



**HAL**  
open science

## A Menger-like property of tree-cut width

Archontia C Giannopoulou, O-Joung Kwon, Jean-Florent Raymond, Dimitrios  
M. Thilikos

► **To cite this version:**

Archontia C Giannopoulou, O-Joung Kwon, Jean-Florent Raymond, Dimitrios M. Thilikos. A Menger-like property of tree-cut width. *Journal of Combinatorial Theory, Series B*, 2021, 148, pp.1-22. 10.1016/j.jctb.2020.12.005 . hal-03094586

**HAL Id: hal-03094586**

**<https://hal.science/hal-03094586v1>**

Submitted on 4 Jan 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# A Menger-like property of tree-cut width\*

Archontia C. Giannopoulou<sup>†‡</sup>

O-joung Kwon<sup>§¶</sup>

Jean-Florent Raymond<sup>‡</sup>

Dimitrios M. Thilikos<sup>||\*\*</sup>

## Abstract

In 1990, Thomas proved that every graph admits a tree decomposition of minimum width that additionally satisfies a certain vertex-connectivity condition called *leanness* [A Menger-like property of tree-width: The finite case. *Journal of Combinatorial Theory, Series B*, 48(1):67 – 76, 1990]. This result had many uses and has been extended to several other decompositions. In this paper, we consider tree-cut decompositions, that have been introduced by Wollan as a possible edge-version of tree decompositions [The structure of graphs not admitting a fixed immersion. *Journal of Combinatorial Theory, Series B*, 110:47 – 66, 2015]. We show that every graph admits a tree-cut decomposition of minimum width that additionally satisfies an edge-connectivity condition analogous to Thomas’ leanness.

## 1 Introduction

The notion of treewidth is a cornerstone of the theory of graph minors of Robertson and Seymour. Formally, a *tree decomposition* of a graph  $G$  is a pair  $(T, \mathcal{X})$  where  $T$  is a tree and  $\mathcal{X} = \{X_t \subseteq V(G), t \in V(T)\}$  is a collection of vertex sets, called *bags*, with the following properties:

1.  $\bigcup_{t \in V(T)} X_t = V(G)$ ;

---

\*A preliminary version of this paper appeared in the proceedings of the 36<sup>th</sup> Symposium on Theoretical Aspects of Computer Science (STACS ’19) [GKRT19].

<sup>†</sup>Logic and Semantics research group, Technische Universität Berlin, Germany. These authors has been supported by the ERC consolidator grant DISTRUCT-648527.

<sup>‡</sup>Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Greece.

<sup>§</sup>Department of Mathematics, Incheon National University, South Korea.

<sup>¶</sup>Supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Education (No. NRF-2018R1D1A1B07050294).

<sup>||</sup>AIGCo project team, CNRS, LIRMM, Montpellier, France.

<sup>\*\*</sup>Supported by the projects “ESIGMA” (ANR-17-CE23-0010) and “DEMOGRAPH” (ANR-16-CE40-0028) and by the Research Council of Norway and the French Ministry of Europe and Foreign Affairs, via the Franco-Norwegian project PHC AURORA 2019.

2. every edge of  $G$  belongs to some bag in  $\mathcal{X}$ ; and
3. for every  $u \in V(G)$ , the set  $\{t \in V(T), u \in X_t\}$  induces a connected subgraph of  $T$ .

The *width* of  $(T, \mathcal{X})$  is  $\max_{t \in V(T)} |X_t| - 1$  and the *treewidth* of  $G$ , that we denote by  $\text{tw}(G)$ , is defined as the minimum width of a tree decomposition of  $G$ .

When writing [RS90] (see [Tho90, Theorem 2] and the introduction of [RS90, Section 5]), Robertson and Seymour proved that there exists tree decompositions of “small” width that satisfy a certain connectivity condition here called *linkedness property*.

**Theorem 1.1** ([RS90]). *Every graph  $G$  admits a tree decomposition  $(T, \{X_t\}_{t \in V(T)})$  of width less than  $3 \cdot 2^{\text{tw}(G)}$  such that the following holds:*

*Linkedness property: for every  $k \in \mathbb{N}$  and  $a, b \in V(T)$ , either there are  $k$  disjoint paths linking  $X_a$  to  $X_b$ , or there is a node  $c$  on the path of  $T$  between  $a$  and  $b$  such that  $|X_c| < k$ .*

That is, while Menger’s theorem [Men27] states the existence of a set of less than  $k$  vertices disconnecting  $X_a$  from  $X_b$ , **Theorem 1.1** additionally guarantees that such vertices that can be found as a bag of size less than  $k$  of the tree decomposition. The exponential bound in **Theorem 1.1** has been subsequently improved by Thomas to its optimal value. In fact, Thomas showed a stronger property called *leanness*.

**Theorem 1.2** ([Tho90]). *Every graph  $G$  admits a tree decomposition  $(T, \{X_t\}_{t \in V(T)})$  of width  $\text{tw}(G)$  such that the following holds:*

*Leanness property: for every  $k \in \mathbb{N}$ ,  $a, b \in V(T)$ ,  $A \subseteq X_a$ , and  $B \subseteq X_b$  such that  $|A| = |B| = k$ , either there are  $k$  disjoint paths linking  $A$  to  $B$ , or there is a node  $c$  on the path of  $T$  between  $a$  and  $b$  such that  $|X_c| < k$ .*

A simplified proof of **Theorem 1.2** was then found by Diestel and Bellenbaum [BD02]. The aim of Robertson and Seymour was to use **Theorem 1.1** as an ingredient in their proof that graphs of bounded treewidth are well-quasi-ordered by the minor relation [RS90]. Since then, the notions of leanness and linkedness have been extensively studied and extended to several different width parameters such as  $\theta$ -tree-width [CDHH14, GJ16], path-width [Lag98], directed path-width [KS15], DAG-width [Kin14], rank-width [Oum05], linear-rankwidth [KK14], profile- and block-width [Erd18], matroid treewidth [GGW02a, Azz11, Erd18] and matroid branchwidth [GGW02a]. They have important applications, for instance in order to bound the size of obstructions for certain classes of graphs [Sey93, Lag98, KK14, GW02, GPR<sup>+</sup>18], in well-quasi-ordering proofs [Oum08, Liu14, GGW02b], in extremal graph theory [OOT93, CRS11], and for algorithmic purpose [CKL<sup>+</sup>18]. We refer to [Erd18] for an unified introduction to lean decompositions.

In this paper, we show that a similar leanness property holds for *tree-cut width*. Tree-cut width is a graph invariant introduced by Wollan in [Wol15] and defined via graph decompositions called *tree-cut decompositions*. Several results are supporting the claim that tree-cut width would be the *right* parameter for studying graph immersions. For instance, there is an analog to the Grid-minor Exclusion Theorem of Robertson and Seymour [RS86] in the

setting of immersions [Wol15]. Also, tree-cut decompositions can be used for dynamic programming in the same way as tree decompositions do, for certain algorithmic problems that cannot be tackled under the bounded-treewidth framework [GKS15, KOP<sup>+</sup>18, GPR<sup>+</sup>17]. Therefore, we expect that this invariant will play a central role in the flourishing theory of graph immersions.

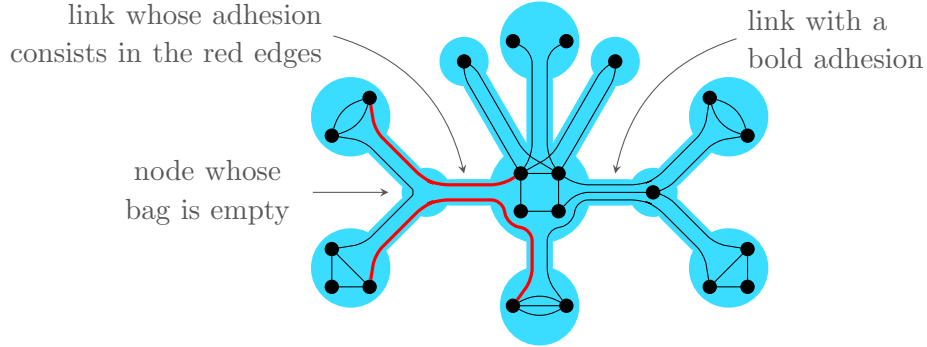


Figure 1: Representation of a tree-cut decomposition. The tree of the decomposition is depicted in blue and the graph is drawn in black on top of it to specify which vertices (resp. edges) belong to which bags (resp. adhesions).

Formally, a *tree-cut decomposition* of a graph  $G$  is a pair  $\mathcal{D} = (T, \mathcal{X})$  where  $T$  is a tree and  $\mathcal{X} = \{X_t \subseteq V(G), t \in V(T)\}$  is a collection of disjoint vertex sets, called *bags*, with the property that  $\bigcup_{t \in V(T)} X_t = V(G)$ .<sup>1</sup> See Figure 1 for an example. To avoid confusion with the vertices or edges of  $G$ , we respectively use the synonyms *nodes* and *links* when we refer to the vertices and edges of the tree of a tree-cut decomposition. Let  $uv$  be a link of  $T$ , let  $T_{uv}$  and  $T_{vu}$  be the two connected components of  $T - uv$ , let  $X_{uv}^T = \bigcup_{t \in V(T_{uv})} X_t$  and symmetrically for  $X_{vu}^T$ . The *adhesion*  $\text{adh}_{\mathcal{D}}(uv)$  of the link  $uv$  is defined as the set of edges of  $G$  with one endpoint in  $X_{uv}^T$  and the other one in  $X_{vu}^T$ . We drop the subscript when it is clear from the context. We say that an adhesion is *bold* if it has size more than two. Then the width of the decomposition  $\mathcal{D}$  is defined as:

$$\text{width}(\mathcal{D}) = \max \left\{ \max_{e \in E(T)} |\text{adh}(e)|, \max_{t \in V(T)} (|X_t| + |\{t' \in N_T(t), \text{adh}(tt') \text{ is bold}\}|) \right\},$$

where  $N_T(t)$  denotes the set of nodes of  $T$  that are adjacent to  $t$ . The tree-cut width of  $G$  is defined as the minimum width of a tree-cut decomposition of it. We note that this definition differs from the original definition of Wollan in [Wol15], however the two definitions have been proved to be equivalent in [GPR<sup>+</sup>17]. Our definition of leanness for tree-cut decompositions is a transposition to the edge setting of the leanness notion of Thomas.

