D) \cdot |V(D)| \geq \sum_{v \in V(D)} d^-(v) = \sum_{v \in V(D)} d^+(v) \geq \ell \cdot |V(D)| \). Hence there is a vertex with in-degree at least \( \ell \) in \( D \) and, consequently, the result follows when \( k = 1 \). Assume now \( k \geq 2 \), and suppose that, for every positive integers \( k' < k \) and \( \ell' \), and every digraph \( H \) with \( \delta^+(H) \geq f(k', \ell') \), \( H \) contains a subdigraph of the \( \ell' \)-branching in-arborescence of depth \( k' \).

Let \( \mathcal{F} \) be a packing of \( \ell \)-branching in-arborescences subdigraphs of any non-zero depth in \( D \) that covers the maximum number of vertices. We denote by \( U \subseteq V(D) \) the set of vertices not covered by \( \mathcal{F} \), that is, \( U = V(D) \setminus \bigcup_{A \in \mathcal{F}} V(A) \). Let \( r_A \) denote the root of the in-arborescence \( A \), for each \( A \in \mathcal{F} \), and let \( R = \{ r_A \in V(D) : A \in \mathcal{F} \} \) be the set of the roots of the arborescences in \( \mathcal{F} \).

We now construct the digraph \( H \) with vertex set \( R \) such that there exists an arc \((r_A, r_B)\) in \( H \) if and only if \( r_A \) dominates some vertex of \( V(B) \) in \( D \).

**Claim 23.1.** If \( \delta^+(H) \geq t(k, \ell) / (b(k-1, \ell) + 1) \), then \( D \) contains a subdivision of \( B(k, \ell) \).

**Subproof.** Let \( p = b(k-1, \ell) \cdot (\ell - 1) + 1 \). By the induction hypothesis, \( H \) contains a subdivision \( T \) of \( B(k-1, p) \). Let \( R' \) be the set of branching vertices of \( T \), that is, \( R' = \{ r \in T : d^-_T(r) = p \} \). We assume that each in-arborescence of \( \mathcal{F} \) has at most \( b(k-1, \ell) \) vertices, as any larger arborescence would yield the theorem. Thus, for each \( r \in R' \), there exists a vertex \( h_r \) in the in-arborescence rooted at \( r \) such that \( h_r \) is dominated in \( D \) by \( \ell \) vertices of \( V(T) \). Similarly, for each \( r \in V(T) \) with in-degree 1, there exists a vertex \( h_r \) in the in-arborescence rooted at \( r \) such that \( h_r \) is dominated in \( D \) by a vertex of \( V(T) \). Using these remarks, we next define a procedure to obtain a subdigraph of \( T \) that is a subdivision of \( B(k-1, \ell) \).

For each \( r \in R' \), we remove from \( T \) all arcs with head \( r \) but exactly \( \ell \) arcs from vertices in \( V(T) \) that dominate \( h_r \) in \( D \). We denote by \( T' \) the component of the subdigraph of \( T \) obtained by applying the above-described procedure and that contains the root of \( T \). One may easily verify that \( T' \) is a
subdivision of $B(k - 1, 1)$. Let $P_r$ be the path from $h_r$ to $r$ in the in-arborescence corresponding to $r$, for every $r \in V(T')$ such that either $r \in R'$ or $r$ has in-degree 1.

Let $Q$ be the in-arborescence obtained from $T'$ in the following way. For each $r \in V(T')$ such that either $r \in R'$ or $r$ has in-degree 1, we add $h_r$ to $T'$, and we add an arc from every in-neighbour of $r$ in $T'$ to $h_r$. Additionally, we remove all arcs with head $r$ in $T'$, and link $h_r$ to $r$ by using the dipath $P_r$. Finally, for each $r \in V(T')$ that is a leaf, we replace $r$ by its corresponding in-arborescence belonging to $F$.

By this construction, we have that $Q$ is a subdigraph of $D$ such that every internal vertex has either in-degree $\ell$ or 1. Furthermore, it has depth at least $k$. Therefore, by possibly pruning some levels of $Q$, we obtain a subdivision of $B(k, \ell)$.

Suppose now $\delta^+(H) < t(k, \ell)/b(k - 1, \ell)$. Observe that, for every $v \in R$ such that $d^+_H(v) < t(k, \ell)/b(k - 1, \ell)$, we have, in the digraph $D$, that $d^+_V(v) \geq t(k, \ell) \cdot (\ell - 1) \cdot k$ since $\delta^+(D) \geq t(k, \ell) \cdot (\ell - 1) \cdot k + t(k, \ell)$. We define

