

Edge stability in secure graph domination

Anton Pierre Burger, Alewyn Petrus Villiers, Jan Harm Vuuren

► **To cite this version:**

Anton Pierre Burger, Alewyn Petrus Villiers, Jan Harm Vuuren. Edge stability in secure graph domination. *Discrete Mathematics and Theoretical Computer Science, DMTCS*, 2015, Vol. 17 no. 1 (in progress) (1), pp.103–122. hal-01196864

HAL Id: hal-01196864

<https://hal.inria.fr/hal-01196864>

Submitted on 10 Sep 2015

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.

Edge stability in secure graph domination

Anton Pierre Burger^{1*} Alewyn Petrus de Villiers^{2†} Jan Harm van Vuuren²

¹Department of Logistics, Stellenbosch University, Private Bag XI, Matieland, 7602, South Africa

²Department of Industrial Engineering, Stellenbosch University, Private Bag XI, Matieland, 7602, South Africa

received 27th June 2014, revised 6th Jan. 2015, accepted 9th Feb. 2015.

A subset X of the vertex set of a graph G is a *secure dominating set* of G if X is a dominating set of G and if, for each vertex u not in X , there is a neighbouring vertex v of u in X such that the swap set $(X - \{v\}) \cup \{u\}$ is again a dominating set of G . The *secure domination number* of G is the cardinality of a smallest secure dominating set of G . A graph G is *p -stable* if the largest arbitrary subset of edges whose removal from G does not increase the secure domination number of the resulting graph, has cardinality p . In this paper we study the problem of computing p -stable graphs for all admissible values of p and determine the exact values of p for which members of various infinite classes of graphs are p -stable. We also consider the problem of determining analytically the largest value ω_n of p for which a graph of order n can be p -stable. We conjecture that $\omega_n = n - 2$ and motivate this conjecture.

Keywords: Secure domination, graph protection, edge removal.

1 Introduction

Let $G = (V, E)$ be a simple graph of order n . A set $D \subseteq V$ is a *dominating set* of G if each vertex $v \in V - D$ is adjacent to a vertex in D . A dominating set $X \subseteq V$ of G is *secure dominating* if, for each vertex $u \in V - X$, there exists a vertex $v \in N(u) \cap X$ such that the *swap set* $(X - \{v\}) \cup \{u\}$ is again a dominating set of G , where $N(u)$ denotes the open neighbourhood of u . In this case v is said to *defend* u . A vertex $u \in V - X$ is an *external private neighbour* of a vertex $v \in X$ with respect to some set X if $N(u) \cap X = \{v\}$ and a vertex $w \in V$ is a *universal vertex* of G if it is adjacent *all* the vertices in $V - \{w\}$. The minimum cardinality of a secure dominating set of G is called the *secure domination number* of G and is denoted by $\gamma_s(G)$. For the graph G_1 in Figure 1, for example, $\gamma_s(G_1) = 2$. Noting that at least one vertex in $\{v_2, v_3\}$ must be included in any secure dominating set of G_1 , it follows that G_1 has three minimum secure dominating sets (up to isomorphism), as shown in the figure. For the minimum secure dominating set in Figure 1(a), v_3 is defended by v_2 , while v_4 and v_5 are both defended by v_1 . The vertex v_2 is a universal vertex of G_1 while the vertex v_3 is an external private neighbour of v_2 with respect to the minimum secure dominating set in Figure 1(a).

A number of general bounds have been established for the parameter $\gamma_s(G)$ in [9], and exact values of $\gamma_s(G)$ have also been established for various graph classes, such as paths, cycles, complete multipartite

*Email: apburger@sun.ac.za.

†Email: antondev@sun.ac.za and vuuren@sun.ac.za.

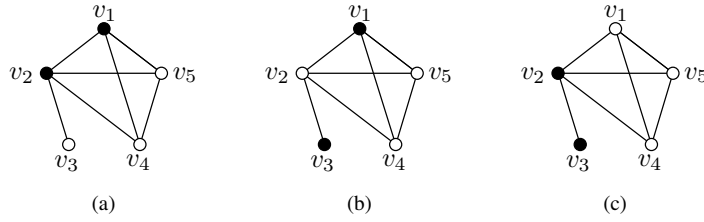


Fig. 1: All the minimum secure dominating sets (up to isomorphism) for a graph G_1 of order 5.

graphs and products of paths and cycles. Various properties of the secure dominating sets of graphs have been studied in [1, 2, 6, 7, 8, 12].

In [4] we considered the cost (measured by the increase in the secure domination number) of deleting a number of edges from a graph. We then used our knowledge of this cost function in [3] to construct the class of all graphs G of order n with the property that the *smallest* number of arbitrary edges whose removal from G necessarily increases the secure domination number of the resulting graph, is some pre-specified number q . This problem is relevant in the generic application where the vertices of G denote locations on some spatial domain, and the edges represent links between these locations along which patrolling guards may move. A secure dominating set of G represents a collection of locations at which guards may be stationed so that the entire location complex modelled by G is securely dominated. The studies in [3, 4] provide threshold information as to the number of edge failures (which may be caused randomly or by an adversary) that will necessitate the hiring of additional guards to secure the resulting location complex.