**Definition 1.3** (leanness property for tree-cut decompositions). A tree-cut decomposition  $(T, \mathcal{X})$  is said to be *lean* if for every  $k \in \mathbb{N}$ , every  $a, b \in E(T)$ , and every  $A \subseteq \text{adh}(a), B \subseteq \text{adh}(b)$  such that  $|A| = |B| = k$ , one of the following holds:

- there are  $k$  edge-disjoint paths linking  $A$  to  $B$ ; or

<sup>1</sup>In other words,  $\{X_t, t \in V(T)\}$  is a partition of  $V(G)$  plus possibly some empty sets.

- there is an link  $c$  on the path of  $T$  between  $a$  and  $b$  such that  $|\text{adh}(c)| < k$ .

Notice that Thomas' notion of leanness for tree decompositions relates vertex-disjoint paths to vertex-separators given by the decomposition, while ours links edge-disjoint paths to edge-separators. A related notion of linkedness has been previously studied in [GPR+18] in the simpler setting of cutwidth orderings. Our main result is the following.

**Theorem 1.4.** *Every graph  $G$  admits a tree-cut decomposition of width  $\text{tcw}(G)$  that is lean.*

This result can be used to give explicit upper-bounds on the size of the immersion-obstructions of graphs of bounded tree-cut width<sup>2</sup>, a result that we postpone to a future paper (see [GKRT19] for an extended abstract containing both results).

## 2 Preliminaries

Given two integers  $a, b$  we denote by  $[a, b]$  the set  $\{a, \dots, b\}$  and by  $[a]$  the set  $\{1, \dots, a\}$ .

**Graphs.** Unless otherwise specified, we follow standard graph theory terminology; see e.g. [Die05]. All graphs considered in this paper are finite, undirected, without loops, and may have multiple edges. The vertex sets of a graph  $G$  is denoted by  $V(G)$  and its multiset of edges by  $E(G)$ . For a subset of vertices  $S \subseteq V(G)$ ,  $G - S$  is the induced subgraph  $G[V(G) \setminus S]$ . For a subset  $F \subseteq E(G)$  of edges,  $G - F$  is the subgraph  $(V(G), E(G) \setminus F)$ . The subgraph of  $G$  induced by  $F$  has the set of endpoints of edges in  $F$  as vertex set and  $F$  as edge set.

A path of  $G$  *links* two edges of  $G$  if it starts with one and ends with the other. Given two sets  $A$  and  $B$  of edges of  $G$ , we say that a path  $P$  *links*  $A$  and  $B$  if it starts with an edge of  $A$ , ends with an edge of  $B$ , and none of its internal edges belong to  $A \cup B$ . In particular, the path reduced to a single edge  $e \in A \cap B$  links  $A$  and  $B$ .

A *cut* in a graph  $G$  is a set  $F \subseteq E(G)$  such that  $G - F$  has more connected components than  $G$ . If  $A, B \subseteq E(G)$ , we say that  $F$  is an  $(A, B)$ -cut if no path links  $A$  and  $B$  in  $G - F$ . In particular,  $A \cup B$  is an  $(A, B)$ -cut.

For two subsets  $X, Y \subseteq V(G)$ , we denote by  $E_G(X, Y)$  the set of all edges  $xy \in E(G)$  for which  $x \in X$  and  $y \in Y$ . For  $k \in \mathbb{N}$ , a graph is said to be  *$k$ -edge-connected* if it has no cut on (strictly) less than  $k$  edges.

**Tree-cut decompositions.** Let  $G$  be a graph and let  $(T, \mathcal{X} = \{X_t\}_{t \in V(T)})$  be a tree-cut decomposition of  $G$ , as defined in the introduction. For any nodes  $u, v \in V(T)$ , we denote by  $uTv$  the (unique) path of  $T$  with endpoints  $u$  and  $v$ . Similarly, if  $e, f \in E(T)$ , we denote by  $eTf$  the (unique) path of  $T$  starting with  $e$  and ending with  $f$ . Notice that if  $G$  is 3-edge-connected, then every link of  $T$  has a bold adhesion. In this case the definition of the width of  $(T, \mathcal{X})$  can be simplified to

$$\max \left\{ \max_{e \in E(T)} |\text{adh}(e)|, \max_{t \in V(T)} (|X_t| + \deg_T(t)) \right\}. \quad (1)$$

---

<sup>2</sup>We refer here, for every  $k \in \mathbb{N}$ , to the immersion-minimal graphs that have tree-cut width more than  $k$ .

When a tree-cut decomposition is not lean (see [Definition 1.3](#)), this is witnessed by what we call a non-leanness certificate, defined as follows.

**Definition 2.1** (non-leanness certificate). Let  $(T, \mathcal{X})$  be a tree-cut decomposition of a graph  $G$ . A *non-leanness certificate* for  $(T, \mathcal{X})$  is a quintuple  $(k, a, b, A, B)$  where  $k \in \mathbb{N}_{\geq 1}$ ,  $a$  and  $b$  are links of  $T$  and  $A$  and  $B$  are sets of edges of  $G$  where  $A \subseteq \text{adh}(a)$ ,  $B \subseteq \text{adh}(b)$  and  $|A| = |B| = k$ , such that the following two conditions hold:

- (A) there is no collection of  $k$  edge-disjoint paths linking  $A$  to  $B$  and
- (B) every link  $e$  in  $aTb$  satisfies  $|\text{adh}(e)| \geq k$ .

A *minimal non-leanness certificate* of  $G$  is a non-leanness certificate of the form  $(k, a, b, A, B)$  (for some  $k, a, b, A, B$  as above) such that, among all non-leanness certificates of  $G$ , the value of  $k$  is minimum and, subject to that, the distance between  $a$  and  $b$  is minimum (possibly  $a = b$ ).

In [Section 3](#) we show how a non-leanness certificate can be used in order to gradually improve a tree-cut decomposition towards leanness. We now define the operation that we use for these improvement steps.

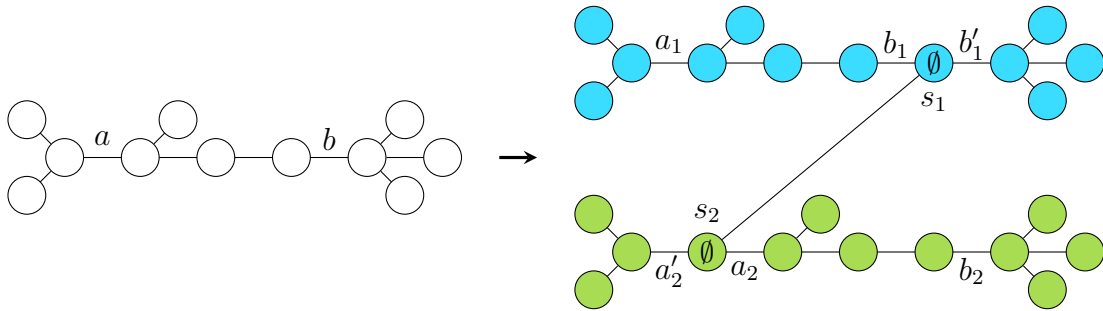


Figure 2: A tree-cut decomposition of a graph  $G$  (left) and its  $(a, b, V_1, V_2)$ -segregation (right), for some partition  $(V_1, V_2)$  of its vertex set. The vertices of  $V_1$  and  $V_2$  respectively lie in blue and green bags. Newly introduced bags, corresponding to nodes  $s_1, s_2$ , are empty. The adhesion of  $s_1 s_2$  is exactly  $E_G(V_1, V_2)$ .

**Definition 2.2** (segregation of a tree-cut decomposition). Let  $(T, \mathcal{X})$  be a tree-cut decomposition of a graph  $G$ , let  $a, b \in E(T)$ , and let  $(V_1, V_2)$  be a partition of  $V(G)$ . We define the  $(a, b, V_1, V_2)$ -segregation of  $(T, \mathcal{X})$  as the pair  $(U, \mathcal{Y})$  obtained as follows:

1. consider a first copy  $U_1$  of  $T$ , subdivide once the link corresponding to  $b$ , call  $s_1$  the subdivision node, and call the two created links  $b_1$  and  $b'_1$ , with the convention that (the copy of)  $a$  is closer to  $b_1$  in  $U_1$  (if  $a = b$ , choose arbitrarily);
2. symmetrically, consider a second copy  $U_2$  of  $T$ , subdivide once the link corresponding to  $a$ , call  $s_2$  the subdivision node, and call the two created links  $a_2$  and  $a'_2$ , with the convention that (the copy of)  $b$  is closer to  $a_2$  in  $U_2$ , or, if  $a = b$ , coherently as the previous step;

3. in the disjoint union of  $U_1$  and  $U_2$ , add a link joining  $s_1$  and  $s_2$ : this gives  $U$ ;

$$4. \text{ for every } t \in V(U), \text{ let } Y_t = \begin{cases} X_t \cap V_1 & \text{if } t \in V(T_1) \setminus \{s_1\} \\ X_t \cap V_2 & \text{if } t \in V(T_2) \setminus \{s_2\}, \text{ and} \\ \emptyset & \text{if } t \in \{s_1, s_2\}. \end{cases}$$

An example of a segregation is presented in [Figure 2](#). The following remark follows from the definition of a segregation.

*Remark 2.3.* Any segregation of a tree-cut decomposition of a graph is a tree-cut decomposition of this graph.

In order to ensure that the aforementioned improvement steps eventually lead to a lean tree-cut decomposition, we use the following notion.

**Definition 2.4** (fatness). Let  $G$  be a graph on  $m$  edges and let  $(T, \mathcal{X})$  be a tree-cut decomposition of  $G$ . For every  $i \in [m]$ , we denote by  $T^{\geq i}$  the subgraph of  $T$  induced by the links that have an adhesion of size at least  $i$ . The *fatness* of  $(T, \mathcal{X})$  is defined as the  $(2m)$ -tuple

$$(\alpha_m, -\beta_m, \alpha_{m-1}, -\beta_{m-1}, \dots, \alpha_1, -\beta_1),$$

where  $\alpha_i$  is the number of links of  $T^{\geq i}$  and  $\beta_i$  is the number of connected components of  $T^{\geq i}$ . We order fatnesses by lexicographic order.