$$X = \{v \in R : d^+_V(v) \geq t(k, \ell) \cdot (\ell - 1) \cdot k\}.$$

Let $D'$ be the digraph obtained from $D[U \cup X]$ by removing all arcs with head in $X$. From $D'$, we construct a digraph $G$ by replacing every vertex $v \in X$ by $t(k, \ell)$ new vertices $v_1, \ldots, v_{t(k, \ell)}$, and adding, for each $i \in [t(k, \ell)]$, at least $(\ell - 1) \cdot k$ arcs from $v_i$ to $N_{D'}^+(v)$ in such a way that $d^+_G(u) = d^+_D(u)$, for all $u \in N_{D'}^+(v)$. In other words, we "redistribute" the out-neighbours of $v$ in $D'$ among its $t(k, \ell)$ copies in $G$ so that every copy has out-degree at least $(\ell - 1) \cdot k$, and the in-degrees of vertices belonging to $U$ are not changed. Let $S \subseteq V(G)$ be the set of vertices that replaced those of $X$, that is, $S = \bigcup_{v \in X} \{v_1, \ldots, v_{t(k, \ell)}\}$. Let $T$ be the set of vertices in $U$ that have large out-degree outside $U$ in the digraph $D$, more formally, $T = \{v \in U : d^+_V(D[U \cup X])v \geq t(k, \ell) + 1\}$.

For every $i \in [k - 1]$, let $F_i = \{A \in F : A$ has depth exactly $i\}$. Note that $\{F_i\}_{i \in [k - 1]}$ forms a partition of the packing $F$. Additionally, observe that, due to the maximality of $F$, every vertex in $U$ is dominated by at most $\ell - 1$ vertices belonging to $U$, and by at most $\ell - 1$ roots of in-arborescences in $F$, for each $i \in [k - 1]$.

Thus, the in-degree in $G$ of every vertex belonging to $U$ is at most $(\ell - 1) + (\ell - 1) \cdot k = (\ell - 1) \cdot k$. Therefore, we have $\Delta^-G(\leq (\ell - 1) \cdot k$. Moreover, since $\delta^+(D) \geq t(k, \ell) \cdot (\ell - 1) \cdot k + t(k, \ell)$, we have $d^+_G(v) \geq t(k, \ell) \cdot (\ell - 1) \cdot k$ for every $v \in U \setminus T$. Hence, $d^+_G(v) \geq (\ell - 1) \cdot k$, for every $v \in V(G) \setminus T$.

By Lemma 22, there exists a set $\mathcal P$ of $|S|$ vertex-disjoint paths from $S$ to $T$ in $G$.

Note that, in $D$, every vertex belonging to $T$ has at least $t(k, \ell) + 1$ out-neighbours in $V(D) \setminus U$. Therefore one can greedily extend each path of $\mathcal P$ with an out-neighbour of its terminal vertex in $V(D) \setminus U$ in order to obtain a set $\mathcal P'$ of $|S|$ vertex-disjoint paths from $S$ to $V(D) \setminus U$ such that for any $v \in X$ all the paths in $\mathcal P'$ with initial vertex $v$ have distinct terminal vertices (and different from $v$).

We now construct the digraph $M$ on the vertex set $R$ where there exists an arc from $v = r_A$ to $r_B$ in $M$ whenever

- either $r_A$ dominates some vertex of $V(B)$ in $D$,
- or there is a dipath from some $v_i$ to $V(B)$ in $\mathcal P'$.

Since, for each $v \in X$, all vertices in $\{v_i\}_{i \in [k, \ell]}$ are the initial vertices of vertex-disjoint dipaths in $\mathcal P'$, we obtain $\delta^+(M) \geq t(k, \ell)/b(k - 1, \ell)$. Therefore, the result follows by Claim 23.1 with $M$ playing the role of $H$. $\square$

### 2.3 Cycles with two blocks

We denote by $C(k_1, k_2)$ the digraph which is the union of two internally disjoint dipaths, one of length $k_1$ and one of length $k_2$ with the same initial vertex and same terminal vertex. $C(k_1, k_2)$ may also be seen as an oriented cycles with two blocks, one of length $k_1$ and one of length $k_2$. Recall that the blocks of an oriented cycle are its maximal directed subpaths.

**Theorem 24.** Let $D$ be a digraph with $\delta^+(D) \geq 2(k_1 + k_2) - 1$. Then $D$ contains a subdivision of $C(k_1, k_2)$.

**Proof.** Let us assume, without loss of generality, that $k_1 \geq k_2$. Let $\ell$ be a positive integer. An $(\ell, k_1, k_2)$-fork is a digraph obtained from the union of three disjoint dipaths $A = (a_0, a_1, \cdots, a\ell)$, $B^1 = (b^1_1, \cdots, b^1_{k_1-1})$ and $B^2 = (b^2_1, \cdots, b^2_{k_2-1})$ by adding the arcs $(a\ell, b^1_1)$ and $(a\ell, b^2_1)$.  

7
Since a $(1, k_1, k_2)$-fork has $k_1 + k_2 + 1$ vertices and $\delta^+(D) \geq k_1 + k_2 + 1$, then $D$ contains a $(1, k_1, k_2)$-fork as a subdigraph. Let $\ell \geq 1$ be the largest integer such that $D$ contains an $(\ell, k_1, k_2)$-fork as a subdigraph. Let $F$ be such a fork. For convenience, we denote its subpaths and vertices by their labels in the above definition.

