

Critical node cut parameterized by treewidth and solution size is $W[1]$ -hard

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Abstract In the CRITICAL NODE CUT problem, given an undirected graph G and two non-negative integers k and μ , the goal is to find a set S of exactly k vertices such that after deleting S we are left with at most μ connected pairs of vertices. Back in 2015, Hermelin et al. studied the aforementioned problem under the framework of parameterized complexity. They considered various natural parameters, namely, the size k of the desired solution, the upper bound μ on the number of remaining connected pairs, the lower bound b on the number of connected pairs to be removed, and the treewidth $\text{tw}(G)$ of the input graph G . For all but one combinations of the above parameters, they determined whether CRITICAL NODE CUT is fixed-parameter tractable and whether it admits a polynomial kernel. The only question they left open is whether the problem remains fixed-parameter tractable when parameterized by $k + \text{tw}(G)$. We answer this question in the negative via a new problem of independent interest, which we call SUMCSP. We believe that SUMCSP can be a useful starting point for showing hardness results of the same nature, i.e. when the treewidth of the graph is part of the parameter.

Keywords Critical Node Cut · Parameterized Complexity · $W[1]$ -hard · SumCSP

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1 Introduction

Consider the following problem, called **CRITICAL NODE CUT** (or **CNC** for short). We are given an undirected graph G and two non-negative integers k and μ . The goal is to determine whether there exists a subset of the vertices of G , say S , of size (exactly) k such that, in the graph $G - S$, we are left with at most μ connected pairs of vertices; $G - S$ denotes the graph obtained from G after deleting vertices in S and the edges incident on them. Alternatively, if we let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$, for some integer ℓ , denote the set of maximal connected components in $G - S$, the objective is to guarantee that $\sum_{C \in \mathcal{C}(G - S)} \binom{C}{2} \leq \mu$. The CNC problem, having many real-world applications such as controlling the spread of viruses in networks [9], has been investigated from various algorithmic perspectives, e.g. heuristics [12] and approximations algorithms [13]. Since the **VERTEX COVER** problem is a special case of CNC, i.e. when $\mu = 0$, the problem is clearly **NP**-complete. On the positive side, it is known that CNC can be solved in polynomial time if we restrict the input graph to trees [4]. More generally, for graphs of bounded treewidth, CNC can be solved in $\mathcal{O}(|V(G)|^{\text{tw}(G)+1})$ time [1], where $\text{tw}(G)$ is the treewidth of G . We refer the reader to [9] for a more extensive survey on CNC and its applications.

Table 1 Summary of results due to Hermelin et al. [9].

k	Parameter			Result	
	μ	b	$\text{tw}(G)$	FPT	Polynomial kernel
✓				no	no
	✓			no	no
		✓		yes	no
			✓	no	no
✓	✓			yes	yes
✓		✓		yes	no
✓			✓	open	no
	✓	✓		yes	yes
	✓		✓	yes	no
		✓	✓	yes	no
✓	✓	✓		yes	yes
✓	✓		✓	yes	yes
✓		✓	✓	yes	no
	✓	✓	✓	yes	yes
✓	✓	✓	✓	yes	yes

Hermelin et al. [9] initiated the study of the parameterized complexity of CNC. In parameterized complexity [6], we are interested in whether the problem can be solved in $f(\kappa) \cdot n^{\mathcal{O}(1)}$ time, for various natural parameters κ and some function f . Alternatively, one can also ask whether or not CNC admits a polynomial kernel for parameter κ , i.e. whether there is an algorithm that reduces any instance of CNC in polynomial time to an equivalent instance of size $\kappa^{\mathcal{O}(1)}$. There are quite a few natural choices for κ in this case and the following choices were considered by Hermelin et al. [9].

- The size k of the desired solution.
- The upper bound μ on the number of remaining connected pairs.
- The lower bound b on the number of connected pairs to be removed.
- The treewidth $\text{tw}(G)$ of the input graph G .

For all but one combinations of the above parameters, Hermelin et al. determined whether CRITICAL NODE CUT is fixed-parameter tractable (FPT) and whether it admits a polynomial kernel. These results are summarized in Table 1.

In this work, we complete the table by showing that CNC is $W[1]$ -hard (or equivalently not likely to be FPT) when parameterized by $k + \text{tw}(G)$. We prove this result via a new problem of independent interest, which we call SUMCSP. We believe that SUMCSP can be a useful starting point for showing hardness results of the same nature, i.e. when the treewidth of the graph is part of the parameter.

Overview of the reduction. Our starting point is the 4-REGULAR PARTITIONED SUBGRAPH ISOMORPHISM (PSI) problem, which is known to be $W[1]$ -hard [8, 10]. The problem is formally defined below.

4-REGULAR PARTITIONED SUBGRAPH ISOMORPHISM (PSI)

Input: A 4-regular pattern graph P with $V(P) = \{p_1, p_2, \dots, p_\ell\}$, a host graph H , and a coloring function $\text{col} : V(H) \rightarrow [\ell]$.

Question: Does there exist an injective function $\phi : V(P) \rightarrow V(H)$ such that for each $i \in [\ell]$, $\text{col}(\phi(p_i)) = i$ and for each $p_i p_j \in E(P)$, we have $\phi(p_i)\phi(p_j) \in E(H)$?

Parameter: $|V(P)|$.

We reduce PSI to SUMCSP, which is formally defined next.

SUMCSP

Input: A directed graph D with vertex set $V(D)$ and arc set $A(D)$, vertex weight function $w_V : V(D) \rightarrow \mathbb{N}$, arc weight function $w_A : A(D) \rightarrow \mathbb{N}$, and a list function $\varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}}$ such that for all $a \in A(D)$, and for all $(x, y), (x', y') \in \varphi(a)$ we have $x + y = x' + y' = w_A(a)$.

Question: Does there exist a function $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ such that for each $a \in A(D)$, $\rho(a) \in \varphi(a)$ and for each $v \in V(D)$, $\sum_{u \in N^+(v)} \text{fir}(\rho(vu)) + \sum_{u \in N^-(v)} \text{sec}(\rho(uv)) = w_V(v)$, where $\text{fir}((x, y)) = x$ and $\text{sec}((x, y)) = y$?

Parameter: $|A(D)|$.

Bodlaender et al. [2] introduced a very closely related problem to show that PLANAR CAPACITATED DOMINATING SET is $W[1]$ -hard. PLANAR CAPACITATED DOMINATING SET was the first bidimensional problem to be shown $W[1]$ -hard and the reduction was via an intermediate problem called PLANAR ARC SUPPLY. The main difference between PLANAR ARC SUPPLY and SUMCSP is the additional constraint we impose using the arc weight function, i.e. the fact that all pairs in $\varphi(a)$, $a \in A(D)$, must sum to $w_A(a)$. This constraint turns

out to be crucial for our reduction. Roughly speaking, the reduction from PSI to SUMCSP constructs a directed graph D whose structure is more or less similar to the pattern graph P (and its size is linear in $|V(P)|$). Edges of H are encoded using the vertex and arc weight functions as well as the function φ . Having established the hardness of SUMCSP, we then reduce SUMCSP to CRITICAL NODE CUT. Let us first state a formal definition of the latter problem.

CRITICAL NODE CUT (CNC)

Input: An undirected graph G and integers k and μ .

Question: Does there exist a set $S \subseteq V(G)$ of size (exactly) k such that $\sum_{C \in \mathcal{C}(G-S)} \binom{C}{2} \leq \mu$, where $\mathcal{C}(G-S) = \{C_1, \dots, C_\ell\}$ denotes the set of maximal connected components in $G-S$?

Parameter: $k + \text{tw}(G)$.

As stated earlier, our reduction from SUMCSP to CNC heavily relies on the arc weight function. Another crucial ingredient is the following proposition (which follows by the convexity of $\frac{x(x-1)}{2}$).

Proposition 1 *Let x_1, \dots, x_k be non-negative integers and let $x_1 + \dots + x_k = kn$. Then, $\sum_{i=1}^{i=k} \binom{x_i}{2}$ is minimized if $x_i = n$, for all i . In other words, $\sum_{i=1}^{i=k} \binom{x_i}{2}$ is minimized if $\sum_{i=1}^{i=k} \binom{x_i}{2} = k \binom{n}{2}$.*

At a very high level, starting from an instance of SUMCSP, we create a graph G (of bounded treewidth) where an optimal solution for CNC must separate the graph into a fixed number of connected components, all having the same size.

2 Preliminaries

We denote the set of natural numbers by \mathbb{N} . For $k \in \mathbb{N}$, by $[k]$ we denote the set $\{1, 2, \dots, k\}$. For sets X, Y , by $X \times Y$ we denote the set $\{(x, y) \mid x \in X, y \in Y\}$. Furthermore, for $(x, y) \in X \times Y$, we let $\text{fir}((x, y)) = x$ and $\text{sec}((x, y)) = y$, i.e. the first and second coordinate of the (ordered) pair (x, y) , respectively.

We use standard terminology from the book of Diestel [5] for graph-related terms that are not explicitly defined here. We consider only finite graphs. For a graph G , by $V(G)$ and $E(G)$ we denote the vertex and edge sets of G , respectively. Similarly, for a directed graph or digraph D , by $V(D)$ and $A(D)$ we denote the vertex and arc sets of D , respectively. For a graph G and $v \in V(G)$, by $N_G(v)$ we denote the set $\{u \in V(G) \mid vu \in E(G)\}$. For a digraph D and $v \in V(D)$, by $N_D^+(v)$ we denote the set $\{u \in V(D) \mid vu \in A(D)\}$, and by $N_D^-(v)$ we denote the set $\{u \in V(D) \mid uv \in A(D)\}$. We drop the subscript G (or D) from $N_G(v)$, $N_D^+(v)$, or $N_D^-(v)$ when the context is clear. For a vertex subset $S \subseteq V(G)$, by $G[S]$ we denote the subgraph of G induced by S , i.e. the graph with vertex set S and edge set $\{vu \in E(G) \mid v, u \in S\}$. By $G-S$ we denote the graph $G[V(G) \setminus S]$.