The following is a slight variant of Menger's Theorem that we use in the next section.

**Lemma 2.5.** *Let  $G$  be a graph,  $A, B \subseteq E(G)$ , and  $k \in \mathbb{N}$ . Then either there is a set of  $k$  pairwise edge-disjoint paths of linking  $A$  and  $B$  in  $G$ , or  $G$  has an  $(A, B)$ -cut of size less than  $k$ .*

*Proof.* Suppose that there is no set of  $k$  pairwise edge-disjoint paths linking  $A$  and  $B$  in  $G$ . We create a new graph  $G'$  by subdividing every edge  $e \in A \cup B$  into a new vertex  $v_e$ . Define  $V_A = \{v_e, e \in A\}$  and symmetrically for  $V_B$ . Observe then that  $G'$  has  $k$  pairwise edge-disjoint paths linking vertex sets  $V_A$  and  $V_B$  if and only if  $G$  has  $k$  pairwise edge-disjoint paths linking edge sets  $A$  and  $B$ . So, by the edge version of Menger's Theorem,  $G'$  has an edge cut  $F'$  of size less than  $k$  separating  $V_A$  from  $V_B$ . Let  $F$  be obtained from  $F'$  by replacing every edge of the form  $v_e$  for  $e \in A \cup B$  (if any) with  $e$ . It follows that  $|F| < k$  and  $F$  separates  $A$  from  $B$  in  $G$ .  $\square$

### 3 The proof of [Theorem 1.4](#)

In order to prove [Theorem 1.4](#), we use the aforementioned notion of fatness as a potential that we aim to minimize. The strategy we follow is to show that if a tree-cut decomposition of a graph is not lean, then it can be modified into a tree-cut decomposition of smaller fatness, without increasing width ([Lemma 3.1](#)). As there is no infinite decreasing sequence of fatnesses of tree-cut decompositions of a given graph, this process will eventually result in a lean tree-cut decomposition. Starting from a tree-cut decomposition of minimum width, we will therefore obtain a lean tree-cut decomposition of the same width, as desired ([Lemma 3.15](#)).

We first focus on the case where the considered graph is 3-edge-connected, which is the crux of the proof. The reduction from the general case is given at the end of the section.



**Lemma 3.1.** *Let  $w \in \mathbb{N}$  and let  $(T, \mathcal{X})$  be a tree-cut decomposition of width  $w$  of a 3-edge connected graph  $G$ . If  $(T, \mathcal{X})$  is not lean, then  $G$  admits a tree-cut decomposition of width at most  $w$  that has smaller fatness than  $(T, \mathcal{X})$ .*

*Proof.* Every edge  $e$  of  $G$  defines two (possibly equal) nodes of  $T$ , those indexing the bags that contain its endpoints. The  $T$ -path of  $e$  is defined as the path of  $T$  linking these vertices. For every  $e \in E(G)$ , we define  $d_{a,b}(e)$  as 0 if the  $T$ -path of  $e$  shares a link with  $aTb$  and  $1+d$  otherwise, where  $d$  denotes the minimal distance between a node of  $aTb$  and a node of the  $T$ -path of  $e$ . For every set  $F \subseteq E(G)$  we set  $d_{a,b}(F) = \sum_{e \in F} d_{a,b}(e)$ .

Let us fix a minimal non-lean certificate  $(k, a, b, A, B)$  of  $(T, \mathcal{X})$ . We set  $m = |E(G)|$ . We associate to  $(k, a, b, A, B)$  an  $(A, B)$ -cut  $F$  as follows. By [Lemma 2.5](#) (the variant of Menger's theorem for edge sets), there is in  $G$  a cut of size strictly smaller than  $k$  that separates  $A$  from  $B$ . Let  $F$  be such an  $(A, B)$ -cut of minimal size that, additionally, minimizes  $d_{a,b}(F)$ . Notice that none of  $A \subseteq F$  and  $B \subseteq F$  is possible, since  $|A| = |B| = k$  and  $|F| < k$ . By the minimality of the size of  $F$ , the graph  $G - F$  has exactly two connected components. We call them  $G_A$  and  $G_B$ , with the convention that

$$A \subseteq E(G_A) \cup F \quad \text{and} \quad B \subseteq E(G_B) \cup F. \quad (2)$$

We denote by  $(U, \mathcal{Y})$  the  $(a, b, V(G_A), V(G_B))$ -segregation of  $G$ . Recall that the tree  $U$  is obtained from two copies  $U_1$  and  $U_2$  of  $T$ . For every node  $t$  of  $T$  and  $i \in [2]$ , we denote by  $t_i$  the copy of  $t$  in  $U_i$ . Similarly, for every link  $e$  of  $T$  and  $i \in [2]$ , we denote by  $e_i$  the copy of  $e$  in  $U_i$  (except for  $a$  and  $b$  where the corresponding subdivided links have already been named in the definition of a segregation). Notice that we can unambiguously use **adh** without specifying the tree-cut decomposition it refers to as  $E(U) \cap E(T) = \emptyset$ . For every link  $e \in E(U) \setminus \{a'_2, b'_1\}$ , we denote by  $\hat{e}$  the corresponding link of  $T$ , that is, the only link such that  $e \in \{\hat{e}_1, \hat{e}_2\}$ . For the special cases  $e = a'_2$  and  $e = b'_1$  we respectively set  $\hat{e} = a$  and  $\hat{e} = b$ .

In what follows we prove that  $\text{width}(U, \mathcal{Y}) \leq \text{width}(T, \mathcal{X})$  ([Sublemma 3.4](#)) and that the fatness of  $(U, \mathcal{Y})$  is (strictly) smaller than that of  $(T, \mathcal{X})$  ([Sublemma 3.14](#)). The proof is split in a series of sublemmas. The end of the proof of each sublemma is marked with a “■”. When a sublemma contains a claim, we use the symbol “◇” to mark the end of its proof. We start with a series of sublemmas related to properties of adhesions.

**Sublemma 3.2.** *For every  $e \in E(T)$  and  $i \in [2]$ ,*

$$(i) \quad |\text{adh}(e_i)| \leq |\text{adh}(e)|;$$

$$(ii) \quad |\text{adh}(a'_2)| \leq |\text{adh}(a)| \quad \text{and} \quad |\text{adh}(b'_1)| \leq |\text{adh}(b)|;$$

$$(iii) \quad \text{if } |\text{adh}(e_i)| = |\text{adh}(e)| \text{ then } \text{adh}(e_{3-i}) \subseteq F;$$

$$(iv) \quad \text{if } |\text{adh}(a_1)| = |\text{adh}(a)| \text{ then } \text{adh}(a'_2) \subseteq F \text{ and if } |\text{adh}(b_2)| = |\text{adh}(b)| \text{ then } \text{adh}(b'_1) \subseteq F.$$

*Proof of [Sublemma 3.2](#).* We assume that  $i = 1$ . The proof for the case  $i = 2$  is symmetric. Before proving the desired inequalities and inclusions, we give some definitions and prove a claim. Let  $e \in E(T)$  and let  $T_1$  and  $T_2$  be the two connected components of  $T - \{e\}$ , named as follows:



- if  $e = a = b$ , then  $T_1$ , corresponds (via the isomorphism from  $T$  to  $U_1$ ) to the connected component of  $U_1 - \{s_1\}$  that is incident with  $a_1$ , and then  $T_2$  to that that is incident with  $b'_1$  (recall that in this case, the edge  $a = b$  is replaced during the construction of  $U_1$  by the two edges  $a_1 = b_1$  and  $b'_1$ , both incident to  $s_1$ );
- otherwise, if  $e \notin E(aTb)$  or  $e \in \{a, b\}$ , we define  $T_1$  and  $T_2$  so that  $aTb$  is disjoint from  $T_1$ ;
- in the remaining case,  $e \in E(aTb) \setminus \{a, b\}$  and we choose them so that  $a \in V(T_1)$  (and then  $b \in V(T_2)$ ).

We define  $C = \bigcup_{t \in V(T_1)} X_t$  and  $D = \bigcup_{t \in V(T_2)} X_t$ .

Also, we set:

$$C_A = C \cap V(G_A), \quad D_A = D \cap V(G_A), \quad (3)$$

$$C_B = C \cap V(G_B), \quad D_B = D \cap V(G_B). \quad (4)$$

See [Figure 3](#) for an example. By the choice of  $T_1$  and  $T_2$ , every edge in  $B$  has an endpoint in  $D$ . This, together with the second statement of [\(2\)](#) ensures that:

$$\text{Every edge in } B \text{ either has an endpoint in } D_B \text{ or is an edge of } E(D_A, C_B). \quad (5)$$

Recall that  $F$  consists of all edges with one endpoint in  $C_A \cup D_A$  and the other in  $C_B \cup D_B$ . This means that:

$$F = E(C_A, C_B) \cup E(C_A, D_B) \cup E(D_A, C_B) \cup E(D_A, D_B). \quad (6)$$

Also, the edges of  $\text{adh}(e)$  are those with one endpoint in  $C$  and the other in  $D$ . This implies that:

$$\text{adh}(e) = E(C_A, D_A) \cup E(C_A, D_B) \cup E(C_B, D_A) \cup E(C_B, D_B) \quad \text{and} \quad (7)$$

$$\text{adh}(e_1) = E(C_A, D_A) \cup E(C_A, C_B) \cup E(C_A, D_B). \quad (8)$$

We now set:

$$F' = (F \setminus E(C_A, C_B)) \cup E(C_B, D_B). \quad (9)$$

**Claim 3.3.**  $F'$  is an  $(A, B)$ -cut and also an  $(E(C_A, D_A), B)$ -cut.

(The second statement will be useful when proving [\(iii\)](#).)