If there exist $i, j \in [\ell] \cup \{0\}$, where $i \leq j$ (resp. $j \leq i$), such that $a_i \in N^+(b_{k_1-1})$ and $a_j \in N^+(b_{k_2-1})$, then the union of the dipaths $(a_\ell, B^1, a_1, \ldots, a_j)$ and $(a_\ell, B^2, a_j, \ldots, a_i)$ is a subdivision of $C(1, k_1, k_2)$.

Suppose now that $b_{k_1-1}$ has no out-neighbour in $\{a_0, \ldots, a_{\ell-1}\}$, that is, $N^+(b_{k_1-1}) \cap (A \setminus \{a_\ell\}) = \emptyset$ (the case $N^+(b_{k_2-1}) \cap (A \setminus \{a_\ell\}) = \emptyset$ is similar). Since $B^1 \cup B^2 \cup \{a_\ell\} = k_1 + k_2 - 1$ and $\delta^+(D) \geq 2(k_1 + k_2 - 1) + 1$, $b_{k_1-1}$ has two distinct out-neighbours, say $c_1^2$ and $c_2^2$, not in $F$.

Let $i_1 \geq 1$ be the largest integer such that there exist two disjoint dipaths $C^1$ and $C^2$ in $D - F$ with initial vertex $c_1^1$ and $c_2^1$, respectively, and length $i_1$ and $i_2 = \min\{k_2, i_1\}$. Set $C^1 = (c_1^1, \ldots, c_{i_1}^1)$ and $C^2 = (c_2^1, \ldots, c_{i_2}^1)$. By maximality of $\ell$, if $i_1 \geq k_2$, then $i_1 < k_1 - 1$. Otherwise, the union of $A \cup B^1, C^1, C^2, (b_{k_1-1}, c_1^1)$ and $(b_{k_1-1}, c_2^1)$ would contain an $(\ell + k_1 - 1, k_1, k_2)$-fork, contradicting the maximality of $\ell$.

Suppose to the contrary that both $c_1^2$ and $c_2^2$ have no out-neighbour in $A \setminus \{a_\ell\}$. Since $|V(B^1) \cup V(B^2) \cup \{a_\ell\} \cup V(C^1) \cup V(C^2)| = k_1 + k_2 + i_1 + i_2 - 1 < 2(k_1 + k_2) - 2$ (since $i_1 + i_2 < k_1 < k_1 + k_2 - 1$ and $\delta^+(D) \geq 2(k_1 + k_2 - 1) + 1$, there exist $c_1^2, c_2^2, c_{i_1+1}^2, c_{i_2+1}^2 \in V(D - (F \cup \{a_\ell\} \cup C^1 \cup C^2))$ such that $(c_1^2, c_2^2, c_{i_1+1}^2, c_{i_2+1}^2) \in A(D)$ and $c_1^2, c_2^2 \neq c_{i_1+1}^2, c_{i_2+1}^2$. This contradicts the maximality of $i_1$. Henceforth, we assume that $c_1^2$ has an out-neighbour $a_j \in A \setminus \{a_\ell\}$ for some $0 < j < \ell$.

Let $i_2$ be the largest integer such that both $c_1^2$ and $c_2^2$ have an out-neighbour in $A \setminus \{a_\ell\}$, and the union of the dipaths $(a_\ell, B^1, C^1)$ and $(a_\ell, B^2, C^2)$ contains an $(i_1, 2-k_1, k_2)$-fork, contradicting the maximality of $\ell$.

If $b_{k_2-2}^2$ has an out-neighbour $a_m \in A \setminus \{a_\ell\}$, then the union of the dipaths $(a_\ell, B^1, C^1, a_m)$ and $(a_\ell, B^2, a_m)$ (if $m \geq 1$) or of the dipaths $(a_\ell, B^1, C^1, a_j)$ and $(a_\ell, B^2, a_m, a_j)$ (if $m < j$) is a subdivision of $C(1, k_1, k_2)$.

By definition, $b_{k_2-2}^2$ has an out-neighbour $z \in V(C^1 \cup C^2)$, say $z = c_1^2$ for some $0 \leq h \leq i_2$ (the case in which $z \in V(C^2)$ is similar), and the union of the dipaths $(a_\ell, B^2, C^2)$ and $(a_\ell, B, C, a_j)$ is a subdivision of $C(1, k_1, k_2)$.

So, we may assume that $b_{k_2-2}^2$ has no out-neighbour in $A \setminus \{a_\ell\} \cup C^1 \cup C^2$. Hence, $b_{k_2-2}^2$ has two distinct out-neighbours, say $c_1^3$ and $c_2^3$, not in $F \cup C^1 \cup C^2$. Let $i_3 \geq 1$ be the largest integer such that there exist two disjoint dipaths $C^3$ and $C^4$ in $D - (F \cup C^1 \cup C^2)$ with initial vertex $c_1^3$ and $c_2^3$, respectively, and length $i_3$ and $i_4 = \min\{k_2, i_3\}$. By the maximality of $\ell$, if $i_3 \geq k_2$ then $i_3 < k_1 - 1$ since otherwise the union of $A \cup B^2, C^3, (b_{k_1-1}, c_1^3)$ and $(b_{k_1-1}, c_2^3)$ would contain an $(\ell + k_1 - 1, k_1, k_2)$-fork, contradicting the maximality of $\ell$.