A *path* in a graph is a sequence of vertices $P = v_1, v_2, \dots, v_\ell$ such that for all $i \in [\ell - 1]$, $v_i v_{i+1} \in E(G)$. We say that such a path is a path between v_1 and v_ℓ or a $v_1 - v_\ell$ path of length $\ell - 1$, and vertices v_1, v_2, \dots, v_ℓ lie on the path P . Two vertices $u, v \in V(G)$ are said to be *connected* if there exists a $u - v$ path in G . A graph is *connected* if there is a path between every pair of vertices. A maximal connected subgraph of G is called a *component* of G . For a pair of vertices $u, v \in V(G)$, by $\text{dist}_G(u, v)$ we denote the length of the shortest path between u and v in G . For a graph G , by G^2 we denote the graph with vertex set $V(G^2) = V(G)$ and edge set $E(G^2) = \{uv \mid \text{dist}_G(u, v) \leq 2\}$.

A *cycle* in a graph is a sequence of vertices $C = v_1, v_2, \dots, v_\ell$ such that C is a $v_1 - v_\ell$ path and $v_1 v_\ell \in E(G)$. A *tree* is a connected graph without any cycles. Note that a tree on n vertices has exactly $n - 1$ edges. A tree is said to be a *rooted tree* if exactly one vertex in it has been designated as its *root*. A *coloring* of a graph G with $\alpha \in \mathbb{N}$ colors is a map $\varphi : V(G) \rightarrow [\alpha]$. A coloring φ of G is said to be a *proper coloring* if for each $uv \in E(G)$, $\varphi(u) \neq \varphi(v)$.

A *tree decomposition* of a graph is a pair $(\mathcal{X}, \mathcal{T})$, where an element $X \in \mathcal{X}$ is a subset of $V(G)$, called a *bag*, and \mathcal{T} is a rooted tree with vertex set \mathcal{X} satisfying the following properties: (i) $\cup_{X \in \mathcal{X}} X = V(G)$; (ii) For every $uv \in E(G)$, there exists $X \in \mathcal{X}$ such that $u, v \in X$; (iii) For all $X, Y, Z \in \mathcal{X}$, if Y lies on the unique path between X and Z in \mathcal{T} , then $X \cap Z \subseteq Y$. For a graph G and its tree decomposition $(\mathcal{X}, \mathcal{T})$, the *width* of the tree decomposition $(\mathcal{X}, \mathcal{T})$ is defined to be $\max_{X \in \mathcal{X}} (|X| - 1)$. The *treewidth* of a graph G , $\text{tw}(G)$, is the minimum of the widths of all its tree decompositions.

Parameterized complexity. A parameterized problem Π is a subset of $\Gamma^* \times \mathbb{N}$, where Γ is a finite alphabet. An instance of a parameterized problem is a tuple (x, κ) , where κ is called the *parameter*. A parameterized problem is said to be *fixed-parameter tractable (FPT)* if, for a given instance (x, κ) , we can decide $(x, \kappa) \in \Pi$ in time $f(\kappa) \cdot |x|^{\mathcal{O}(1)}$, where $f(\cdot)$ is an arbitrary function depending only on κ . To prove that a problem is FPT, it is possible to give an explicit algorithm, called a *parameterized algorithm* (or FPT algorithm), which runs in time $f(\kappa) \cdot |x|^{\mathcal{O}(1)}$. On the other hand, to show that a problem is unlikely to be FPT, it is possible to use polynomial-time parameter-preserving reductions analogous to the concept of reductions in classical complexity theory. Here, the notion of $\text{W}[1]$ -hardness replaces that of NP-hardness. For more details on parameterized complexity we refer to the books of Downey and Fellows [6], Flum and Grohe [7], Niedermeier [11], and the recent book by Cygan et al. [3].

3 $\text{W}[1]$ -hardness of SumCSP

Let $(P, H, \text{col} : V(H) \rightarrow [\ell])$ be an instance of PSI, where $V(P) = \{p_i \mid i \in [\ell]\}$ and $V(H) = \{h_i \mid i \in [n]\}$. For $i \in [\ell]$, we let $C_i^H = \{h \in V(H) \mid \text{col}(h) = i\}$. We make a few assumption and adopt some conventions that will help simplify the presentation. All numbers that appear in the construction will be represented in binary. We assume that $|V(H)| = n = 2^t$, for some $t \in \mathbb{N}$,

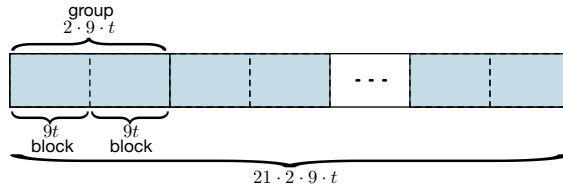


Fig. 1 An illustration of the division of a bitstring into groups and blocks.

i.e. $t = \log n$. Otherwise, if $|V(H)| = 2^{t'} - \delta$, for some $0 < \delta < 2^{t'-1}$, we can construct an equivalent instance $(H', P', \text{col}' : V(H') \rightarrow [\ell'])$ of PSI with $|V(H')| = 2^{t'+3}$, where H' is obtained from H by taking the disjoint union of H at most 8 times and adding δ copies of a 4-regular graph on 8 vertices (which exists) to H' and adjusting P to obtain P' and col to obtain col' appropriately. Note that P is a 4-regular graph, which implies that it has no isolated vertices. We assume a fixed cyclic ordering \prec_H on the vertices in H and a fixed cyclic ordering \prec_P on the vertices in P . Simply put, we have $h_1 \prec_H \dots \prec_H h_n \prec_H h_1$ and $p_1 \prec_P \dots \prec_P p_\ell \prec_P p_1$. With each vertex $h_i \in V(H)$, or equivalently integer $i \in [n]$, we assign two binary strings (or bitstrings for short) B_{h_i} and \overline{B}_{h_i} as follows. We let \mathbb{B}_i denote the binary representation of integer i and $\overline{\mathbb{B}}_i$ denote the (bitwise) complement of \mathbb{B}_i . We use $\mathbb{0}_z$ and $\mathbb{1}_z$ to denote the bitstrings of length z consisting of all zeros and all ones, respectively. We let $B_{h_i} = \mathbb{0}_{4t}\mathbb{B}_i\mathbb{0}_{4t}$ and $\overline{B}_{h_i} = \mathbb{0}_{4t}\overline{\mathbb{B}}_i\mathbb{0}_{4t}$. Note that B_{h_i} and \overline{B}_{h_i} are of length $9 \log n = 9t$. The purpose of the additional zero bits is to allow us to “correctly” handle overflows when summing binary numbers. For two bitstrings B and B' , we slightly abuse notation and sometimes treat the result of $B + B'$ as another bitstring (obtained after applying the usual binary addition operator) or as an integer (in base 10). The context will be clear.

We also assume that, along with instance $(P, H, \text{col} : V(H) \rightarrow [\ell])$, we are given a proper coloring $\text{col}_{P^2} : V(P) \rightarrow [21]$ of P^2 . Observe that such a coloring exists and can be computed in time polynomial in the size of the graph P ; the maximum degree of a vertex in P^2 is bounded by 20 and a graph with maximum degree d admits a $d + 1$ proper coloring. For a vertex $p_i \in V(P)$, we let $\text{idx}_i = \text{col}_{P^2}(p_i)$. In what follows, we will always deal with bitstrings of length $21 \cdot 2 \cdot 9 \cdot t$. A *block* consists of $9t$ consecutive bits. We note that two distinct blocks do not intersect in any bit position. Blocks will usually be set to bitstrings of the form $\mathbb{0}_{4t}\mathbb{B}_i\mathbb{0}_{4t}$, $\mathbb{0}_{4t}\overline{\mathbb{B}}_i\mathbb{0}_{4t}$, $\mathbb{0}_{4t}\mathbb{1}_t\mathbb{0}_{4t}$, $\mathbb{0}_{9t}$, or $\mathbb{1}_{9t}$, $i \in [n]$. A *group* consists of $2 \cdot 9 \cdot t$ consecutive bits. Two distinct groups do not intersect in any bit position and a group consists of two blocks (see Figure 1). Note that we have exactly 21 groups, which is equal to the number of colors in col_{P^2} . The reason why we need col_{P^2} will become clearer later. Intuitively, since we will be encoding the possible edges (from H) between a vertex in P and its four neighbors, we need to make sure that two of its neighbors do not get assigned the same group in a bitstring. Given a bitstring S of length $21 \cdot 2 \cdot 9 \cdot t$, we let $\text{block}[i](S)$ denote the i th block of S , $i \in [42]$, and we let $\text{group}[j](S)$ denote

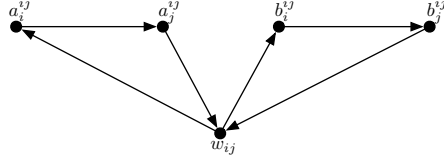


Fig. 2 An illustration of the edge selection gadget E_{ij} .

the j th group of S , $j \in [21]$. We also use the notation $\text{group}[i | j](S)$ to denote the i th and j th group of S , $i, j \in [21]$. Finally, we note that, since the length of bitstrings will be bounded by $\mathcal{O}(\log n)$, all numbers in the construction will be bounded by $n^{\mathcal{O}(1)}$. We are now ready to describe the construction of instance $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ of SUMCSP. We start with the description of the edge selection gadget.