*Proof.* Looking for a contradiction, let us assume that there is a path  $P$  linking an edge of  $A \cup E(C_A, D_A)$  and an edge of  $B$  in  $G - F'$ . We denote by  $e_A$  and  $e_B$  the edges of  $P$  that are incident to its endpoints, with  $e_A \in A \cup E(C_A, D_A)$  and  $e_B \in B$ . From [\(5\)](#), either  $e_B$  has an endpoint in  $D_B$  or  $e_B \in E(D_A, C_B)$ . We first exclude the case where  $e_B \in E(D_A, C_B)$ . Indeed, if this is the case then, using [\(6\)](#), we obtain that  $e_B \in F \setminus E(C_A, C_B) \subseteq F'$  a contradiction. We conclude that  $e_B$  has an endpoint, say  $y$ , where  $y \in D_B$ .

As  $P$  links an edge of  $F \cup E(G_A)$  to an edge of  $F \cup E(G_B)$ ,  $P$  contains at least one edge of  $F$ . Since  $P$  does not contain edges of  $F'$ , we deduce that this edge belongs to  $E(C_A, C_B)$ .

Among all edges of  $P$  that belong to  $E(C_A, C_B)$  let  $g$  be the one that is closer to  $e_B$  in  $P$  and let  $x_g$  be the endpoint of  $g$  that belongs to  $C_B$ . By the choice of  $g$ , we know that the subpath  $P'$  of  $P$  that is between  $x_g$  and  $y$  is a subgraph of  $G_B$ . As  $x_g \in C_B$  and  $y \in D_B$ , we have that  $P'$  (and therefore  $P$  as well) contains an edge  $f \in E(C_B, D_B)$ . However  $E(C_B, D_B) \subseteq F'$ , a contradiction. Therefore  $F'$  is indeed an  $(A, B)$ -cut and a  $(E(C_A, D_A), B)$ -cut. The claim follows.  $\diamond$

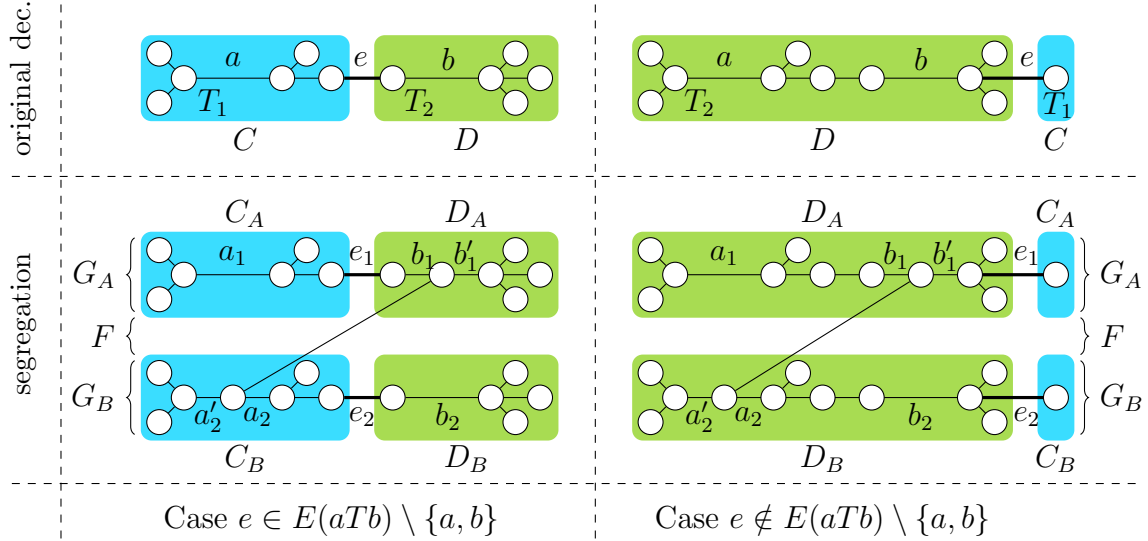


Figure 3: The sets  $C$ ,  $D$ ,  $C_A$ ,  $D_A$ ,  $C_B$ , and  $D_B$  in the original decomposition and in the segregation considered in the proof of [Sublemma 3.2](#), depending on the position of  $e$ . Note that  $e$  could also be an edge of  $E(T) \setminus E(aTb)$  such that its closest vertex on  $aTb$  is an internal vertex.

Now we prove (i)–(iv).

*Proof of (i).* Assume for contradiction that  $|\text{adh}(e_1)| > |\text{adh}(e)|$ . Comparing (7) with (8), we get  $|E(C_A, C_B)| > |E(C_B, D_A)| + |E(C_B, D_B)|$  which implies:

$$|E(C_A, C_B)| > |E(C_B, D_B)|. \quad (10)$$

In particular  $E(C_A, C_B)$  is non-empty. From (6),  $E(C_A, C_B) \subseteq F$ . Using (10) and the definition of  $F'$  in (9), we deduce that  $|F'| < |F|$ , a contradiction to the minimality of  $|F|$ . This proves (i).

*Proof of (ii).* The proof is identical to the proof of (i), using  $e = a$ ,  $i = 2$ ,  $e_2 = a'_2$  (resp.  $e = b$ ,  $i = 1$ ,  $e_1 = b'_1$ ) to get the first (resp. second) inequality.

*Proof of (iii).* Let us assume that  $|\text{adh}(e_1)| = |\text{adh}(e)|$  (the case where  $|\text{adh}(e_2)| = |\text{adh}(e)|$  is symmetric). As we assume  $|\text{adh}(e_1)| = |\text{adh}(e)|$ , using (7) and (8), we get

$$|E(C_A, C_B)| \geq |E(C_B, D_B)|, \quad (11)$$

Considering  $F'$  as defined in (9), we deduce from (11) that  $|F'| \leq |F|$ , which we will use later. Towards a contradiction with (iii), let us assume that  $\text{adh}(e_2) \not\subseteq F$  or, equivalently, that  $|\text{adh}(e_2) \setminus F| > 0$ . We consider two different cases.

*First case:*  $e \notin E(aTb)$  or  $e \in \{a, b\}$ . We notice the following equality:

$$\text{adh}(e_2) = E(C_A, C_B) \cup E(C_B, D_A) \cup E(C_B, D_B). \quad (12)$$

Eq. (12) together with (6), implies that  $\text{adh}(e_2) \setminus F = E(C_B, D_B)$  and we deduce  $|E(C_B, D_B)| > 0$ . With (11) this implies that  $E(C_A, C_B)$  is non-empty. Also, from **Claim 3.3** we have that  $F'$  is an  $(A, B)$ -cut and we proved above that it is not larger than  $F$ . Notice that the  $T$ -path of any edge of  $E(C_B, D_B)$  contains  $e$ . On the other hand,

- when  $e \in \{a, b\}$ , no  $T$ -path of an edge of  $E(C_A, C_B)$  does contain  $e$ , and
- when  $e \notin E(aTb)$ , no  $T$ -path of an edge of  $E(C_A, C_B)$  does contain the endpoint  $t_e$  of  $e$  that is the closest to a node of  $aTb$ .

Therefore, for every  $f \in E(C_A, C_B)$  and  $f' \in E(C_B, D_B)$ ,

- either  $e \in \{a, b\}$ , then  $d_{a,b}(f') = 0$  (because the  $T$ -path of  $f'$  contains an edge of  $aTb$ , which is  $e$ ) and  $d_{a,b}(f) > 0$  (for the opposite reason);
- or  $e \notin E(aTb)$ , then  $d_{a,b}(f') \leq \text{dist}_T(V(aTb), t_e)$  (because the  $T$ -path of  $f'$  contains  $t_e$ ) and  $d_{a,b}(f) \geq \text{dist}_T(V(aTb), t_e) + 1$  (for the opposite reason, and by definition of  $t_e$ ).

In both cases we have  $d_{a,b}(f') < d_{a,b}(f)$ . The fact that  $E(C_A, C_B)$  is non-empty, together with (11), imply that  $d_{a,b}(E(C_A, C_B)) > d_{a,b}(E(C_B, D_B)) \geq 0$ , hence  $d_{a,b}(F') < d_{a,b}(F)$ . This contradicts the choice of  $F$ , thus this case is not possible.

*Second case:*  $e \in E(aTb) \setminus \{a, b\}$ . Recall (**Claim 3.3**) that  $F'$  is a  $(E(C_A, D_A), B)$ -cut. Notice that because of (6) and (9), it follows that  $\text{adh}(e) \setminus F' = E(C_A, D_A)$ . We deduce that  $F'$ , in fact, a  $(\text{adh}(e), B)$ -cut.

We choose a subset  $F''$  of  $\text{adh}(e)$  such that  $|F''| = k$ . (Because  $e \in aTb$  and of the definition of  $a, b$ ,  $|\text{adh}(e)| \geq k$  and such a subset always exists.) We claim that the quintuple  $(k, e, b, F'', B)$  satisfies conditions (A) and (B) of **Definition 2.1** (non-leanness certificate). Since  $eTb$  is a subpath of  $aTb$ , we have  $|\text{adh}(e')| \geq k$  for every  $e' \in E(eTb)$  and thus Condition (B) holds. For Condition (A) observe that  $F'$  separates  $\text{adh}(e)$  from  $B$  and  $|F'| \leq |F| < k$ , therefore there are no  $k$  edge-disjoint paths linking  $\text{adh}(e)$  to  $B$ .

Besides Conditions (A) and (B),  $e \in E(aTb) \setminus \{a, b\}$ , and therefore  $eTb$  is shorter than  $aTb$ . This contradicts the minimality of the distance between  $a$  and  $b$  that we assumed. Therefore, this case is not possible either and we have in both cases that  $\text{adh}(e_2) \subseteq F$ .

*Proof of (iv).* The proof follows the very same steps as the proof of (iii) (first case) using  $e = a$ ,  $i = 1$ ,  $e_2 = a'_2$  (resp.  $e = b$ ,  $i = 2$ ,  $e_1 = b'_1$ ).  $\blacksquare$

We can now complete the first goal of this proof.