For sake of contradiction, assume that both $c_1^3$ and $c_2^3$ have no out-neighbour in $(A \setminus \{a_\ell\}) \cup C^1 \cup C^2$. Because $|V(B^1) \cup V(B^2) \cup V(C^1) \cup V(C^2) \cup \{a_\ell\}| = k_1 + k_2 + i_3 + i_4 - 1 < 2(k_1 + k_2) - 2$ (since $i_3 + i_4 < k_1 + k_2 - 1$ and $\delta^+(D) \geq 2(k_1 + k_2 - 1) + 1$, then there exist distinct vertices $c_3^3, c_4^3, c_{i_3+1}^3, c_{i_4+1}^3 \in V(D - (F \cup C^1 \cup C^2 \cup C^3 \cup C^4))$ if $i_3 \geq k_2$, we only define $c_{i_3+1}^3$) such that $(c_3^3, c_4^3, c_{i_3+1}^3, c_{i_4+1}^3) \in A(D)$. This contradicts the maximality of $i_3$.

So one of $c_3^3, c_4^3$ has an out-neighbour in $(A \setminus \{a_\ell\}) \cup C^1 \cup C^2$. We assume that it is $c_3^3$; the case when it is $c_4^3$ is similar.

If $c_3^3$ has an out-neighbour $a_q \in A \setminus \{a_\ell\}$ (for some $q < \ell$), then the union of either the dipaths $(a_\ell, B^1, C^1, a_q)$ and $(a_\ell, B^3, C^3, a_q)$ (if $q \geq 1$), or the dipaths $(a_\ell, B^1, C^1, a_j)$ and $(a_\ell, B^3, C^3, a_j)$ (if $q < j$), is a subdivision of $C(1, k_1, k_2)$.

If $c_3^3$ has an out-neighbour $c_3^3 \in V(C^1)$ for some $1 \leq h \leq i_1$, then the union of the dipaths $(a_\ell, B^1, c_3^3, a_j)$ and $(a_\ell, B^3, C^3, c_3^3)$ is a subdivision of $C(1, k_1, k_2)$. Similarly, we find a subdivision of $C(k_1, k_2)$ if $c_3^3$ has an out-neighbour in $C^2$.

Theorem 24 shows that an oriented cycle with two blocks $C$ is maderian and $\text{mader}_{\text{95}}(C) \leq 2|V(C)| - 1$. A natural question is to ask whether this upper bound is tight or not.

**Problem 25.** What is the value of $\text{mader}_{\text{95}}(C(1, k_1, k_2))$?

**Proposition 26.** For any positive integer $k$, $\text{mader}_{\text{95}}(C(k, 1)) = \text{mader}_{\text{95}}(C(k, 1)) = k$.

**Proof.** The complete digraph on $k$ vertices has minimum in- and out-degree $k - 1$, and it trivially contains no subdivision of $C(k, 1)$ because it has less vertices than $C(k, 1)$. Hence $\text{mader}_{\text{95}}(C(k, 1)) \geq \text{mader}_{\text{95}}(C(k, 1)) \geq k$.  

8
Consider now a digraph $D$ with $\delta^+(D) \geq k$. Let $P$ be a longest dipath in $D$ and let $u$ be its terminal vertex. Necessarily $N^+(u) \subseteq V(P)$. Let $v$ (resp. $w$) be the first (resp. last) vertex of $N^+(u)$ along $P$. The path $P[v, w]$ contains all vertices of $N^+(u)$, so it has length at least $k - 1$. Hence the union of $(u, v) \cup P[v, w]$ and $(u, w)$ is a subdivision of $C(k, 1)$.

A step further towards Conjecture 2 would be to prove that every oriented cycle is $\delta^+$-maderian. We even conjecture that for every oriented cycle $C$ mader$_{3^+} (C) \leq 2|V(C)| - 1$.

**Conjecture 27.** Let $D$ be a digraph with $\delta^+(D) \geq 2k - 1$. Then $D$ contains a subdivision of any oriented cycle of order $k$

### 2.4 Three dipaths between two vertices

A slight adaptation of the proof of Theorem 24 leads to a stronger result. Let $k_1, k_2, k_3$ be positive integers. Let $P(k_1, k_2, k_3)$ be the digraph formed by three internally disjoint paths between two vertices $x, y$, two $(x, y)$-dipaths, one of size at least $k_1$, the other of size at least $k_2$, and one $(y, x)$-dipath of size at least $k_3$. When we want to insist on the vertices $x$ and $y$, we denote it by $P_{xy}(k_1, k_2, k_3)$.