Edge selection gadget. For every (unordered) pair of numbers $i, j \in [\ell]$ such that $p_i p_j \in E(P)$, we add an edge selection gadget E_{ij} (E_{ij} is a graph and not an edge set) to D . Note that both E_{ij} and E_{ji} refer to the same edge selection gadget, which will be responsible for selecting an edge in the host graph H . Moreover, $\text{idx}_i \neq \text{idx}_j$, since col_{P^2} is a proper coloring of P^2 . We assume, without loss of generality, that $i < j$. We let $V(E_{ij}) = \{a_i^{ij}, a_j^{ij}, b_i^{ij}, b_j^{ij}, w_{ij}\}$ and we let $A(E_{ij}) = \{a_i^{ij} a_j^{ij}, a_j^{ij} w_{ij}, w_{ij} a_i^{ij}, b_i^{ij} b_j^{ij}, b_j^{ij} w_{ij}, w_{ij} b_i^{ij}\}$ (see Figure 2). We now describe the construction of $\varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}}$ and $w_A : A(D) \rightarrow \mathbb{N}$. We assume that all bitstrings are initialized to \mathbb{O}_{378t} . That is, whenever we do not explicitly specify the value of a group (block) in a bitstring, it is set to all zeros.

- Consider $a_i^{ij} a_j^{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(a_i^{ij} a_j^{ij}), T_{uv}(a_i^{ij} a_j^{ij}))$ and add it to $\varphi(a_i^{ij} a_j^{ij})$. We set the following groups:

$$\text{group}[\text{idx}_i | \text{idx}_j](S_{uv}(a_i^{ij} a_j^{ij})) = B_u \bar{B}_u | \bar{B}_v B_v;$$

$$\text{group}[\text{idx}_i | \text{idx}_j](T_{uv}(a_i^{ij} a_j^{ij})) = \bar{B}_u B_u | B_v B_v;$$

$$\text{group}[\text{idx}_i | \text{idx}_j](w_A(a_i^{ij} a_j^{ij})) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} | \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}.$$
- Consider $a_j^{ij} w_{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(a_j^{ij} w_{ij}), T_{uv}(a_j^{ij} w_{ij}))$ and add it to $\varphi(a_j^{ij} w_{ij})$. We set the following groups:

$$\text{group}[\text{idx}_i | \text{idx}_j](S_{uv}(a_j^{ij} w_{ij})) = B_u \bar{B}_u | \mathbb{O}_{9t} \bar{B}_v;$$

$$\text{group}[\text{idx}_i | \text{idx}_j](T_{uv}(a_j^{ij} w_{ij})) = \bar{B}_u B_u | \mathbb{O}_{9t} B_v;$$

$$\text{group}[\text{idx}_i | \text{idx}_j](w_A(a_j^{ij} w_{ij})) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} | \mathbb{O}_{4t} \mathbb{O}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}.$$
- Consider $w_{ij} a_i^{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(w_{ij} a_i^{ij}), T_{uv}(w_{ij} a_i^{ij}))$ and add it to $\varphi(w_{ij} a_i^{ij})$. We set the following groups:

- $\text{group}[\text{idx}_i \mid \text{idx}_j](S_{uv}(w_{ij}a_i^{ij})) = \mathbb{O}_{9t}\overline{B}_u \mid \overline{B}_v\overline{B}_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](T_{uv}(w_{ij}a_i^{ij})) = \mathbb{O}_{9t}B_u \mid B_vB_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](w_A(w_{ij}a_i^{ij})) = \mathbb{O}_{4t}\mathbb{O}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t} \mid \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}.$
- Consider $b_i^{ij}b_j^{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(b_i^{ij}b_j^{ij}), T_{uv}(b_i^{ij}b_j^{ij}))$ and add it to $\varphi(b_i^{ij}b_j^{ij})$. We set the following groups:

$\text{group}[\text{idx}_i \mid \text{idx}_j](S_{uv}(b_i^{ij}b_j^{ij})) = \overline{B}_uB_u \mid B_vB_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](T_{uv}(b_i^{ij}b_j^{ij})) = B_u\overline{B}_u \mid \overline{B}_v\overline{B}_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](w_A(b_i^{ij}b_j^{ij})) = \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t} \mid \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}.$
 - Consider $b_j^{ij}w_{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(b_j^{ij}w_{ij}), T_{uv}(b_j^{ij}w_{ij}))$ and add it to $\varphi(b_j^{ij}w_{ij})$. We set the following groups:

$\text{group}[\text{idx}_i \mid \text{idx}_j](S_{uv}(b_j^{ij}w_{ij})) = \overline{B}_uB_u \mid \mathbb{O}_{9t}B_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](T_{uv}(b_j^{ij}w_{ij})) = B_u\overline{B}_u \mid \mathbb{O}_{9t}\overline{B}_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](w_A(b_j^{ij}w_{ij})) = \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t} \mid \mathbb{O}_{4t}\mathbb{O}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}.$
 - Consider $w_{ij}b_i^{ij} \in A(E_{ij})$. For each $u \in C_i^H$ and $v \in C_j^H$ such that $uv \in E(H)$, we create a pair of bitstrings $(S_{uv}(w_{ij}b_i^{ij}), T_{uv}(w_{ij}b_i^{ij}))$ and add it to $\varphi(w_{ij}b_i^{ij})$. We set the following groups:

$\text{group}[\text{idx}_i \mid \text{idx}_j](S_{uv}(w_{ij}b_i^{ij})) = \mathbb{O}_{9t}B_u \mid B_vB_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](T_{uv}(w_{ij}b_i^{ij})) = \mathbb{O}_{9t}\overline{B}_u \mid \overline{B}_v\overline{B}_v;$
 $\text{group}[\text{idx}_i \mid \text{idx}_j](w_A(w_{ij}b_i^{ij})) = \mathbb{O}_{4t}\mathbb{O}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t} \mid \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}.$

Compatibility between edge selection gadgets. We add edges between various edge selection gadgets to ensure that for each $i \in [\ell]$, the edges selected by the gadgets are incident on the same vertex in C_i^H . The selection of an edge by a gadget will be determined by the pair of number selected from $\varphi(a)$, where $a \in A(E_{ij})$ and $p_i p_j \in E(P)$. For each $p_i \in V(P)$, we have $|N_P(p_i)| = 4$, since P is a 4-regular graph. For $i \in [\ell]$, let $N_P(p_i) = \{p_{j_1}, p_{j_2}, p_{j_3}, p_{j_4}\}$, where we assume a (fixed and cyclic) ordering on the vertices in $N_P(p_i)$ based on the ordering \prec_P . That is, we assume $p_{j_1} \prec_P p_{j_2} \prec_P p_{j_3} \prec_P p_{j_4} \prec_P p_{j_1}$. Below we describe the set of arcs added between $E_{ij_1}, E_{ij_2}, E_{ij_3}$ and E_{ij_4} , we call this set A_i . We also describe the values assigned by $w_A(\cdot)$ and $\varphi(\cdot)$ to arcs in A_i (see Figure 3).

- We add the arc $a_i^{ij_1}b_i^{ij_2}$ to A_i and, for each $u \in C_i^H$, we add a pair of bitstrings $(S_u(a_i^{ij_1}b_i^{ij_2}), T_u(a_i^{ij_1}b_i^{ij_2}))$ to $\varphi(a_i^{ij_1}b_i^{ij_2})$. We set the following groups:

$\text{group}[\text{idx}_i](S_u(a_i^{ij_1}b_i^{ij_2})) = \overline{B}_u\mathbb{O}_{9t};$
 $\text{group}[\text{idx}_i](T_u(a_i^{ij_1}b_i^{ij_2})) = B_u\mathbb{O}_{9t};$
 $\text{group}[\text{idx}_i](w_A(a_i^{ij_1}b_i^{ij_2})) = \mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}\mathbb{O}_{9t}.$
- We add the arc $a_i^{ij_2}b_i^{ij_3}$ to A_i and, for each $u \in C_i^H$, we add a pair of bitstrings $(S_u(a_i^{ij_2}b_i^{ij_3}), T_u(a_i^{ij_2}b_i^{ij_3}))$ to $\varphi(a_i^{ij_2}b_i^{ij_3})$. We set the following

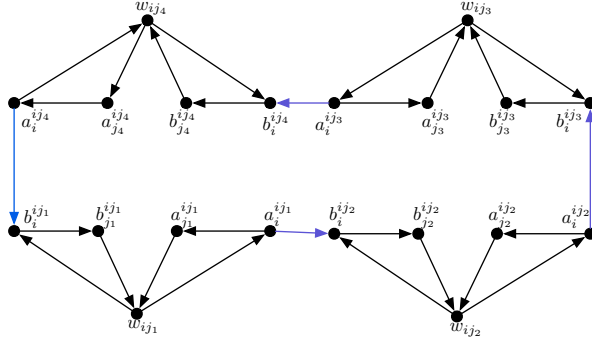


Fig. 3 An illustration of edge selection gadgets and the additional edges between them.

groups:

$$\text{group}[\text{id}x_i](S_u(a_i^{ij_2} b_i^{ij_3})) = \overline{B}_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](T_u(a_i^{ij_2} b_i^{ij_3})) = B_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](w_A(a_i^{ij_2} b_i^{ij_3})) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{9t}.$$