**Sublemma 3.4.**  $\text{width}(U, \mathcal{Y}) \leq \text{width}(T, \mathcal{X})$

*Proof.* From Sublemma 3.2.(i) and Sublemma 3.2.(ii) we obtain that

$$\max_{g \in E(U)} |\mathbf{adh}(g)| \leq \max_{g \in E(T)} |\mathbf{adh}(g)|.$$

By definition of a segregation, for every  $i \in [2]$  and  $t \in V(T)$ , we have  $Y_{t_i} \subseteq X_t$  and  $\deg_U(t_i) = \deg_T(t)$ , hence  $|X_t| + \deg_T(t) \geq |Y_{t_i}| + \deg_U(t_i)$ . For  $i \in [2]$  we also have  $Y_{s_i} = \emptyset$ , and  $\deg_U(s_i) = 3$ . As  $G$  is 3-edge-connected and  $\mathbf{adh}(a)$  is not empty,  $|\mathbf{adh}(a)| \geq 3$  so in particular,  $|\mathbf{adh}(a)| \geq |Y_{s_i}| + \deg_U(s_i)$ . Using the simplified definition of width for tree-cut decompositions of 3-edge-connected graphs (1), we conclude that  $\mathbf{width}(U, \mathcal{Y}) \leq \mathbf{width}(T, \mathcal{X})$ .  $\blacksquare$

In the rest of the proof we focus on the second goal, i.e. showing that the fatness of  $(U, \mathcal{Y})$  is smaller than that of  $(T, \mathcal{X})$ . Let  $(\alpha_m, -\beta_m, \alpha_{m-1}, -\beta_{m-1}, \dots, \alpha_1, -\beta_1)$  be the fatness of  $(T, \mathcal{X})$  and let  $(\alpha'_m, -\beta'_m, \alpha'_{m-1}, -\beta'_{m-1}, \dots, \alpha'_1, -\beta'_1)$  be that of  $(U, \mathcal{Y})$ , as defined in Definition 2.4 (recall that  $m = |E(G)|$ ).

**Sublemma 3.5.** *For every  $e \in E(T)$ ,*

- *either  $|\mathbf{adh}(e)| > |\mathbf{adh}(e_1)|$  and  $|\mathbf{adh}(e)| > |\mathbf{adh}(e_2)|$ ;*
- *or there is some  $i \in [2]$  such that  $|\mathbf{adh}(e)| = |\mathbf{adh}(e_i)|$  and  $\mathbf{adh}(e_{3-i}) \subseteq F$ .*

*Proof of Sublemma 3.5.* This sublemma is a direct corollary of Sublemma 3.2.(i) and Sublemma 3.2.(iii).  $\blacksquare$

**Sublemma 3.6.**  *$A \subseteq \mathbf{adh}(a_1) \cup F$  and  $B \subseteq \mathbf{adh}(b_2) \cup F$ .*

*Proof of Sublemma 3.6.* We only prove the first statement as the proof of the second one is symmetric. We define  $C_A, C_B, D_A$ , and  $D_B$  as in (3) and (4) in the proof of Sublemma 3.2 for the case where  $e = a$ . Under this setting, (6), (7), and (8) are still valid; we restate them below for clarity.

$$F = E(C_A, C_B) \cup E(C_A, D_B) \cup E(D_A, C_B) \cup E(D_A, D_B), \quad (13)$$

$$\mathbf{adh}(a_1) = E(C_A, D_A) \cup E(C_A, C_B) \cup E(C_A, D_B), \text{ and} \quad (14)$$

$$\mathbf{adh}(a) = E(C_A, D_A) \cup E(C_A, D_B) \cup E(C_B, D_A) \cup E(C_B, D_B). \quad (15)$$

Recall that  $A \subseteq E(G_A) \cup F$  (see (2)). Also, from (4), we obtain that  $E(C_B, D_B) \subseteq E(G_B)$ . These two relations imply that  $A \cap E(C_B, D_B) = \emptyset$ . Combining this last relation with (15), we get:

$$A \subseteq E(C_A, D_A) \cup E(C_A, D_B) \cup E(C_B, D_A). \quad (16)$$

As each of the terms of the right side of (16) appears on the right side of either (13) or (14), we conclude that  $A \subseteq F \cup \mathbf{adh}(a_1)$  as required.  $\blacksquare$

Given an integer  $p$ , we say that a link  $e \in E(T)$  is *p-excessive* if

$$|\mathbf{adh}(e)| \geq p, \quad |\mathbf{adh}(e)| > |\mathbf{adh}(e_1)|, \quad \text{and} \quad |\mathbf{adh}(e)| > |\mathbf{adh}(e_2)|. \quad (17)$$

**Sublemma 3.7.** *Let  $l$  be an integer such that  $l \geq k$  and none of the links of  $T$  of adhesion more than  $l$  is  $k$ -excessive. Then*

(i)  $\alpha'_l \leq \alpha_l$  and  $\beta'_l \geq \beta_l$ , and

(ii) for every  $j \in [l+1, m]$ ,  $\alpha'_j = \alpha_j$  and  $\beta'_j \geq \beta_j$ .

*Proof of Sublemma 3.7.* Let  $j \in [l, m]$ . Recall that we denote by  $U^{\geq j}$  the subgraph of  $U$  induced by links that have an adhesion of size at least  $j$ . We need first the following claim:

**Claim 3.8.** *If  $f$  is a link of  $T$  such that  $f_i$  belongs to  $U^{\geq j}$  for some  $i \in [2]$ , then  $|\text{adh}(f)| = |\text{adh}(f_i)|$  and  $\text{adh}(f_{3-i}) \subseteq F$ .*

*Proof.* We first prove that it is not possible that  $|\text{adh}(f)| > |\text{adh}(f_1)|$  and  $|\text{adh}(f)| > |\text{adh}(f_2)|$ . Towards a contradiction, let us suppose that it holds. If  $|\text{adh}(f)| > l$ , then  $f$  is a  $k$ -excessive link of adhesion greater than  $l$ , a contradiction to the hypothesis of the lemma. If  $|\text{adh}(f)| \leq l$ , then for every  $i \in [2]$  we have  $|\text{adh}(f_i)| < l \leq j$ , hence  $f_i \notin E(U^{\geq j})$ , a contradiction. By **Sublemma 3.5**, there is some  $i' \in [2]$  such that  $|\text{adh}(f)| = |\text{adh}(f_{i'})|$  and  $\text{adh}(f_{3-i'}) \subseteq F$ . As  $|\text{adh}(f_{3-i'})| \leq |F| < k \leq j \leq |\text{adh}(f_i)|$ , we have that  $i = i'$ , and therefore  $|\text{adh}(f)| = |\text{adh}(f_i)|$  and  $\text{adh}(f_{3-i}) \subseteq F$ , as desired.  $\diamond$

Let  $f \in E(T)$ . From the above claim we have the following:

$$\text{If } f_i \in E(U^{\geq j}) \text{ for some } i \in [2], \text{ then } f \in E(T^{\geq j}) \text{ and } f_{3-i} \notin E(U^{\geq j}). \quad (18)$$

We next claim that if  $f \in \{a, b\}$  and  $f_i$  belongs to  $U^{\geq j}$  for some  $i \in [2]$ , then  $i = 1$  in case  $f = a$  and  $i = 2$  in case  $f = b$ . We present the proof of this claim for the case where  $f = a$  (the case  $f = b$  is symmetric). Assume to the contrary that  $i = 2$ . Then, from the above claim,  $\text{adh}(a_1) \subseteq F$ . Recall that  $A \subseteq \text{adh}(a_1) \cup F$ , according to **Sublemma 3.6**. We conclude that  $A \subseteq F$ , a contradiction as  $|A| = k$  and  $|F| < k$ . Thus, the claim holds.

By **Claim 3.8**, if  $a_1 \in E(U^{\geq j})$  then  $|\text{adh}(a_1)| = |\text{adh}(a)|$  and  $|\text{adh}(a_2)| \leq |F| < k \leq j$ . Therefore  $a \in E(T^{\geq j})$  and  $a_2 \notin E(U^{\geq j})$ . Moreover, the fact that  $|\text{adh}(a_1)| = |\text{adh}(a)|$  together with the first statement of **Sublemma 3.2(iv)** implies that  $\text{adh}(a'_2) \subseteq F$ . This implies that  $|\text{adh}(a'_2)| \leq |F| < k \leq j$ , therefore  $a'_2 \notin E(U^{\geq j})$ . We resume these observations, along with the symmetric observations for the case where  $b_2 \in E(U^{\geq j})$ , to the following statements:

$$\text{If } a_1 \in E(U^{\geq j}), \text{ then } a \in E(T^{\geq j}), a_2 \notin E(U^{\geq j}), \text{ and } a'_2 \notin E(U^{\geq j}). \quad (19)$$

$$\text{If } b_2 \in E(U^{\geq j}), \text{ then } b \in E(T^{\geq j}), b_1 \notin E(U^{\geq j}), \text{ and } b'_1 \notin E(U^{\geq j}). \quad (20)$$

Let  $j \in [l, m]$  and let us define now the function  $\varphi: E(U^{\geq j}) \rightarrow E(T^{\geq j})$  so that  $\varphi(e) = \hat{e}$  for every  $e \in E(U^{\geq j})$ . (Recall that  $\hat{e}$  is the edge of  $T$  from which  $e$  has been copied, see the paragraph following (2) for the definition.) According to (18), (19), and (20), the function  $\varphi$  is injective. Hence  $|E(U^{\geq j})| \leq |E(T^{\geq j})|$ , i.e.,  $\alpha'_j \leq \alpha_j$ . This proves the first half of (i).

When  $j \in [l+1, m]$ , the function  $\varphi$  is even surjective: by definition of  $l$ , every link  $f \in E(T^{\geq j})$  satisfies  $|\text{adh}(f)| = |\text{adh}(f_i)|$  for some  $i \in [2]$ , therefore  $f_i \in U^{\geq j}$  is the preimage of  $f$  by  $\varphi$ . As a consequence, for every  $j \in [l+1, m]$ , we have  $|E(U^{\geq j})| = |E(T^{\geq j})|$ , that is,  $\alpha'_j = \alpha_j$  and the first part of (ii) holds.