**Theorem 28.** Let $k_1, k_2, k_3$ be positive integers with $k_1 \geq k_2$. Let $D$ be a digraph with $\delta^+(D) \geq 3k_1 + 2k_2 + k_3 - 5$. Then $D$ contains $P(k_1, k_2, k_3)$.

**Proof.** Let $\ell$ be an integer. An $(\ell; k_1, k_2, k_3)$-fork is a digraph obtained from the union of four disjoint directed paths $P = (p_1, \ldots, p_\ell)$, $A = (a_1, \ldots, a_{k_1-1})$, $B^1 = (b_1^1, \ldots, b_{k_1-1}^1)$ and $B^2 = (b_1^2, \ldots, b_{k_2-1}^2)$ by adding the arcs $(p_1, a_1), (a_{k_1-1}, b_1^1)$ and $(a_{k_1-1}, b_1^2)$.

Since a $(1, k_1; k_1, k_2)$-fork has $k_1 + k_2 + k_3 - 2$ vertices and $\delta^+(D) \geq k_1 + k_2 + k_3 - 2$, then $D$ contains a $(1, k_1; k_1, k_2)$-fork as a subdigraph. So, let $\ell \geq 1$ be the largest integer such that $D$ contains an $(\ell; k_1, k_1, k_2)$-fork as a subdigraph. Let $F$ be such a fork. For convenience, we denote its subpaths and vertices by their labels in the above definition.

If there exist $i, j \in [\ell]$, with $i < j$, such that $p_i \in N^+(b_{k_1-1}^1)$ and $p_j \in N^+(b_{k_2-1}^2)$ or $p_i \in N^+(b_{k_1-1}^1)$ and $p_j \in N^+(b_{k_2-1}^2)$, then $F$ contains a $P_{k_1-k_2; k_1, k_2; k_3}$.

So, let us assume that $b_{k_1-1}^1$ has no out-neighbour in $P$ (the case where $b_{k_2-1}^2$ has no out-neighbour in $P$ is similar). Since $|A \cup B^1 \cup B^2| = k_1 + k_2 + k_3 - 3$ and $\delta^+(D) \geq k_1 + k_2 + k_3 - 1$, $b_{k_1-1}^1$ has two distinct out-neighbours, say $c_1^1$ and $c_2^1$, not in $F$.

Let $i_1 \geq 1$ be the largest integer such that there exist two disjoint directed paths $C^1$ and $C^2$ in $D - F$ with initial vertex $c_1^1$ and $c_2^1$ respectively and length $i_1$ and $i_2 = \min\{k_2 - 1, i_1\}$. If $i_1 \geq k_1 - 1$, then $i_2 \geq k_1 - 1$, and thus $P \cup A \cup B^1 \cup C^1 \cup C^2$ would contain a fork that contradicts the maximality of $\ell$. Hence we may assume that $i_1 \leq k_1 - 2$ (and in particular $|V(C^1) \cup V(C^2)| \leq k_1 + k_2 - 3$).

For sake of contradiction, assume that both $c_1^1$ and $c_2^1$ have no out-neighbour in $P$. Since $|V(A) \cup V(B^1) \cup V(B^2) \cup V(C^1) \cup V(C^2)| \leq 2k_1 + 2k_2 + k_3 - 6 < \delta^+(D) - 2$, then there exist $c_{i_1+1}^1, c_{i_2+1}^1 \in V(D - (F \cup C^1 \cup C^2))$ such that $(c_{i_1+1}^1, c_{i_1+1}^1), (c_{i_2+1}^1, c_{i_2+1}^1) \in A(D)$ and $c_{i_1+1}^1 \neq c_{i_2+1}^1$. This contradicts the maximality of $\ell_1$. Henceforth, we assume that $c_{i_1}^1$ has an out-neighbour $p_i \in P$ (the case in which $c_2^1$ has an out-neighbour in $P$ is similar).

If $b_{k_1-1}^2$ has also an out-neighbour $p_j \in P$, then $F \cup C_1$ contains a $P_{k_2-k_3; k_1, k_2; k_3}$ if $i < j$, and a $P_{k_2-k_1; k_1, k_2; k_3}$ if $j \leq i$.

So, we may assume that $b_{k_1-1}^2$ has no out-neighbour in $P$. Hence, $b_{k_1-1}^2$ has two distinct out-neighbours, say $c_1^1$ and $c_2^1$, not in $F \cup C^1$. Let $i_3 \geq 1$ be the largest integer such that there exist two disjoint dipaths $C^3$ and $C^4$ in $D - (F \cup C^1)$ with initial vertex $c_3^1$ and $c_1^1$ respectively and length $i_3$ and $i_4 = \min\{k_3 - 1, i_3\}$. If $i_3 \geq k_1$, then $i_4 \geq k_2 - 1$ and thus $P \cup A \cup B^1 \cup C^3 \cup C^4$ contains a fork that contradicts the maximality of $F$. Thus, we may assume that $i_3 \leq k_1 - 2$. In particular $|V(C^3) \cup V(C^4)| \leq k_1 + k_2 - 3$.