- We add the arc $a_i^{ij_3} b_i^{ij_4}$ to A_i and, for each $u \in C_i^H$, we add a pair of bitstrings $(S_u(a_i^{ij_3} b_i^{ij_4}), T_u(a_i^{ij_3} b_i^{ij_4}))$ to $\varphi(a_i^{ij_3} b_i^{ij_4})$. We set the following groups:

$$\text{group}[\text{id}x_i](S_u(a_i^{ij_3} b_i^{ij_4})) = \overline{B}_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](T_u(a_i^{ij_3} b_i^{ij_4})) = B_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](w_A(a_i^{ij_3} b_i^{ij_4})) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{9t}.$$

- We add the arc $a_i^{ij_4} b_i^{ij_1}$ to A_i and, for each $u \in C_i^H$, we add a pair of bitstrings $(S_u(a_i^{ij_4} b_i^{ij_1}), T_u(a_i^{ij_4} b_i^{ij_1}))$ to $\varphi(a_i^{ij_4} b_i^{ij_1})$. We set the following groups:

$$\text{group}[\text{id}x_i](S_u(a_i^{ij_4} b_i^{ij_1})) = \overline{B}_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](T_u(a_i^{ij_4} b_i^{ij_1})) = B_u \mathbb{O}_{9t};$$

$$\text{group}[\text{id}x_i](w_A(a_i^{ij_4} b_i^{ij_1})) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{9t}.$$

This completes the description of the vertices and arcs of D , and the functions $w_A : A(D) \rightarrow \mathbb{N}$ and $\varphi : A(D) \rightarrow 2^{\mathbb{R} \times \mathbb{R}}$. We now move to description of the functions $w_V : V(D) \rightarrow \mathbb{N}$.

The vertex weight function. For each $i, j \in [\ell]$, $i < j$, we set $w_V(\cdot)$ as follows.

- For all $u \in \{a_i^{ij}, a_j^{ij}, b_i^{ij}, b_j^{ij}\}$, we set $w_V(u)$ to be the bitstring X_u of length $378 \log n$, where $\text{group}[\text{id}x_i](X_u) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$ and $\text{group}[\text{id}x_j](X_u) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$.
- For w_{ij} , we set $w_V(w_{ij})$ to be the bitstring $X_{w_{ij}}$ of length $378 \log n$, which we construct as follows. We let Y be the bitstring of length t corresponding to the integer $2^t - 2$, i.e. a bitstring of length t with the last bit set to zero and all other bits set to one. Let Y' to be the bitstring of length $4t$ corresponding to the integer 1, i.e. the bitstring of length $4t$ with the last bit set to one

and all other bits set to zero. We set $\text{group}[\text{idx}_i](X_{w_{ij}}) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} Y' Y \mathbb{O}_{4t}$ and $\text{group}[\text{idx}_j](X_{w_{ij}}) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t} Y' Y \mathbb{O}_{4t}$.

This finishes the description of the instance $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ of SUMCSP for a given instance $(P, H, \text{col} : V(H) \rightarrow [\ell])$ of PSI. Below we state some propositions and lemmata that will be useful in establishing the equivalence of the two instances.

Proposition 2 *Let X, Y be two bitstrings of length $\log q$. Then $X + Y = 2^q - 1$ if and only if $\overline{X} = Y$.*

Proposition 3 *Let X and Y be two bitstrings each of length $42 \cdot 9 \cdot t$ and consisting of 21 groups, where $t = \log n$. Assume that, for each $i \in [21]$, group i in X consists of a bitstring of the form $X_i = \mathbb{O}_{4t} \mathbb{B}_x \mathbb{O}_{4t}$ and group i in Y consists of a bitstring of the form $Y_i = \mathbb{O}_{4t} \mathbb{B}_y \mathbb{O}_{4t}$, $x, y \in [n]$. Then, $X + Y$ is a bitstring of length $42 \cdot 9 \cdot t$ with the i th group equal to $X_i + Y_i$, $i \in [21]$.*

Lemma 1 *Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. Consider $p_i, p_{i'}, p_j, p_{j'} \in V(P)$ such that $a_i^{ij} b_i^{i'j'}, a_j^{ij} b_j^{i'j'} \in A(D)$. For $u \in C_i^H$ and $v \in C_j^H$, we have $\rho(a_i^{ij} a_j^{ij}) = (S_{uv}(a_i^{ij} a_j^{ij}), T_{uv}(a_i^{ij} a_j^{ij}))$ if and only if $\rho(a_i^{ij} b_i^{i'j'}) = (S_u(a_i^{ij} b_i^{i'j'}), T_u(a_i^{ij} b_i^{i'j'}))$ and $\rho(a_j^{ij} b_j^{i'j'}) = (S_v(a_j^{ij} b_j^{i'j'}), T_v(a_j^{ij} b_j^{i'j'}))$.*

Proof Let $u \in C_i^H$ and $v \in C_j^H$ such that $\rho(a_i^{ij} b_i^{i'j'}) = (S_u(a_i^{ij} b_i^{i'j'}), T_u(a_i^{ij} b_i^{i'j'}))$ and $\rho(a_j^{ij} b_j^{i'j'}) = (S_v(a_j^{ij} b_j^{i'j'}), T_v(a_j^{ij} b_j^{i'j'}))$. Also, let $u' \in C_i^H$ and $v' \in C_j^H$ such that $\rho(a_i^{ij} a_j^{ij}) = (S_{u'v'}(a_i^{ij} a_j^{ij}), T_{u'v'}(a_i^{ij} a_j^{ij}))$. Observe that it is enough to show that $u = u'$ and $v = v'$. Recall that by construction we have $N_D^-(a_i^{ij}) = \{w_{ij}\}$, $N_D^+(a_i^{ij}) = \{a_j^{ij}, b_i^{i'j'}\}$, and $\text{block}[1](\text{group}[\text{idx}_i](w_V(a_i^{ij}))) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$, i.e. the first block of the idx_i th group of $w_V(a_i^{ij})$ is $\mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$. Moreover, we have $\text{block}[1](\text{group}[\text{idx}_i](T_{uv}(w_{ij} a_i^{ij}))) = \mathbb{O}_{9t}$, $\text{block}[1](\text{group}[\text{idx}_i](S_{u'v'}(a_i^{ij} a_j^{ij}))) = B_{u'}$, and $\text{block}[1](\text{group}[\text{idx}_i](S_{uv}(a_i^{ij} b_i^{i'j'}))) = \overline{B}_u$. Combining Propositions 2 and 3 with the fact that \mathbb{O}_{9t} , $B_{u'}$, and \overline{B}_u must sum to $\mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$ implies that $u = u'$. An analogous argument can be given to show that $v = v'$. \square

Lemma 2 *Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. Consider $p_i, p_{i'}, p_j, p_{j'} \in V(P)$ such that $a_i^{i'j} b_i^{ij}, a_j^{i'j} b_j^{ij} \in A(D)$. For $u \in C_i^H$ and $v \in C_j^H$, we have $\rho(b_i^{i'j} b_j^{ij}) = (S_{uv}(b_i^{i'j} b_j^{ij}), T_{uv}(b_i^{i'j} b_j^{ij}))$ if and only if $\rho(a_i^{i'j} b_i^{ij}) = (S_u(a_i^{i'j} b_i^{ij}), T_u(a_i^{i'j} b_i^{ij}))$ and $\rho(a_j^{i'j} b_j^{ij}) = (S_v(a_j^{i'j} b_j^{ij}), T_v(a_j^{i'j} b_j^{ij}))$.*

Proof Let $u \in C_i^H$ and $v \in C_j^H$ such that $\rho(a_i^{i'j} b_i^{ij}) = (S_u(a_i^{i'j} b_i^{ij}), T_u(a_i^{i'j} b_i^{ij}))$ and $\rho(a_j^{i'j} b_j^{ij}) = (S_v(a_j^{i'j} b_j^{ij}), T_v(a_j^{i'j} b_j^{ij}))$. Also, let $u' \in C_i^H$ and $v' \in C_j^H$ such that $\rho(b_i^{i'j} b_j^{ij}) = (S_{u'v'}(b_i^{i'j} b_j^{ij}), T_{u'v'}(b_i^{i'j} b_j^{ij}))$. It is enough to show that $u = u'$ and $v = v'$. Recall that by construction we have $N_D^-(b_i^{i'j}) = \{w_{ij}, a_i^{i'j'}\}$,

$N_D^+(b_i^{ij}) = \{b_j^{ij}\}$, and $\text{block}[1](\text{group}[\text{idx}_i](w_V(a_i^{ij}))) = \mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$. Moreover, we have $\text{block}[1](\text{group}[\text{idx}_i](T_{uv}^{(w_{ij}, b_i^{ij})})) = \mathbb{O}_{9t}$, $\text{block}[1](\text{group}[\text{idx}_i](S_{u'v'}(b_i^{ij} b_j^{ij}))) = \overline{B}_{u'}$, and $\text{block}[1](\text{group}[\text{idx}_i](T_{uv}(a_i^{ij'} b_i^{ij}))) = B_u$. Combining Propositions 2 and 3 with the fact that \mathbb{O}_{9t} , $\overline{B}_{u'}$, and B_u must sum to $\mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$ implies that $u = u'$. An analogous argument can be given to show that $v = v'$. \square

Lemma 3 *Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. Let $i, j \in [\ell]$, where $i < j$ and $p_i p_j \in E(P)$, and let $u \in C_i^H$ and $v \in C_j^H$. Then, the following three statements are equivalent:*

- (1) $\rho(a_i^{ij} a_j^{ij}) = (S_{uv}(a_i^{ij} a_j^{ij}), T_{uv}(a_i^{ij} a_j^{ij}))$;
- (2) $\rho(w_{ij} a_i^{ij}) = (S_{uv}(w_{ij} a_i^{ij}), T_{uv}(w_{ij} a_i^{ij}))$;
- (3) $\rho(a_j^{ij} w_{ij}) = (S_{uv}(a_j^{ij} w_{ij}), T_{uv}(a_j^{ij} w_{ij}))$.