We now deal with the second parts of (i) and (ii). Let  $j \in [l, m]$ ; we will prove that  $\beta'_j \geq \beta_j$ . Recall that  $s_1s_2$  is the link joining the nodes  $s_1$  and  $s_2$  in  $U$  and  $\text{adh}(s_1s_2) = F$ . As  $|F| < k \leq l \leq j$ , we have that  $s_1s_2 \notin E(U^{\geq j})$ . This means that none of the connected components of  $U^{\geq j}$  contains  $s_1s_2$ . Let  $Q$  be a connected component of  $U^{\geq j}$ . Then, from (18), for every  $f \in E(Q)$  it holds that  $\hat{f} \in E(T^{\geq j})$ . Therefore, if  $Q$  is a connected component of  $U^{\geq j}$ , then the subgraph  $T_Q$  of  $T$  with link set  $\{\hat{f} : f \in E(Q)\}$  is a (connected) subtree of  $T^{\geq j}$ . Let  $\psi$  be the function that maps every connected component  $C$  of  $U^{\geq j}$  to the connected component of  $T^{\geq j}$  that contains the subgraph  $T_Q$ , defined as above. Recall that by definition of  $l$ , if  $f$  is a link of  $T^{\geq j}$  then  $f$  is not  $k$ -excessive and, thus,  $f_i$  is a link in  $U^{\geq j}$ , for some  $i \in [2]$ . Therefore, the connected component of  $T^{\geq j}$  containing  $f$  is the image by  $\psi$  of the connected component of  $U^{\geq j}$  containing  $f_i$ . This proves that  $\psi$  is surjective. The forest  $U^{\geq j}$  then has at least as many connected components as  $T^{\geq j}$  or, in other words,  $\beta'_j \geq \beta_j$ . This proves the second part of (ii) and concludes the proof.  $\blacksquare$

**Sublemma 3.9.** *If  $T$  has a  $k$ -excessive link, then there is an integer  $l \geq k$  such that*

(i)  $\alpha'_l < \alpha_l$  and

(ii) for every  $j \in [l + 1, m]$ ,  $\alpha'_j = \alpha_j$  and  $\beta'_j \geq \beta_j$ .

*Proof of Sublemma 3.9.* Let  $g$  be an  $k$ -excessive link of maximum adhesion and let  $l = |\text{adh}(g)|$ . By definition of  $k$ -excessive (see (17)), we have  $l \geq k$ . By the choice of  $g$ , the integer  $l$  satisfies the requirements of Sublemma 3.7. Item (ii) then directly follows. Let us consider the same function  $\varphi$  as in the proof of Sublemma 3.7 (i.e., we set  $\varphi(e) = \hat{e}$ ). By definition of  $g$ , we have  $g \in E(T^{\geq l})$  whereas  $g_1, g_2 \notin E(U^{\geq l})$ . Therefore  $g$  has no preimage in  $E(T^{\geq l})$  by  $\varphi$ : this function is not surjective. Thus,  $|E(U^{\geq l})| < |E(T^{\geq l})|$ , or, equivalently,  $\alpha'_l < \alpha_l$ .  $\blacksquare$

**Sublemma 3.10.** *If  $a$  and  $b$  are distinct and not incident in  $T$ , then  $aTb$  has at least one  $k$ -excessive link.*

*Proof of Sublemma 3.10.* Towards a contradiction, let us assume the opposite statement: for every link  $e \in E(aTb)$ , (at least) one of the following holds:  $|\text{adh}(e)| \leq |\text{adh}(e_1)|$  or  $|\text{adh}(e)| \leq |\text{adh}(e_2)|$  (the case where  $|\text{adh}(e)| < k$  is excluded because  $e \in E(aTb)$  and Condition (B) holds). Our aim is to find a non-leanness certificate for  $(T, \mathcal{X})$  that contradicts the minimality of  $(k, a, b, A, B)$ .

Let  $e \in E(aTb)$  and  $i \in [2]$  such that  $|\text{adh}(e)| \leq |\text{adh}(e_i)|$ . By Sublemma 3.2.(i)-(iii), we in fact have  $|\text{adh}(e)| = |\text{adh}(e_i)|$  and  $\text{adh}(e_{3-i}) \subseteq F$ . In particular  $|\text{adh}(e_{3-i})| < |\text{adh}(e)|$ , because  $|\text{adh}(e)| \geq k$ , as noted above, while  $|F| < k$ . We deduce:

$$\forall e \in E(aTb), \exists i \in [2], \begin{cases} |\text{adh}(e_i)| = |\text{adh}(e)| \text{ and} \\ |\text{adh}(e_{3-i})| < |\text{adh}(e)|. \end{cases} \quad (21)$$

For the case where  $e = a$  in (21), we claim that  $i = 1$ , i.e.

$$|\text{adh}(a_1)| = |\text{adh}(a)| \quad \text{and} \quad |\text{adh}(a_2)| < |\text{adh}(a)|. \quad (22)$$

If this claim was not correct, then we would have  $|\text{adh}(a_2)| = |\text{adh}(a)|$  and by applying Sublemma 3.2.(iii) for  $e = a$  we would get  $\text{adh}(a_1) \subseteq F$ . Together with  $A \subseteq \text{adh}(a_1) \cup F$  (from [Sublemma 3.6](#)), this would imply  $A \subseteq F$ . Hence  $k = |A| \leq |F| < k$ , a contradiction.

By replacing  $a, A, a_1$  by  $b, B, b_2$  in the argument above, we can similarly show

$$|\text{adh}(b_1)| < |\text{adh}(b)| \quad \text{and} \quad |\text{adh}(b_2)| = |\text{adh}(b)|. \quad (23)$$

**Claim 3.11.** *There are two incident links  $e, f \in E(aTb)$  and  $i \in [2]$  such that*

1.  $\{e, f\} \neq \{a, b\}$ ,
2.  $e \in E(aTf)$ , and
3.  $|\text{adh}(e)| = |\text{adh}(e_1)|$  and  $|\text{adh}(f)| = |\text{adh}(f_2)|$ .

*Proof.* Let us color in blue every edge  $e$  of  $aTb$  such that  $|\text{adh}(e)| = |\text{adh}(e_1)|$  and in red every edge such that  $|\text{adh}(e)| = |\text{adh}(e_2)|$ . By the virtue of (21), every edge receives exactly one color. By (22) and (23),  $a$  is colored blue and  $b$  is colored red. Let  $f$  be the first red edge met when following  $aTb$  from  $a$  and let  $e$  be the edge met just before. This choice ensures the two last desired properties. We assumed that  $a$  and  $b$  are not incident, so  $\{e, f\} \neq \{a, b\}$ .  $\diamond$

**Claim 3.12.** *Let  $e, f \in E(T)$  be links satisfying the conditions of [Claim 3.11](#). Then  $F$  separates  $\text{adh}(e)$  from  $\text{adh}(f)$ .*

*Proof.* The third condition of [Claim 3.11](#) along with Sublemma 3.2.(iii), implies that

$$\text{adh}(e_2) \subseteq F \quad \text{and} \quad \text{adh}(f_1) \subseteq F. \quad (24)$$

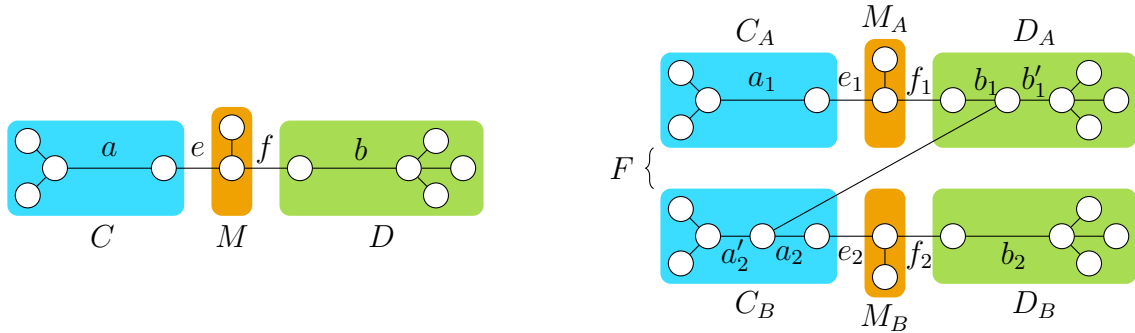


Figure 4: The sets  $C, D, C_A, M_A, D_A, C_B, M_B,$  and  $D_B$  in the original decomposition (left) and in the segregation that we consider in the proof of [Claim 3.12](#) (right).

Let us call  $T_C, T_M$  and  $T_D$  the connected components of  $T - \{e, f\}$  that contain, respectively, one endpoint of  $e$  and none of  $f$ , both one endpoint of  $e$  one of  $f$ , and one endpoint of  $f$  but none of  $e$ . As in the proof of [Sublemma 3.2](#), we set  $C = \bigcup_{t \in V(T_C)} X_t$ ,  $M = \bigcup_{t \in V(T_M)} X_t$ , and  $D = \bigcup_{t \in V(T_D)} X_t$ , and for every  $i \in [2]$  we define

$$\begin{aligned} C_A &= C \cap V(G_A) & M_A &= M \cap V(G_A) & D_A &= D \cap V(G_A). \\ C_B &= C \cap V(G_B) & M_B &= M \cap V(G_B) & D_B &= D \cap V(G_B). \end{aligned}$$



These sets are depicted in [Figure 4](#) on an example of a tree-cut decomposition. Notice that  $F$  contains all edges that have the one endpoint in  $C_A \cup M_A \cup D_A$  and the other in  $C_B \cup M_B \cup D_B$ . In other words:

$$F = E(C_A, C_B) \cup E(C_A, M_B \cup D_B) \cup E(C_B, M_A \cup D_A) \cup E(M_A \cup D_A, M_B \cup D_B), \quad (25)$$

$$F = E(D_A, D_B) \cup E(D_A, M_B \cup C_B) \cup E(D_B, M_A \cup C_A) \cup E(M_A \cup C_A, M_B \cup C_B). \quad (26)$$