Suppose to the contrary that both $c_3^1$ and $c_1^1$ have no out-neighbour in $P$, where $c_3^1$ and $c_1^1$ are the last vertices of $C^3$ and $C^4$. Note that $|V(A) \cup V(B^1) \cup V(B^2) \cup V(C^3) \cup V(C^4)| \leq 3k_1 + 2k_2 + k_3 - 7 \leq \delta^+(D) - 2$. Hence, there exist distinct vertices $c_{i_3+1}^1, c_{i_4+1}^1 \in V(D - (F \cup C^1 \cup C^3 \cup C^4))$ such that $(c_{i_3+1}^1, c_{i_3+1}^1), (c_{i_4+1}^1, c_{i_4+1}^1) \in A(D)$. This contradicts the maximality of $i_3$.

Therefore, one of $c_{i_3}^1, c_{i_4}^1$ has an out-neighbour in $p_j$ in $P$. We assume that it is $c_{i_3}^1$; the case when it is $c_{i_4}^1$ is similar. We conclude that $F \cup C_1 \cup C_3$ contains a $P_{k_2-k_1; k_1, k_2; k_3}$ if $i < j$, and a $P_{k_2-k_3; k_1, k_2; k_3}$ if $j < i$. 

\[ \square \]
3 Subdivisions in digraphs with large dichromatic number

Recall that a $k$-dicolouring is a $k$-partition $\{V_1, \ldots, V_k\}$ of $V(D)$ such that $D(V_i)$ is acyclic for every $i \in [k]$, and that the dichromatic number of $D$ is the minimum $k$ such that $D$ admits a $k$-dicolouring. In this section, we first prove that every digraph is $\vec{\chi}$-maderian. We need some preliminaries. The first one is an easy lemma, whose proof is left to the reader.

Lemma 29. The dichromatic number of a digraph is the maximum of the dichromatic numbers of its strong components.

Our proof is based on levelling. Forthwith, we introduce the necessary definitions. Given a digraph $D$, the distance from a vertex $x$ to another $y$, denoted by $\text{dist}_D(x, y)$ or simply $\text{dist}(x, y)$ when $D$ is clear from the context, is the minimum length of an $(x, y)$-dipath or $+\infty$ if no such dipath exists. An out-generator in $D$ is a vertex $u$ such that, for every $x \in V(D)$, there exists an $(u, x)$-dipath in $D$. Analogously, an in-generator in $D$ is a vertex $v$ such that, for every $x \in V(D)$, there exists an $(x, v)$-dipath in $D$. For simplicity, we call a vertex generator if it is an in- or out-generator. Observe that every vertex in a strong digraph is an in- and out-generator.

Let $D$ be a digraph. Let $u, v$ be in- and out-generators of $D$, respectively. We remark that $w$ and $u$ are not necessarily different. For every nonnegative integer $i$, the $i$th out-level from $u$ in $D$ is the set $L^{u,+}_i = \{v \in V(D) \mid \text{dist}_D(u, v) = i\}$, and the $i$th in-level from $w$ in $D$ is the set $L^{w,-}_i = \{v \in V(D) \mid \text{dist}_D(w, v) = i\}$. Note that $\bigcup_i L^{u,+}_i = \bigcup_i L^{w,-}_i = V(D)$.

An out-Breadth-First-Search Tree or out-BFS-tree $T^+$ with root $u$, is a subdigraph of $D$ spanning $V(D)$ such that $T^+$ is an oriented tree, and, for every $v \in V(D)$, $\text{dist}_D^+(u, v) = \text{dist}_D^-(u, v)$. Similarly, an in-Breadth-First-Search Tree or in-BFS-tree $T^-$ with root $w$, is a subdigraph of $D$ spanning $V(D)$ such that $T^-$ is an oriented tree, and, for every $v \in V(D)$, $\text{dist}_D^-(v, w) = \text{dist}_D^+(v, w)$.

It is well-known that if $D$ has an in-generator, then there exists an out-BFS-tree rooted at this vertex. Likewise, if $D$ has an out-generator, then there exists an in-BFS-tree rooted at this generator.

Let $T$ denote an in- or out-BFS-tree rooted at $u$. For any vertex $x$ of $D$, there is a single $(u, x)$-dipath in $T$ if $T$ is an out-BFS-tree, and a single $(x, u)$-dipath in $T$ if $T$ is an in-BFS-tree. The ancestors or successors of $x$ in $T$ are naturally defined. If $y$ is an ancestor of $x$, we denote by $T[y, x]$ the $(y, x)$-dipath in $T$. If $y$ is a successor of $x$, we denote by $T[x, y]$ the $(x, y)$-dipath in $T$.