Proof Let $u \in C_i^H$, $v \in C_j^H$, and $\rho(a_i^{ij} a_j^{ij}) = (S_{uv}(a_i^{ij} a_j^{ij}), T_{uv}(a_i^{ij} a_j^{ij}))$. Moreover, let $\rho(w_{ij} a_i^{ij}) = (S_{u'v'}(w_{ij} a_i^{ij}), T_{u'v'}(w_{ij} a_i^{ij}))$, where $u' \in C_i^H$ and $v' \in C_j^H$. To prove that statement (1) holds if and only statement (2) holds, it is enough to show that $u = u'$ and $v = v'$. Recall that by construction we have $N_D^-(a_i^{ij}) = \{w_{ij}\}$ and $N_D^+(a_i^{ij}) = \{a_j^{ij}, b_i^{ij'}\}$, for some $b_i^{ij'} \in V(D)$ where $p_{j'}$ is a neighbor of p_i which comes after p_j in the fixed cyclic ordering of the neighbors of p_i . Moreover, we have $\text{block}[2](\text{group}[\text{idx}_i](T_{u'v'}(w_{ij} a_i^{ij}))) = B_{u'}$, $\text{block}[2](\text{group}[\text{idx}_i](S_{uv}(a_i^{ij} a_j^{ij}))) = \overline{B}_u$, and $\text{block}[2](\text{group}[\text{idx}_i](T_{u''v''}(a_i^{ij} b_i^{ij'}))) = \mathbb{O}_{9t}$, where $u'' \in C_i^H$, $v'' \in C_j^H$, and $\rho(b_i^{ij'} a_i^{ij'}) = (S_{u''v''}(b_i^{ij'} a_i^{ij'}), T_{u''v''}(b_i^{ij'} a_i^{ij'}))$. This together with the fact that the second block in the idx_i th group of $w_V(a_i^{ij})$ is $\mathbb{O}_{4t} \mathbb{1}_t \mathbb{O}_{4t}$ (and Propositions 2 and 3) implies that $u = u'$. An analogous argument can be given to show that $v = v'$. Using a symmetric argument, it can be shown that statement (1) holds if and only statement (3) holds. \square

Lemma 4 *Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. Let $i, j \in [\ell]$, where $i < j$ and $p_i p_j \in E(P)$, and let $u \in C_i^H$ and $v \in C_j^H$. Then, the following three statements are equivalent:*

- (1) $\rho(b_i^{ij} b_j^{ij}) = (S_{uv}(b_i^{ij} b_j^{ij}), T_{uv}(b_i^{ij} b_j^{ij}))$
- (2) $\rho(w_{ij} b_i^{ij}) = (S_{uv}^{(w_{ij}, b_i^{ij})}, T_{uv}^{(w_{ij}, b_i^{ij})})$;
- (3) $\rho(b_j^{ij} w_{ij}) = (S_{uv}(b_j^{ij} w_{ij}), T_{uv}(b_j^{ij} w_{ij}))$.

Proof For $u \in C_i^H$ and $v \in C_j^H$, let $\rho(b_i^{ij} b_j^{ij}) = (S_{uv}(b_i^{ij} b_j^{ij}), T_{uv}(b_i^{ij} b_j^{ij}))$. Moreover, let $\rho(w_{ij} b_i^{ij}) = (S_{u'v'}(w_{ij} b_i^{ij}), T_{u'v'}(w_{ij} b_i^{ij}))$, where $u' \in C_i^H$ and $v' \in C_j^H$. To prove that statement (1) holds if and only statement (2) holds, it is enough to show that $u = u'$ and $v = v'$. Recall that by construction we have $N_D^+(a_i^{ij}) = \{b_j^{ij}\}$ and $N_D^-(b_i^{ij}) = \{w_{ij}, a_i^{ij'}\}$, for some $b_i^{ij'} \in V(D)$ where $p_{j'}$ is a neighbor of p_i which comes after p_j in the fixed cyclic ordering of the

neighbors of p_i . Moreover, we have $\text{block}[2](\text{group}[\text{idx}_i](T_{u'v'}(w_{ij}a_i^{ij}))) = \overline{B}_{u'}$, $\text{block}[2](\text{group}[\text{idx}_i](S_{uv}(b_i^{ij}b_j^{ij}))) = B_u$, and $\text{block}[2](\text{group}[\text{idx}_i](T_{u''v''}(b_i^{ij}a_i^{ij'}))) = \mathbb{O}_{9t}$, where $u'' \in C_i^H$, $v'' \in C_j^H$, and $\rho(b_i^{ij}a_i^{ij'}) = (S_{u''v''}(b_i^{ij}a_i^{ij'}), T_{u''v''}(b_i^{ij}a_i^{ij'}))$. This together with the fact that second block in the idx_i th group of $w_V(b_i^{ij})$ is $\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}$ (and Propositions 2 and 3) implies that $u = u'$. An analogous argument can be given to show that $v = v'$. Using a symmetric argument, it can be shown that statement (1) holds if and only statement (3) holds. \square

Lemma 5 *Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. Let $i, j \in [\ell]$, $i < j$, $p_i p_j \in E(P)$, and $u \in C_i^H$ and $v \in C_j^H$. Then, $\rho(a_i^{ij}a_j^{ij}) = (S_{uv}(a_i^{ij}a_j^{ij}), T_{uv}(a_i^{ij}a_j^{ij}))$ if and only if $\rho(b_i^{ij}b_j^{ij}) = (S_{uv}(b_i^{ij}b_j^{ij}), T_{uv}(b_i^{ij}b_j^{ij}))$.*

Proof Let $i, j \in [\ell]$, $i < j$, and let $(p_i, p_j) \in E(P)$. Let $u, u' \in C_i^H$ and $v, v' \in C_j^H$ such that $\rho(a_i^{ij}a_j^{ij}) = (S_{uv}(a_i^{ij}a_j^{ij}), T_{uv}(a_i^{ij}a_j^{ij}))$ and $\rho(b_i^{ij}b_j^{ij}) = (S_{u'v'}(b_i^{ij}b_j^{ij}), T_{u'v'}(b_i^{ij}b_j^{ij}))$. We need to show that $u' = u$ and $v' = v$. From Lemmas 3 and 4, we know that $\rho(w_{ij}a_i^{ij}) = (S_{uv}(w_{ij}a_i^{ij}), T_{uv}(w_{ij}a_i^{ij}))$, $\rho(a_j^{ij}w_{ij}) = (S_{uv}(a_j^{ij}w_{ij}), T_{uv}(a_j^{ij}w_{ij}))$, $\rho(b_j^{ij}w_{ij}) = (S_{uv}(b_j^{ij}w_{ij}), T_{uv}(b_j^{ij}w_{ij}))$, and $\rho(w_{ij}b_i^{ij}) = (S_{u'v'}(w_{ij}b_i^{ij}), T_{u'v'}(w_{ij}b_i^{ij}))$. Moreover, we have $\text{block}[1](\text{group}[\text{idx}_j](S_{uv}(w_{ij}a_i^{ij}))) = \overline{B}_v$, $\text{block}[1](\text{group}[\text{idx}_j](S_{u'v'}(w_{ij}b_i^{ij}))) = B_{v'}$, $\text{block}[1](\text{group}[\text{idx}_j](T_{uv}(a_j^{ij}w_{ij}))) = \mathbb{O}_{9t}$, and $\text{block}[1](\text{group}[\text{idx}_j](T_{u'v'}(b_j^{ij}w_{ij}))) = \mathbb{O}_{9t}$. This together with the fact that first block in the idx_j th group of $w_V(w_{ij})$ is $\mathbb{O}_{4t}\mathbb{1}_t\mathbb{O}_{4t}$ (and Propositions 2 and 3) implies that $v = v'$. An analogous argument shows that $u = u'$. \square

Lemma 6 *$(P, H, \text{col} : V(H) \rightarrow [\ell])$ is a yes-instance of PSI if and only if $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ is a yes-instance of SUMCSP.*

Proof In the forward direction, let $(P, H, \text{col} : V(H) \rightarrow [\ell])$ be a yes-instance of PSI and $\phi : V(P) \rightarrow V(H)$ be an injective function such that for each $i \in [\ell]$, $\text{col}(\phi(p_i)) = i$, and, for each $(p_i, p_j) \in E(P)$, we have $(\phi(p_i), \phi(p_j)) \in E(H)$. For $i \in [\ell]$, let $h_i^* = \phi(p_i)$. We now define $\rho : A(D) \rightarrow \mathbb{R} \times \mathbb{R}$ such that for each $e \in A(D)$, we have $\rho(e) \in \varphi(e)$ and for each $v \in V(D)$, $\sum_{u \in N^+(v)} 1(\rho((v, u))) + \sum_{u \in N^-(v)} 2(\rho((u, v))) = w_V(v)$. For $i \in [\ell]$ and for each $e \in E_i$, we set $\rho(e) = (S_{\phi(p_i)}^e, T_{\phi(p_i)}^e)$. For $i, j \in [\ell]$, $i < j$ such that $(p_i, p_j) \in E(P)$ and for each $e \in A(E_{ij})$, we set $\rho(e) = (S_{\phi(p_i)\phi(p_j)}^e, T_{\phi(p_i)\phi(p_j)}^e)$. Recall that by construction, ρ satisfies all the desired properties.