On the other hand, we have

$$E(C_B, M_B \cup D_B) \subseteq \text{adh}(e_2), \quad (27)$$

$$E(D_A, M_A \cup C_A) \subseteq \text{adh}(f_1), \quad (28)$$

and

$$\begin{aligned} \text{adh}(e) = & E(C_A, M_A \cup D_A) \cup E(C_A, M_B \cup D_B) \\ & \cup E(C_B, M_A \cup D_A) \cup E(C_B, M_B \cup D_B), \end{aligned} \quad (29)$$

$$\begin{aligned} \text{adh}(f) = & E(D_A, M_A \cup C_A) \cup E(D_A, M_B \cup C_B) \\ & \cup E(D_B, M_A \cup C_A) \cup E(D_B, M_B \cup C_B). \end{aligned} \quad (30)$$

From [\(27\)](#), [\(28\)](#), and [\(24\)](#) we have

$$E(C_B, M_B \cup D_B) \subseteq F, \quad (31)$$

$$E(D_A, M_A \cup C_A) \subseteq F. \quad (32)$$

Using [\(25\)](#), [\(29\)](#), and [\(31\)](#) and also [\(26\)](#), [\(30\)](#) and [\(32\)](#), we deduce:

$$\text{adh}(e) \setminus F = E(C_A, M_A \cup D_A), \quad \text{and} \quad (33)$$

$$\text{adh}(f) \setminus F = E(D_B, M_B \cup C_B). \quad (34)$$

In order to prove that  $F$  separates  $\text{adh}(e)$  from  $\text{adh}(f)$ , let  $P$  be a path in  $G$  connecting an edge of  $\text{adh}(e)$  and an edge of  $\text{adh}(f)$ . If this path contains an edge of  $F$ , then we are done. Otherwise, from [\(33\)](#) and [\(34\)](#),  $P$  should be a path from an edge from  $E(C_A, M_A \cup D_A) \subseteq E(G_A)$  to an edge from  $E(D_B, M_B \cup C_B) \subseteq E(G_B)$ . Clearly, this path will have an edge in  $F$  and the claim follows.  $\diamond$

Let  $e, f \in E(T)$  be links satisfying the conditions of [Claim 3.11](#). We now claim that the quintuple  $(k, e, f, \text{adh}(e), \text{adh}(f))$  is a non-leanness certificate for  $(T, \mathcal{X})$ . Condition [\(A\)](#) follows as, from [Claim 3.12](#),  $F$  separates  $\text{adh}(e)$  from  $\text{adh}(f)$ . Condition [\(B\)](#) holds because  $eTf$  is a subpath of  $aTb$ . Notice now that  $e$  and  $f$  are incident while  $a$  and  $b$  are not. Therefore, the distance between  $e$  and  $f$  in  $T$  is smaller than that between  $a$  and  $b$ . This contradicts the minimality of the choice of  $(k, a, b, A, B)$  as a minimal non-leanness certificate for  $(T, \mathcal{X})$ . [Sublemma 3.10](#) follows.  $\blacksquare$

**Sublemma 3.13.** *If  $T$  does not contain any  $k$ -excessive link, then there is an integer  $l \geq k$  such that*

- for every  $j \in [l + 1, m]$ ,  $\alpha'_j = \alpha_j$  and  $\beta'_j \geq \beta_j$ , while

- $\alpha'_i \leq \alpha_i$  and  $\beta'_i > \beta_i$ .

*Proof of Sublemma 3.13.* Let us assume that  $T$  has no  $k$ -excessive link. By Sublemma 3.10,  $a$  and  $b$  are either incident edges, or they are the same edge. We set  $l = \min\{|\text{adh}(a)|, |\text{adh}(b)|\}$  and observe that  $l \geq k$ . Clearly,  $l$  satisfies the requirements of Sublemma 3.7, so we have  $\alpha'_j = \alpha_j$  and  $\beta'_j \geq \beta_j$  for every  $j \in [l+1, m]$  and  $\alpha'_i \leq \alpha_i$ . Let  $\psi$  be the function that maps connected components of  $U^{\geq l}$  to connected components of  $T^{\geq l}$ , as defined in the proof of Sublemma 3.7 (for  $j = l$ ), where it is shown to be surjective.

As  $a$  is not  $k$ -excessive, the first statement of Sublemma 3.5 does not hold for  $e = a$ . We conclude that for some  $i \in [2]$ ,  $|\text{adh}(a)| = |\text{adh}(a_i)|$  and  $\text{adh}(a_{3-i}) \subseteq F$ . The case  $i = 2$  is not possible because then  $\text{adh}(a_1) \subseteq F$  which, together with  $A \subseteq \text{adh}(a_1) \cup F$  from Sublemma 3.6, implies  $k \leq |\text{adh}(a_1)| \leq |F| < k$ , a contradiction. Hence  $i = 1$  and we have that  $|\text{adh}(a)| = |\text{adh}(a_1)|$ . By definition  $l \leq |\text{adh}(a)|$ , hence  $a_1$  belongs to  $U^{\geq l}$ . Symmetrically, we can show that  $b_2$  belongs to  $U^{\geq l}$ .

From the definition of  $l$ , both  $a$  and  $b$  belong to  $T^{\geq l}$ . As they are incident or equal we get that they belong to the same connected component of this graph. Besides, as noted above, both  $a_1$  and  $b_2$  belong to  $U^{\geq l}$ . However these links are separated in  $U$  by the link  $s_1s_2$ , which has adhesion  $|F| < k \leq l$ . (Recall that  $s_1s_2$  is the link added in the construction of  $U$  to join the two copies  $U_1$  and  $U_2$  of  $T$ ; see Definition 2.2 for a reminder.) Therefore,  $a_1$  and  $b_2$  do not belong to the same connected component of  $U^{\geq l}$ . This proves that  $\psi$  is not injective:  $U^{\geq l}$  has more connected components than  $T^{\geq l}$ . Therefore,  $\beta'_i > \beta_i$ . ■

We are now in position to conclude the proof of Lemma 3.1.

**Sublemma 3.14.** *The fatness of  $(U, \mathcal{Y})$  is smaller than that of  $(T, \mathcal{X})$ .*

*Proof.* Recall that we respectively denote by

$$(\alpha_m, -\beta_m, \alpha_{m-1}, -\beta_{m-1}, \dots, \alpha_1, -\beta_1) \quad \text{and} \quad (\alpha'_m, -\beta'_m, \alpha'_{m-1}, -\beta'_{m-1}, \dots, \alpha'_1, -\beta'_1)$$

the fatnesses of  $(T, \mathcal{X})$  and  $(U, \mathcal{Y})$ . Notice that if the assumption of Sublemma 3.9 or of Sublemma 3.13 holds, then the fatness of  $(U, \mathcal{Y})$  is (strictly) smaller than that of  $(T, \mathcal{X})$ . As the assumptions of Sublemma 3.9 and Sublemma 3.13 are complementary, we are done. □

Sublemmas 3.4 and 3.14 show that  $(U, \mathcal{Y})$  has the desired properties, so we are done. □

**Lemma 3.15.** *Every 3-edge connected graph  $G$  has a lean tree-cut decomposition of width  $\text{tcw}(G)$ .*

*Proof.* Recall that we order fatnesses by lexicographic order. The lemma follows from Lemma 3.1 and the fact that the set of fatnesses of tree-cut decompositions of a given graph does not contain an infinite decreasing sequence. □

Based on Lemma 3.15, we are now ready to give the proof of Theorem 1.4. The proof is essentially a reduction of the general case to that of 3-edge-connected graphs, that is handled by Lemma 3.15.

*Proof of Theorem 1.4.* For every  $w \in \mathbb{N}$ , we show that every graph  $G$  such that  $\mathbf{tcw}(G) \leq w$  has a tree-cut decomposition of width at most  $w$  that is lean, by induction on the number of vertices of  $G$ .

Let  $w \in \mathbb{N}$  and let  $G$  be a graph of tree-cut width at most  $w$ . If  $|V(G)| \leq w$ , then the tree-cut decomposition  $((\{t\}, \emptyset), \{V(G)\})$  has width at most  $w$  and is trivially lean. Suppose now that  $|V(G)| > w$  and that the statement holds for all graphs with less vertices than  $G$  (induction hypothesis).

Let  $F$  be a cut of  $G$  of minimum order and let  $\{V_1, V_2\}$  be the corresponding partition of  $V(G)$ . (As we allow multiedges, it is possible that the edges in  $F$  share both endpoints.) If  $|F| > 2$  then  $G$  is 3-edge-connected and the result follows because of [Lemma 3.15](#). Suppose now that  $|F| \leq 2$ . For every  $i \in [2]$  we define  $G_i$  as follows. If  $|F| = 2$  and the endpoints of  $F$  in  $V_i$  are distinct, we denote by  $G_i$  the graph obtained from  $G[V_i]$  by adding an edge between these endpoints (or increasing the multiplicity by one if the edge already exists). In all the other cases, we set  $G_i = G[V_i]$ . Notice that  $G_1$  and  $G_2$  are both immersions of  $G$ , hence they have tree-cut-width at most  $w$ . Also, they have less vertices than  $G$ , so we can apply our induction hypothesis.