Lemma 30. Let $D$ be a strong digraph and let $T$ be an in- or out-BFS-tree in $D$. There is a level $L$ such that $\vec{\chi}(D(L)) \geq \vec{\chi}(D)/2$.

Proof. First, let us suppose, without loss of generality, that $T$ is an out-BFS-tree in $D$. The proof when $T$ is an in-BFS-tree is analogous.

Let $D_1$ and $D_2$ be the subdigraphs of $D$ induced by the vertices of odd and even levels, respectively. Since there is no arc from $L_i$ to $L_j$ for every $j \geq i + 2$, the strong components of $D_1$ and $D_2$ are contained in the levels. Hence, by Lemma 29, $\vec{\chi}(D_1) = \max\{\vec{\chi}(D(L)) \mid i \text{ is odd}\}$ and $\vec{\chi}(D_2) = \max\{\vec{\chi}(D(L)) \mid i \text{ is even}\}$. Moreover, note that $V(D_1) \cup V(D_2) = V(D)$ because $D$ is strong. Therefore, $\vec{\chi}(D) \leq \vec{\chi}(D_1) + \vec{\chi}(D_2) \leq 2 \cdot \max\{\vec{\chi}(D(L)) \mid i \in \mathbb{N}\}$. \qed

Lemma 31. Let $F$ be a digraph and let $a = xy$ be an arc in $A(F)$. If $F - a$ is $\vec{\chi}$-maderian, then $F$ is $\vec{\chi}$-maderian, and $\text{mader}_\vec{\chi}(F) \leq 4 \cdot \text{mader}_\vec{\chi}(F - a) - 3$.

Proof. Let $c = \text{mader}_\vec{\chi}(F - a)$ and let $D$ be a digraph with $\vec{\chi}(D) \geq 4c - 3$. We shall prove that $D$ contains a subdivision of $F$.

By Lemma 29, we may assume that $D$ is strong. Let $u$ be a vertex in $D$ and $T_u$ an out-BFS-tree with root $u$. By Lemma 30, there is a level $L^u$ such that $\vec{\chi}(D(L^u)) \geq 2c - 1$. By Lemma 29, there is a strong component $C$ of $D(L^u)$ such that $\vec{\chi}(C) = \vec{\chi}(D(L^u)) \geq 2c - 1$. Since $D$ is strong, there is a shortest $(v, u)$-dipath $P$ in $D$ such that $V(P) \cap V(C) = \{v\}$. Let $T_v$ be an in-BFS-tree in $C$ rooted at $v$. By Lemma 30, there is a level $L^v$ of $T_v$ such that $\vec{\chi}(D(L^v)) \geq c$. Now since $\text{mader}_\vec{\chi}(F - a) = c$, $D(L^v)$ contains a subdivision $S$ of $F - a$. With a slight abuse of notation, let us call $x$ and $y$ the vertices in $S$ corresponding to the vertices $x$ and $y$ of $F$. Now $T_u[x, y] \cup P \cup T_v[u, y]$ is a directed $(x, y)$-walk with no internal vertex in $L^v$. Hence it contains an $(x, y)$-dipath $Q$ whose internal vertices are not in $S$. Therefore, $S \cup Q$ is a subdivision of $F$ in $D$. \qed
Theorem 32. Every digraph $F$ is $\overline{\chi}$-maderian. More precisely, $\text{mader}_{\overline{\chi}}(F) \leq 4^m(n-1) + 1$, where $m = |A(F)|$ and $n = |V(F)|$.

Proof. We prove the result by induction on $m$. If $m = 0$, then $F$ is an empty digraph which is trivially $\overline{\chi}$-maderian and $\text{mader}_{\overline{\chi}}(F) = n$. If $m > 0$, then consider an arc $a \in A(F)$. By Lemma 31, we obtain $\text{mader}_{\overline{\chi}}(F) \leq 4 \cdot \text{mader}_{\overline{\chi}}(F-a) - 3$. By the induction hypothesis, $\text{mader}_{\overline{\chi}}(F-a) \leq 4^{m-1}(n-1) + 1$. Therefore, $\text{mader}_{\overline{\chi}}(F) \leq 4^m(n-1) + 1$.

Observe that Theorem 32 generalizes the consequence of Theorem 1, stating that every graph with sufficiently large chromatic number contains a subdivision of $K_k$. In fact this statement corresponds to the case of symmetric digraphs of Theorem 32.

3.1 Better bounds on mader$_{\overline{\chi}}$

The bound on mader$_{\overline{\chi}}$ given in Theorem 32 is not optimal. The aim of this subsection is to find better upper bounds.

A digraph is $k$-$\overline{\chi}$-critical if $\overline{\chi}(D) = k$ and $\overline{\chi}(D') < k$ for every proper subdigraph $D'$ of $D$.

Proposition 33. If $D$ is $k$-$\overline{\chi}$-critical, then $\delta^0(D) \geq k - 1$.