In the reverse direction let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be a yes-instance of SUMCSP and $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution. From Lemmas 1 to 5, it follows that for each $i, j \in [\ell]$, $i < j$ with $(p_i, p_j) \in E(P)$, there exists $u \in C_i^H$ and $v \in C_j^H$ such that for all $e \in A(E_{ij})$, $\rho(e) = (S_{uv}^e, T_{uv}^e)$, for all $e \in A(E_i)$, $\rho(e) = (S_u^e, T_e^e)$ and, for all $e \in A(E_j)$,

$\rho(e) = (S_v^e, T_v^e)$. For $i \in [\ell]$, let h_i^* be the vertex such that for all $e \in A(E_i)$, we have $\rho(e) = (S_{h_i^*}^e, T_{h_i^*}^e)$. We show that $\phi : V(P) \rightarrow V(H)$ such that for $i \in [\ell]$, $\phi(p_i) = h_i^*$, is a solution for PSI.

For $i \in [\ell]$ and $k \in [4]$, let p_{j_k} be neighbors of p_i in P such that for each $k' \in [3]$, $j_{k'} < j_{k'+1}$. Further, let h_i^* be the vertex such that $\rho((a_i^{ij_1}, b_i^{ij_2})) = (S_{h_i^*}^{(a_i^{ij_1}, b_i^{ij_2})}, T_{h_i^*}^{(a_i^{ij_1}, b_i^{ij_2})})$. We will show that $\phi : V(P) \rightarrow V(H)$ such that for $i' \in [\ell]$, $\phi(p_{i'}) = h_{i'}^*$ is a solution for PSI. From construction it follows that for each $i \in [\ell]$, $\text{col}(h_i^*) = i$. Consider an edge $(p_i, p_j) \in E(P)$, where $i < j$. From construction of D we know that we have E_{ij} as sub-digraph of D . Furthermore, we also have $(h_i^*, h_j^*) \in E(H)$ since for each $e \in A(E_{ij})$ we have $(S_{h_i^*}^e, T_{h_j^*}^e) \in \varphi(e)$ and we added such a pair only if h_i^* and h_j^* are adjacent. \square

Theorem 1 *SUMCSP is W[1]-hard when parameterized by the number of vertices in the pattern graph.*

Proof Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be the constructed instance of SUMCSP given instance $(P, H, \text{col} : V(H) \rightarrow [\ell])$ of PSI. An easy trace of the construction shows that it can be accomplished in time polynomial in $|V(H)|$ and that all the numbers appearing in the construction are bounded by $|V(H)|^{\mathcal{O}(1)}$. Moreover, note that P is 4-regular and therefore $|E(P)| = \mathcal{O}(|V(P)|)$. Since (by construction) the number of arcs in D is linear in the number of edges in P , we have $|A(D)| = \mathcal{O}(|V(P)|)$. Combining all of the above with Lemma 6 and the W[1]-hardness of PSI completes the proof. \square

4 W[1]-hardness of CNC

Let $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ be an instance of SUMCSP. We let $w_{vmax} = \max_{v \in V(D)}(w_V(v))$, i.e. the maximum weight of a vertex in D , we let $w_{amax} = \max_{a \in A(D)}(w_A(a))$, i.e. the maximum weight of an arc in D , and we let $w_{big} = (w_{amax} \cdot w_{vmax})^{100}$. We assume, without loss of generality, that the number of arcs in D is greater than some constant, say $|A(D)| \geq 50$, and that $w_{vmax} > 2|A(D)|$ (otherwise we can increase all numbers in the SUMCSP instance appropriately). Moreover, we let $W^* = (k+3)(w_{big} + w_{vmax} + 2)$. For each vertex $v \in V(D)$, we define a quantity $W_v = W^* - (k+3)(w_V(v) + 2) = (k+3)(w_{big} + w_{vmax} - w_V(v))$. We shall create an instance (G, k, μ) of CNC, where $k = 2|A(D)|$, $\mu = |V(D)| \cdot \binom{W^*}{2}$, and $\text{tw}(G) = k^{\mathcal{O}(1)}$. We now proceed to the construction of the graph G .

Construction. For each vertex $v \in V(D)$, we create a clique K_v of size $2(k+3)$ and an independent set I_v of size W_v . We add all edges between vertices in K_v and vertices in I_v . For each arc $a = uv \in A(D)$, we create a *chain* H_{uv} (which will connect K_u and K_v) as follows. H_{uv} consists of $w_A(a) + 1$ *connecting pairs* of vertices $\mathcal{P}_{uv} = \{p_0, \dots, p_{w_A(a)}\}$, i.e. each pair $p_i \in \mathcal{P}_{uv}$ consists of two (independent) vertices $\{p_i^1, p_i^2\}$. Moreover, we have $w_A(a)$ *border*

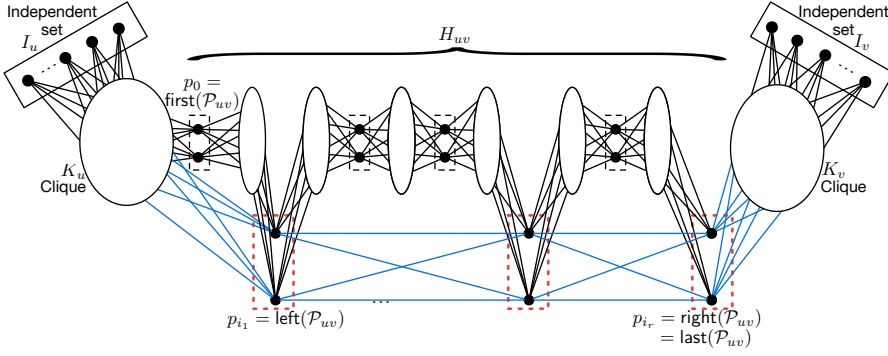


Fig. 4 An illustration of parts of the construction of the graph G .

walls $\mathcal{B}_{uv} = \{b_1, \dots, b_{w_A(a)}\}$, each of size $k + 1$, i.e. each wall consists of $k + 1$ (independent) vertices. We add all edges between K_u and pair p_0 and we add all edges between K_v and $p_{w_A(uv)}$. Next, we add all edges between p_{i-1} and b_i and all edges between b_i and p_i , for $i \in [w_A(a)]$. We call the pair p_0 the *first pair* of \mathcal{P}_{uv} and denote it by $\text{first}(\mathcal{P}_{uv})$. Similarly, we call the pair $p_{w_A(uv)}$ the *last pair* of \mathcal{P}_{uv} and denote it by $\text{last}(\mathcal{P}_{uv})$. Then, we sort all entries $(i, j) \in \varphi(a)$ in increasing order based on the first coordinate. Let $\{(i_1, j_1), (i_2, j_2), \dots, (i_r, j_r)\}$ denote the resulting sorted set. We assume, without loss of generality, that the set contains no duplicates. This assumption is justified by the fact that for all $(i, j), (i', j') \in \varphi(a)$ we have $i + i' = i' + j' = w_A(a)$. We add all edges (if they do not already exist) between K_u and vertices $\{p_{i_1}^1, p_{i_1}^2\}$ and all edges between K_v and vertices $\{p_{i_1}^1, p_{i_1}^2\}$. We call the pair p_{i_1} the *left pair* of \mathcal{P}_{uv} and denote it by $\text{left}(\mathcal{P}_{uv})$. Similarly, we call the pair p_{i_r} the *right pair* of \mathcal{P}_{uv} and denote it by $\text{right}(\mathcal{P}_{uv})$. Finally, for each two consecutive entries (i, j) and (i', j') we add all edges between $\{p_i^1, p_i^2\}$ and $\{p_{i'}^1, p_{i'}^2\}$. This completes the construction of the graph G (see Figure 4).

Proposition 4 $\text{tw}(G) = k^{\mathcal{O}(1)}$.

Below we prove a series of lemmas that allows us to transform any solution S to an instance (G, k, μ) of CNC into an “equally good” solution S' having some “nice” structural properties. We say that a solution S *splits* a connecting pair $\{p^1, p^2\}$ if $|S \cap \{p^1, p^2\}| = 1$. We let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$ denote the maximal connected components in $G - S$. We classify a component $C \in \mathcal{C}(G - S)$ into one of three types. We say C is a *small* component whenever C does not contain any vertices from K_v or I_v , for all $v \in V(D)$. We say C is a *large* component whenever C intersects with at least two cliques K_u and K_v , $u, v \in V(D)$. We say that C is a *medium* component otherwise. Note that, for any $v \in V(D)$, any solution of size k cannot separate $G[V(I_v) \cup V(K_v)]$ into two or more components. Therefore, if $\mathcal{C}(G - S)$ consists of only medium components then $|\mathcal{C}(G - S)|$ is exactly $|V(D)|$ and S includes exactly one connecting pair from

each chain H_{uv} , $uv \in A(D)$. We say S is *well structured* whenever $\mathcal{C}(G - S)$ consists of only medium components.