For every  $i \in [2]$ , let  $(T^i, \mathcal{X}^i)$  be a tree-cut decomposition of width  $\mathbf{tcw}(G_i) \leq w$  of  $G_i$ , that is lean. Let  $x_i$  be an endpoint of  $F$  in  $V_i$  or, in the case  $F = \emptyset$ , any vertex of  $V_i$ . Let  $t_i$  be the node of  $T^i$  such that  $x_i \in X_{t_i}^i$ . We define  $T$  as the tree obtained from the disjoint union of  $T^1$  and  $T^2$  by adding the link  $t_1 t_2$ . We also set  $\mathcal{X} = \mathcal{X}^1 \cup \mathcal{X}^2$ . Clearly  $(T, \mathcal{X})$  is a tree-cut decomposition of  $G$ . Notice that the adhesion of  $t_1 t_2$  is  $F$  whose size is at most 2, hence it is not bold. Also, for every  $i \in [2]$  and  $e \in T^i$ , if  $\mathbf{adh}_{T^i}(e)$  contains the edge added in the construction of  $G_i$  (if any), then  $\mathbf{adh}_T(e)$  contains instead one of the edges of  $F$ . Hence the size of the adhesion of  $e$  does not change from  $T^i$  to  $T$ . We can therefore express the width of  $(T, \mathcal{X})$  in terms of  $(T^i, \mathcal{X}^i)$  and  $F$ :

$$\begin{aligned} \mathbf{width}(T, \mathcal{X}) &= \max \left\{ \max_{e \in E(T)} |\mathbf{adh}_{(T, \mathcal{X})}(e)|, \max_{t \in V(T)} (|X_t| + |\{t' \in N_T(t), \mathbf{adh}_{(T, \mathcal{X})}(tt') \text{ is bold}\}|) \right\} \\ &= \max \left\{ \max_{e \in E(T^1)} |\mathbf{adh}_{(T^1, \mathcal{X}^1)}(e)|, \max_{e \in E(T^2)} |\mathbf{adh}_{(T^2, \mathcal{X}^2)}(e)|, |F|, \right. \\ &\quad \max_{t \in V(T^1)} (|X_t| + |\{t' \in N_{T^1}(t), \mathbf{adh}_{(T^1, \mathcal{X}^1)}(tt') \text{ is bold}\}|), \\ &\quad \left. \max_{t \in V(T^2)} (|X_t| + |\{t' \in N_{T^2}(t), \mathbf{adh}_{(T^2, \mathcal{X}^2)}(tt') \text{ is bold}\}|) \right\} \\ &= \max \{ \mathbf{width}(T^1, \mathcal{X}^1), \mathbf{width}(T^2, \mathcal{X}^2), |F| \} \\ &\leq \max \{ w, |F| \} \end{aligned}$$

As  $|V(G)| > w \geq \mathbf{tcw}(G)$ , the tree of any minimum-width tree-cut decomposition of  $G$  has at least one link and the adhesion of this link has size at most  $w$ . Hence  $G$  has a cut of size at most  $w$ . By minimality of  $F$ , we deduce  $|F| \leq w$ , hence  $\mathbf{width}(T, \mathcal{X}) \leq w$  from the inequalities above.

At this point of the proof we have constructed a tree-cut decomposition  $(T, \mathcal{X})$  of  $G$  of width at most  $w$ . It remains to show that it is lean. For this, we consider some  $a, b \in E(T)$  and subsets  $A \subseteq \mathbf{adh}(a)$  and  $B \subseteq \mathbf{adh}(b)$  of the same size  $k$ . It is enough in order to conclude

the proof to assume that there is no collection of  $k$  edge-disjoint paths linking  $A$  to  $B$  in  $G$  and show that  $aTb$  has a link whose adhesion has size less than  $k$ .

In the case where  $a, b \in E(T^i)$  for some  $i \in [2]$ , we observe that, as it is an immersion of  $G$ ,  $G_i$  does not contain  $k$  edge-disjoint paths linking  $A$  to  $B$ . Because  $(T^i, \mathcal{X}^i)$  is lean, there is a link  $e$  in  $aT^ib$  such that  $|\text{adh}_{(T^i, \mathcal{X}^i)}(e)| < k$  (in particular,  $a \neq b$ ). As noted above,  $|\text{adh}_{(T^i, \mathcal{X}^i)}(e)| = |\text{adh}_{(T, \mathcal{X})}(e)|$  for every  $e \in E(T^i)$ , hence  $|\text{adh}_{(T, \mathcal{X})}(e)| < k$  and we are done. It remains to consider the case where  $a$  and  $b$  do not belong to the same of  $T^1$  and  $T^2$ . By [Lemma 2.5](#) (the variant of Menger's Theorem), there is in  $G$  a cut of size strictly smaller than  $k$  that separates  $A$  from  $B$ . By minimality of  $F$ , this implies  $|F| < k$ . Observe then that  $t_1t_2$  is an edge of  $aTb$  and  $|\text{adh}(t_1t_2)| = |F| < k$ , as desired.  $\square$

## Acknowledgments

The authors wish to thank Michał Pilipczuk and Marcin Wrochna for valuable discussions about lean tree-cut decompositions.

## References

- [Azz11] Jeffrey Azzato. Linked tree-decompositions of represented infinite matroids. *Journal of Combinatorial Theory, Series B*, 101(3):123 – 140, 2011.
- [BD02] Patrick Bellenbaum and Reinhard Diestel. Two short proofs concerning tree-decompositions. *Combinatorics, Probability and Computing*, 11(6):541–547, 2002.
- [CDHH14] Johannes Carmesin, Reinhard Diestel, M. Hamann, and Fabian Hundertmark.  $k$ -blocks: A connectivity invariant for graphs. *SIAM Journal on Discrete Mathematics*, 28(4):1876–1891, 2014.
- [CKL<sup>+</sup>18] Marek Cygan, Paweł Komosa, Daniel Lokshantov, Michał Pilipczuk, Marcin Pilipczuk, and Saket Saurabh. Randomized contractions meet lean decompositions. *arXiv e-prints*, page arXiv:1810.06864, October 2018.
- [CRS11] Maria Chudnovsky, Bruce Reed, and Paul Seymour. The edge-density for  $k2, t$ -minors. *Journal of Combinatorial Theory, Series B*, 101(1):18–46, 2011.
- [Die05] Reinhard Diestel. *Graph Theory*, volume 173 of *Graduate Texts in Mathematics*. Springer-Verlag, Heidelberg, third edition, 2005.
- [Erd18] Joshua Erde. A unified treatment of linked and lean tree-decompositions. *Journal of Combinatorial Theory, Series B*, 130:114 – 143, 2018.
- [GGW02a] James F. Geelen, A. M. H. Gerards, and Geoff Whittle. Branch-width and well-quasi-ordering in matroids and graphs. *Journal of Combinatorial Theory, Series B*, 84(2):270–290, 2002.

- [GGW02b] James F. Geelen, A.M.H. Gerards, and Geoff Whittle. Branch-width and well-quasi-ordering in matroids and graphs. *Journal of Combinatorial Theory, Series B*, 84(2):270 – 290, 2002.
- [GJ16] Jim Geelen and Benson Joeris. A generalization of the grid theorem. *arXiv preprint arXiv:1609.09098*, 2016.
- [GKRT19] Archontia C. Giannopoulou, O-joung Kwon, Jean-Florent Raymond, and Dimitrios M. Thilikos. Lean tree-cut decompositions: obstructions and algorithms. In *36<sup>th</sup> Symposium on Theoretical Aspects of Computer Science, STACS 2019, March 13-16, 2019, Berlin, Germany*, volume 96 of *LIPICs*, pages 30:1–30:13. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2019. To appear.
- [GKS15] Robert Ganian, Eun Jung Kim, and Stefan Szeider. Algorithmic applications of tree-cut width. In *Mathematical foundations of computer science 2015. Part II*, volume 9235 of *Lecture Notes in Computer Science*, pages 348–360. Springer, Heidelberg, 2015.
- [GPR<sup>+</sup>17] Archontia C. Giannopoulou, Michał Pilipczuk, Jean-Florent Raymond, Dimitrios M. Thilikos, and Marcin Wrochna. Linear kernels for edge deletion problems to immersion-closed graph classes. In *44<sup>th</sup> International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland*, pages 57:1–57:15, 2017.
- [GPR<sup>+</sup>18] Archontia C. Giannopoulou, Michał Pilipczuk, Jean-Florent Raymond, Dimitrios M. Thilikos, and Marcin Wrochna. Cutwidth: Obstructions and algorithmic aspects. *Algorithmica*, Mar 2018.
- [GW02] James Geelen and Geoff Whittle. Branch-width and rota’s conjecture. *Journal of Combinatorial Theory Series B*, 86(2):315–330, 2002.
- [Kin14] Shiva Kintali. Directed minors III. Directed linked decompositions. *CoRR*, abs/1404.5976, 2014.
- [KK14] Mamadou Moustapha Kanté and O-joung Kwon. An upper bound on the size of obstructions for bounded linear rank-width. *CoRR*, abs/1412.6201, 2014.
- [KOP<sup>+</sup>18] Eun Jung Kim, Sang-il Oum, Christophe Paul, Ignasi Sau, and Dimitrios M. Thilikos. An FPT 2-approximation for tree-cut decomposition. *Algorithmica*, 80(1):116–135, 2018.
- [KS15] Ilhee Kim and Paul D. Seymour. Tournament minors. *Journal of Combinatorial Theory, Series B*, 112:138–153, 2015.
- [Lag98] Jens Lagergren. Upper bounds on the size of obstructions and intertwines. *Journal of Combinatorial Theory, Series B*, 73(1):7–40, 1998.
- [Liu14] Chun-Hung Liu. *Graph structures and well-quasi-ordering*. PhD thesis, Georgia Institute of Technology, 2014.

- [Men27] Karl Menger. Zur allgemeinen kurventheorie. *Fundamenta Mathematicae*, 1(10):96–115, 1927.
- [OOT93] Bogdan Oporowski, James Oxley, and Robin Thomas. Typical subgraphs of 3- and 4-connected graphs. *Journal of Combinatorial Theory, Series B*, 57(2):239–257, 1993.
- [Oum05] Sang-il Oum. Rank-width and vertex-minors. *Journal of Combinatorial Theory, Series B*, 95(1):79 – 100, 2005.
- [Oum08] Sang-il Oum. Rank-width and well-quasi-ordering. *SIAM Journal on Discrete Mathematics*, 22(2):666–682, 2008.
- [RS86] Neil Robertson and Paul D. Seymour. Graph Minors. V. Excluding a planar graph. *Journal of Combinatorial Theory, Series B*, 41(2):92–114, 1986.
- [RS90] Neil Robertson and Paul D. Seymour. Graph minors. IV. Tree-width and well-quasi-ordering. *Journal of Combinatorial Theory, Series B*, 48(2):227–254, 1990.
- [Sey93] Paul D. Seymour. A bound on the excluded minors for a surface. *Manuscript*, 1993. <https://web.math.princeton.edu/~pds/papers/surfacebound/bound.pdf>.
- [Tho90] Robin Thomas. A Menger-like property of tree-width: The finite case. *Journal of Combinatorial Theory, Series B*, 48(1):67 – 76, 1990.
- [Wol15] Paul Wollan. The structure of graphs not admitting a fixed immersion. *Journal of Combinatorial Theory, Series B*, 110:47 – 66, 2015.