Proof. Let $v$ be a vertex of $D$. Since $D$ is $k$-$\overline{\chi}$-critical, $\overline{\chi}(D - v) \leq k - 1$, so $D - v$ admits a $(k-1)$-dicolouring $\{V_1, \ldots, V_{k-1}\}$. Thus, for each $i \in [k-1]$, $D(V_i \cup \{v\})$ has a directed cycle that contains $v$. Therefore, $v$ has an in-neighbour and an out-neighbour in each $V_i$. □

Corollary 34. $\text{mader}_{\overline{\chi}}(F) \leq \text{mader}_{\overline{\chi}}(F) + 1$ for all digraph $F$.

Corollary 35. $\text{mader}_{\overline{\chi}}(F) = |V(F)|$ for all oriented forest $F$.

Let us denote by cc($F$) the number of connected components of $F$, that are the connected components of the underlying graph.

Corollary 36. For every digraph $F$, we have $\text{mader}_{\overline{\chi}}(F) \leq 4^{m-n + \text{cc}(F)}(n-1) + 1$, where $m = |A(F)|$ and $n = |V(F)|$.

Proof. The proof is identical to the one of Theorem 32, but instead of starting the induction with empty digraphs, we start it with a forest that is the union of spanning trees of the connected components. □

Corollary 36 implies that $\text{mader}_{\overline{\chi}}(K_n) \geq 4^{n(n-2)+1}(n-1) + 1$. On the other hand, we have $\text{mader}_{\overline{\chi}}(K_n) \geq \Omega\left(\frac{n^2}{\log n}\right)$. Indeed, consider a tournament $T_p$ on $p$ vertices with a subdivision $S$ of $K_n$. For every two distinct vertices $u, v$ of $K_n$, at least one of the arcs $(u, v), (v, u)$ is subdivided in $S$. Hence, $S$ has at least $n + \binom{n}{2} = \binom{n+1}{2}$ vertices, so $p \geq \binom{n+1}{2}$. Erdős and Moser [13] proved that for every integer $p$, there exists a tournament $T_p$ on $p$ vertices with no transitive tournament of order $2 \log p + 1$. Thus $\overline{\chi}(T_p) \geq \frac{p}{2 \log p}$. Now set $p = \binom{n+1}{2} - 1$. The tournament $T_p$ contains no subdivision of $K_n$ and $\overline{\chi}(T_p) \geq \frac{p}{2 \log p} \geq 1 + \Omega\left(\frac{n^2}{\log n}\right)$.

A $k$-source in a digraph is a vertex $x$ with in-degree 0 and out-degree at most $k$; a $k$-sink in a digraph is a vertex $x$ with out-degree 0 and in-degree at most $k$. A digraph is $k$-reducible if it can be reduced to the empty digraph by repeated deletion of $k$-sources or $k$-sinks. For instance, the 1-reducible digraphs are the oriented forests.

Lemma 37. Let $F$ be a digraph having a 2-source $x$. Then $\text{mader}_{\overline{\chi}}(F) \leq 2 \text{mader}_{\overline{\chi}}(F - x) - 1$.

Proof. Suppose that $F - x$ is ($\overline{\chi} \geq c$)-maderian. We shall prove that $F$ is ($\overline{\chi} \geq 2c - 1$)-maderian. Let $D$ be a digraph with $\overline{\chi}(D) \geq 2c - 1$. By Lemma 29, we may assume that $D$ is strong. Let $u$ be a vertex in $D$, and let $T$ be a BFS-tree with root $u$. By Lemma 30, there is a level such that $\overline{\chi}(D(L)) \geq c$. Consequently, $D(L)$ contains a subdivision $S$ of $F - x$. Let $y_1$ and $y_2$ be the vertices in $S$ corresponding to the two out-neighbours of $x$ in $F$. Let $v$ be the least common ancestor of $y_1$ and $y_2$ and, for $i \in \{1, 2\}$, let $P_i$ be the $(v,y_i)$-dipath in $T$. Therefore, we conclude that the digraph $S \cup P_1 \cup P_2$ is a subdivision of $F$ in $D$. □
Corollary 38. The following statements hold.

(a) $\text{mader}_\chi(F) \leq 2^{|V(F)| - 2} + 1$ for every 2-reducible digraph $F$ or order at least 2.

(b) $\text{mader}_\chi(C) \leq 2 \cdot |V(C)| - 3$ for every oriented cycle $C$ of order at least 3.

Proof. Statement (a) follows by induction on $|V(F)|$. Observe that the result trivially holds when $|V(F)| = 2$.

To prove statement (b), consider the following two complementary cases. If $C$ is directed, say $C = \vec{C}_k$, then $\text{mader}_\chi(C) \leq \text{mader}_\delta^+(C) + 1 \leq k \leq 2k - 3$. If $C$ is not directed, then it contains a 2-source $x$. Hence $C - x$ is an oriented path, and, by Corollary 35, it follows that $\text{mader}_\chi(C - x) = |C - x| = |C| - 1$.

Conjecture 39. $\text{mader}_\chi(C) \leq |C|$ for every oriented cycle $C$.

References