Lemma 7 *Let S be a solution to (G, k, μ) and let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$. If $|S \cap \bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))| > 0$ then there exists a solution S' such that $|S'| = |S|$, $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$, and $|S' \cap \bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))| = |S \cap \bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))| - 1$.*

Proof Let w be a vertex in $S \cap (V(I_u) \cup V(K_u))$, for some $u \in V(D)$. Note that (by construction) $|V(I_u)| > k$ and $|V(K_u)| > k$. Moreover, for all $w_1, w_2 \in V(I_u) \cup V(K_u)$, we have $N_G(w_1) = N_G(w_2)$. Therefore, since $|S| = k$, we have $|\mathcal{C}(G - S)| = |\mathcal{C}((G - S) \cup \{w\})|$. In other words, if $w \in V(I_u)$ or $w \in V(K_u)$ then there exists at least one vertex $w' \notin S$ such that $w' \in V(I_u)$ or $w' \in V(K_u)$, respectively. Let $C_{w'} \in \mathcal{C}(G - S)$ denote the component in $G - S$ containing w' . Note that $C_{w'}$ is either a medium or a large component, since a small component (by definition) does not intersect with $\bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))$. If $C_{w'}$ is a large component then it must contain a vertex w'' which belongs to some chain H_{uv} , for some $v \in V(D)$. We let $S' = (S \setminus \{w\}) \cup \{w''\}$. It is not hard to see that S' does in fact satisfy all the required properties. If $C_{w'}$ is a medium component then we have two cases to consider. If we can find a w'' (belonging to some chain) then the same replacement argument as above holds. Otherwise, we know that the size of $V(C_{w'})$ is at most $|V(I_u)| + |V(K_u)| = W_u + 2(k + 3) = (k + 3)(w_{big} + w_{vmax} - w_V(u) + 2) \leq (k + 3)(w_{big} + w_{vmax} + 2)$. However, since S does not include exactly two vertices from each chain, we know that $\mathcal{C}(G - S)$ must include at least one large component, say C'' , of size at least $2(k + 3)w_{big}$. Replacing w with a vertex $w'' \in V(C'') \cap H_{u'v'}$, for some $u'v' \in V(D)$, produces the required set S' (recall that we assume $w_{vmax} > 2|A(D)| = k$). \square

By repeated applications of Lemma 7, we can assume that a solution S does not intersect with $V(I_u) \cup V(K_u)$, for all $u \in V(D)$. In what follows, we always assume that S satisfies this property. Using similar arguments, we can show that S also does not intersect with any border walls.

Lemma 8 *Let S be a solution to (G, k, μ) and let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$. If $|S \cap \bigcup_{uv \in A(D)} \mathcal{B}_{uv}| > 0$ then there exists a solution S' such that $|S'| = |S|$, $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$, $|S' \cap \bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))| = |S \cap \bigcup_{u \in V(D)} (V(I_u) \cup V(K_u))|$, and $|S' \cap \bigcup_{uv \in A(D)} \mathcal{B}_{uv}|$ is strictly less than $|S \cap \bigcup_{uv \in A(D)} \mathcal{B}_{uv}|$.*

Proof Let w be a vertex in $S \cap b$, where $b \in \mathcal{B}_{uv}$ for some $uv \in A(D)$. Recall that (by construction) $|b| = k + 1$ and, for all $w_1, w_2 \in b$, we have $N_G(w_1) = N_G(w_2)$. Therefore, since $|S| = k$, we have $|\mathcal{C}(G - S)| = |\mathcal{C}((G - S) \cup \{w\})|$. In other words, there exists at least one vertex $w' \notin S$ such that $w' \in b$. Let $C_{w'} \in \mathcal{C}(G - S)$ denote the component in $G - S$ containing w' . If $C_{w'}$ is a medium or large component then we can always find a vertex w'' from some connecting pair,

i.e. $w'' \in \mathcal{P}_{uv}$, to replace w and obtain S' . If $C_{w'}$ is a small component then either $|V(C_{w'})| = 1$, in which case we can replace w by any connecting pair vertex, or $C_{w'}$ contains some vertex $w'' \in \mathcal{P}_{uv}$, as needed. \square

Lemmas 7 and 8 imply that we can always assume that S includes vertices from connecting pairs only. We now proceed to showing that S does not split any connecting pair. We use $\text{split}(G, S)$ to denote the number of connecting pairs split by S in G .

Lemma 9 *Let S be a solution to (G, k, μ) such that $S \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$ and let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$. If $\text{split}(G, S) > 0$ then there exists a solution S' such that $|S'| = |S|$, $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$, $S' \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$, and $\text{split}(G, S') < \text{split}(G, S)$.*

Proof Given that k is even, we know that $\text{split}(G, S)$ must also be even. Assume that S splits two connecting pairs $\{p^1, p^2\}$ and $\{q^1, q^2\}$. Without loss of generality, we assume that $p^1, q^1 \in S$, $p^2, q^2 \notin S$, $p_2 \in V(C_p)$, $q_2 \in V(C_q)$, and $|V(C_p)| \leq |V(C_q)|$, where $C_p, C_q \in \mathcal{C}(G - S)$. We let $S' = (S \setminus \{p_1\}) \cup \{q_2\}$. It is not hard to see that regardless of whether $C_p = C_q$ or not, $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$, as needed. \square

Lemma 10 *Let S be a solution to (G, k, μ) such that $S \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$ and $\text{split}(G, S) = 0$. Let $\mathcal{C}(G - S) = \{C_1, \dots, C_\ell\}$. Assume that $|S \cap \mathcal{P}_{uv}| = 2x \geq 10$, for some $uv \in A(D)$, and hence there exists $u_1v_1, \dots, u_{x-1}v_{x-1} \in A(D)$ such that $|S \cap \mathcal{P}_{u_i v_i}| = 0$, for $i \in [x - 1]$. Then, there exists S' such that $|S'| = |S|$, $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$, $S' \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$, $\text{split}(G, S') = 0$, $\text{left}(\mathcal{P}_{uv}) \cup \text{right}(\mathcal{P}_{uv}) \cup \text{first}(\mathcal{P}_{uv}) \cup \text{last}(\mathcal{P}_{uv}) \subseteq S'$, $|S' \cap \mathcal{P}_{uv}| = 8$, and $|S' \cap \mathcal{P}_{u_i v_i}| = 2$, for $i \in [x - 1]$.*

Proof Recall the construction of $\mathcal{P}_{uv} = \{p_0, \dots, p_{w_A(uv)}\}$. We add all edges between K_u and pair $p_0 = \text{first}(\mathcal{P}_{uv})$ and we add all edges between K_v and $p_{w_A(uv)} = \text{last}(\mathcal{P}_{uv})$. Next, we sort all entries $(i, j) \in \varphi(uv)$ in increasing order based on the first coordinate. Let $\{(i_1, j_1), (i_2, j_2), \dots, (i_r, j_r)\}$ denote the resulting sorted set. We add all edges between K_u and vertex $p_{i_1} = \text{left}(\mathcal{P}_{uv})$ and all edges between K_v and vertex $p_{i_r} = \text{right}(\mathcal{P}_{uv})$. Finally, for each two consecutive entries (i, j) and (i', j') , we add all edges between p_i and $p_{i'}$. Let us assume that $0 \neq i_1 \neq i_r \neq w_A(uv)$, as the same arguments hold when that is not case. Since $|S \cap \mathcal{P}_{uv}| \geq 10$, we know that S includes at least 5 pairs from \mathcal{P}_{uv} . Let $S' = (S \setminus \mathcal{P}_{uv}) \cup \text{left}(\mathcal{P}_{uv}) \cup \text{right}(\mathcal{P}_{uv}) \cup \text{first}(\mathcal{P}_{uv}) \cup \text{last}(\mathcal{P}_{uv}) \cup \text{left}(\mathcal{P}_{u_1 v_1}) \cup \dots \cup \text{left}(\mathcal{P}_{u_{x-1} v_{x-1}})$. It remains to show that $\sum_{C' \in \mathcal{C}(G - S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G - S)} \binom{C}{2}$. Note that in the graph $G[V(K_u) \cup V(K_v) \cup H_{uv}] - S'$ we have five connected components, where two of those components are exactly K_u and K_v . Hence, the total number of connected pairs that are introduced by removing some of the pairs in $S \cap \mathcal{P}_{uv}$ is at most $\binom{(k+3)w_{amax}}{2}$. However, for each pair $\text{left}(\mathcal{P}_{u_i v_i})$ that we add to S' the number of connected pairs decreases by at least $(k+3)w_{big} > \binom{(k+3)w_{amax}}{2}$ (recall that $w_{vmax} \geq k+1$ and $k \geq 100$). \square

Since k is even, we know (from Lemma 10 and the fact that $\text{split}(G, S) = 0$) that, for all $uv \in A(D)$, $|S \cap \mathcal{P}_{uv}| \in \{0, 2, 4, 6, 8\}$.

Lemma 11 *Let S be a solution satisfying the following properties: (1) $S \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$; (2) $\text{split}(G, S) = 0$; (3) $|S \cap \mathcal{P}_{uv}| \in \{0, 2, 4, 6, 8\}$, for all $uv \in A(D)$; (4) If $|S \cap \mathcal{P}_{uv}| = 8$, for $uv \in A(D)$, then $\text{left}(\mathcal{P}_{uv}) \cup \text{right}(\mathcal{P}_{uv}) \cup \text{first}(\mathcal{P}_{uv}) \cup \text{last}(\mathcal{P}_{uv}) \subseteq S$. Then, there exists a solution S' satisfying the following properties: (i) $S' \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$; (ii) $\text{split}(G, S') = 0$; (iii) $|S' \cap \mathcal{P}_{uv}| = 2$, for all $uv \in A(D)$.*

Proof Let $s_0, s_1, s_2, s_3,$ and s_4 denote the cardinality of $\{uv \in A(D) \mid |S \cap \mathcal{P}_{uv}| = 0\}$, $\{uv \in A(D) \mid |S \cap \mathcal{P}_{uv}| = 2\}$, $\{uv \in A(D) \mid |S \cap \mathcal{P}_{uv}| = 4\}$, $\{uv \in A(D) \mid |S \cap \mathcal{P}_{uv}| = 6\}$, and $\{uv \in A(D) \mid |S \cap \mathcal{P}_{uv}| = 8\}$, respectively. Note that $s_0 + s_1 + s_2 + s_3 + s_4 = |A(D)|$ and $2s_1 + 4s_2 + 6s_3 + 8s_4 = k$. Hence, $2(s_0 + s_1 + s_2 + s_3 + s_4) = 2s_1 + 4s_2 + 6s_3 + 8s_4$ and $s_0 = s_2 + 2s_3 + 3s_4$.

Let $s_0^u, s_1^u, s_2^u, s_3^u,$ and s_4^u denote the cardinality of $\{vw \in A(D) \mid (u = v \vee u = w) \wedge |S \cap \mathcal{P}_{vw}| = 0\}$, $\{vw \in A(D) \mid (u = v \vee u = w) \wedge |S \cap \mathcal{P}_{vw}| = 2\}$, $\{vw \in A(D) \mid (u = v \vee u = w) \wedge |S \cap \mathcal{P}_{vw}| = 4\}$, $\{vw \in A(D) \mid (u = v \vee u = w) \wedge |S \cap \mathcal{P}_{vw}| = 6\}$, and $\{vw \in A(D) \mid (u = v \vee u = w) \wedge |S \cap \mathcal{P}_{vw}| = 8\}$, respectively. We claim that there exists a vertex $u \in V(D)$ such that $0 < s_0^u$ implies $s_0^u \leq s_2^u + 2s_3^u + 3s_4^u$. Assume otherwise. Since $\sum_{u \in V(D)} s_i^u = 2s_i, i \in \{0, 1, 2, 3, 4\}$, we have $\sum_{u \in V(D)} s_0^u > \sum_{u \in V(D)} s_2^u + \sum_{u \in V(D)} 2s_3^u + \sum_{u \in V(D)} 3s_4^u$, which is equivalent to $2s_0 > 2s_2 + 4s_3 + 6s_4$, a contradiction to the fact that $s_0 = s_2 + 2s_3 + 3s_4$. Hence, the claim follows.

Now, we let $u \in V(D)$ such that $s_0^u \leq s_2^u + 2s_3^u + 3s_4^u$. We create a new solution S' as follows. We let $S' = S \setminus \bigcup_{vw \in A(D) \wedge (u=v \vee u=w)} \mathcal{P}_{vw}$. Then, for each $vw \in A(D)$, if $u = v$ we add $\text{right}(\mathcal{P}_{uv})$ to S' and if $u = w$ we add $\text{left}(\mathcal{P}_{vu})$ to S' . If we are left with additional non-used budget, i.e. if $|S'| < k$, we pick the remaining pairs from chains whose intersection with S' is empty. Note that, after this replacement, we reduce the number of large components by at least one. Therefore, $\sum_{C' \in \mathcal{C}(G-S')} \binom{C'}{2} \leq \sum_{C \in \mathcal{C}(G-S)} \binom{C}{2}$. In other words, the number of connected pairs increases by at most $\binom{(k+3)(w_{big} + w_{vmax} + 2) + k(k+3)w_{amax}}{2}$. However, since we reduce the number of large components, the number of connected pairs decreases by at least $\binom{2(k+3)w_{big}}{2}$. The lemma follows by repeating the replacement procedure as long as we can find a vertex u with $0 < s_0^u \leq s_2^u + 2s_3^u + 3s_4^u$. When no such vertex exists, it must be the case that $|S' \cap \mathcal{P}_{uv}| = 2$, for all $uv \in A(D)$. \square

We are now ready to prove the correctness of the reduction, which is implied by Lemmas 12 and 13 below.

Lemma 12 *If $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ is a yes-instance of SUMCSP then (G, k, μ) is a yes-instance of CNC.*

Proof Let $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ be a solution to the SUMCSP instance. We construct a solution S to the CNC instance by picking one connecting pair from each chain as follows. Initially, we set $S = \emptyset$. For each $uv \in A(D)$, we let

$\mathcal{P}_{uv} = \{p_0, \dots, p_{w_A(uv)}\}$, we let $\rho(uv) = (x_{uv}, y_{uv})$, and we set $S = S \cup p_{x_{uv}}$. It is not hard to see that $G - S$ consists of exactly $|V(D)|$ components (as we pick one connecting pair from each chain). We associate each component with some vertex $u \in V(D)$. The size of each component is exactly $|V(K_u)| + |V(I_u)| + \sum_{v \in N^+(u)} (k+3)x_{uv} + \sum_{v \in N^-(u)} (k+3)y_{vu} = |V(K_u)| + |V(I_u)| + (k+3)w_V(u) = 2(k+3) + (k+3)(w_{big} + w_{vmax} - w_V(v)) + (k+3)w_V(u) = (k+3)(w_{big} + w_{vmax} + 2) = W^*$. \square

Lemma 13 *If (G, k, μ) is a yes-instance of CNC then $(D, w_V : V(D) \rightarrow \mathbb{N}, w_A : A(D) \rightarrow \mathbb{N}, \varphi : A(D) \rightarrow 2^{\mathbb{N} \times \mathbb{N}})$ is a yes-instance of SUMCSP.*

Proof Let S be a solution to (G, k, μ) . From Lemmas 7 to 11, we know that S must be well structured. In other words, $S \subseteq \bigcup_{uv \in A(D)} \mathcal{P}_{uv}$, $\text{split}(G, S) = 0$, and $|S \cap \mathcal{P}_{uv}| = 2$, for all $uv \in A(D)$. Hence, the number of components in $G - S$ is exactly $|V(D)|$. Let $\mathcal{C}(G - S) = \{C_1, \dots, C_{|V(D)|}\}$. Recall that $W^* = (k+3)(w_{big} + w_{vmax} + 2)$ and $\mu = |V(D)| \cdot \binom{W^*}{2}$. Therefore, we have $\sum_{C \in \mathcal{C}(G-S)} \binom{C}{2} \leq |V(D)| \cdot \binom{W^*}{2}$. Applying Proposition 1, we know that each component in $\mathcal{C}(G - S)$ must have W^* vertices. We associate each component with some vertex $u \in V(D)$. Note that K_u contains $2(k+3)$ vertices and I_u contains $(k+3)(w_{big} + w_{vmax} - w_V(v))$ vertices. Therefore, $W^* - |V(K_u)| - |V(I_u)| = (k+3)w_V(u)$. Since each chain H_{uv} or H_{vu} , v is a neighbor of u , contributes $(k+3)x$ vertices, for some x , to the component associated with u , the sum of those contributions must equal $(k+3)w_V(u)$. But this implies that there exists $\rho : A(D) \rightarrow \mathbb{N} \times \mathbb{N}$ such that for each $uv, vu \in A(D)$, $\rho(uv) \in \varphi(uv)$, $\rho(vu) \in \varphi(vu)$ and $\sum_{v \in N^+(u)} \text{fir}(\rho(uv)) + \sum_{v \in N^-(u)} \text{sec}(\rho(vu)) = w_V(u)$. \square

Theorem 2 *CNC is $W[1]$ -hard when parameterized by solution size and the treewidth of the input graph.*

References

1. Addis, B., Summa, M.D., Grosso, A.: Removing critical nodes from a graph: complexity results and polynomial algorithms for the case of bounded treewidth. Optimization online (www.optimization-online.org) (2011)
2. Bodlaender, H.L., Lokshtanov, D., Penninkx, E.: Planar capacitated dominating set is $W[1]$ -hard. In: IWPEC, *Lecture Notes in Computer Science*, vol. 5917, pp. 50–60. Springer (2009)
3. Cygan, M., Fomin, F.V., Kowalik, L., Lokshtanov, D., Marx, D., Pilipczuk, M., Pilipczuk, M., Saurabh, S.: Parameterized Algorithms. Springer (2015)
4. Di Summa, M., Grosso, A., Locatelli, M.: Complexity of the critical node problem over trees. *Comput. Oper. Res.* **38**(12), 1766–1774 (2011)
5. Diestel, R.: Graph Theory, 4th Edition, *Graduate texts in mathematics*, vol. 173. Springer (2012)
6. Downey, R.G., Fellows, M.R.: Parameterized complexity. Springer-Verlag (1997)
7. Flum, J., Grohe, M.: Parameterized Complexity Theory. Texts in Theoretical Computer Science. An EATCS Series. Springer (2006)
8. Grohe, M., Marx, D.: On tree width, bramble size, and expansion. *Journal of Combinatorial Theory Series B* **99**(1), 218–228 (2009)
9. Hermelin, D., Kaspi, M., Komusiewicz, C., Navon, B.: Parameterized complexity of critical node cuts. *Theor. Comput. Sci.* **651**, 62–75 (2016)

-
10. Marx, D.: Can you beat treewidth? *Theory of Computing* **6**(1), 85–112 (2010)
 11. Niedermeier, R.: *Invitation to fixed-parameter algorithms*. Oxford Lecture Series in Mathematics and Its Applications. Oxford University Press (2006)
 12. Ventresca, M.: Global search algorithms using a combinatorial unranking-based problem representation for the critical node detection problem. *Comput. Oper. Res.* **39**(11), 2763–2775 (2012)
 13. Ventresca, M., Aleman, D.: A derandomized approximation algorithm for the critical node detection problem. *Comput. Oper. Res.* **43**, 261–270 (2014)