In this paper we focus our attention on the dual problem of determining graphs G with the property that the *largest* number of arbitrary edges whose removal from G necessarily does *not* increase the secure domination number of the resulting graph, is a pre-specified value p . This dual problem is relevant in the same generic application as described above, but where threshold information is sought with respect to the largest number of arbitrary edge failures which does *not* result in a requirement of additional guards to dominate the location complex securely.

The paper opens in §2 with a formalisation of the notion of p -stability in secure domination (with respect to edge removal). We characterise the class of p -stable graphs for all admissible values of p in an inductive fashion in terms of $(p - 1)$ -stable graphs in §3. In §4 we turn our attention to the intriguing problem of determining the largest value of p for which a graph of order n can be p -stable, before determining exact values of p for which paths and cycles are p -stable in §5. The paper closes in §6 with three suggestions for further work.

2 The notion of p -stability

We denote the set of all non-isomorphic graphs obtained by removing exactly $p \in \{0, 1, \dots, m\}$ edges from a given graph G of size m by $G - pe$. Similarly, $G + qe$ denotes the class of non-isomorphic graphs obtained by inserting exactly $q \in \{0, 1, \dots, \binom{n}{2} - m\}$ edges between pairs of non-adjacent vertices of a graph G of order n and size m . Furthermore, $\gamma_s(G - pe)$ denotes the set of values of $\gamma_s(H)$ as $H \in G - pe$ varies (for a fixed value of p). The notation $\gamma_s(G + qe)$ has a similar meaning. We distinguish between the graph obtained by removing a *specific* edge e from G , by writing $G - e$, and the class of graphs obtained

by removing *any* single edge from G , by writing $G - 1e$. A similar distinction is made for edge insertion. It is not hard to prove the following basic result, which shows that the secure domination number of a graph cannot decrease upon removal of a subset of its edges.

Proposition 1 ([3]) *Let G be any nonempty graph and let e be any edge of G . Then exactly one of the following statements is true:*

- (a) $\gamma_s(G - e) = \gamma_s(G)$, or
- (b) $\gamma_s(G - e) = \gamma_s(G) + 1$.

The following result is an immediate consequence of Proposition 1.

Corollary 1 *For any graph G of size at least p , $\gamma_s(G - pe) \subseteq \{\gamma_s(G), \gamma_s(G) + 1, \dots, \gamma_s(G) + p\}$.* □

It follows from Corollary 1 that the cost function

$$C_p(G) = \max \gamma_s(G - pe) - \gamma_s(G)$$

is nonnegative and bounded from above by p for all $p \in \{0, 1, \dots, m\}$. This cost function measures the *largest possible* increase in the secure domination number of a member of $G - pe$, relative to the secure domination number of a graph G of size m , when an arbitrary set of $p \in \{0, 1, \dots, m\}$ edges are removed from G . Note that a graph G is p -stable if $C_p(G) = 0$, but $C_{p+1}(G) > 0$.

The following result shows that for any graph G , the associated stability value is non-increasing as more and more edges are removed from G , as long as the secure domination number does not change as a result of the edge removals.

Proposition 2 *Let G_1 be a nonempty graph and suppose $G_2 \in G_1 - 1e$ such that $\gamma_s(G_1) = \gamma_s(G_2)$. If G_1 is p_1 -stable and G_2 is p_2 -stable, then $p_1 > p_2$.*

Proof: Let G_1 be a p_1 -stable graph and let G_2 be a p_2 -stable member of $G_1 - 1e$ such that $\gamma_s(G_1) = \gamma_s(G_2)$, but suppose, to the contrary, that $p_2 = p_1 + p'$ for some $p' \in \mathbb{N}$. Then

$$\begin{aligned} C_{p_2}(G_2) &= \max \gamma_s(G_2 - p_2e) - \gamma_s(G_2) \\ &= \max \gamma_s((G_2 + 1e) - (p_2 + 1)e) - \gamma_s(G_2) \\ &\geq \max \gamma_s(G_1 - (p_1 + p' + 1)e) - \gamma_s(G_1) \\ &= \max \gamma_s((G_1 - p_1e) - (p' + 1)e) - \gamma_s(G_1) \\ &\geq 1, \end{aligned}$$

contradicting the p_2 -stability of G_2 . □

3 Computing the class of p -stable graphs of order n

Let \mathcal{S}_n^p be the class of non-isomorphic p -stable graphs of order $n \geq 2$. We open this section with a characterisation of the graph class \mathcal{S}_n^p in terms of the graph class \mathcal{S}_n^{p-1} for any $p \in \mathbb{N}$.

Proposition 3 A graph G of size at least $p > 0$ is p -stable if and only if

- (a) $\gamma_s(H) = \gamma_s(G)$ for each $H \in G - 1e$ and
- (b) each member of $G - 1e$ is r -stable for some $r \geq p - 1$ and at least one member of $G - 1e$ is $(p - 1)$ -stable.

Proof: Let G be a p -stable graph for some $p > 0$. Then $\gamma_s(G) = \gamma_s(H)$ for all graphs $H \in G - 1e$, implying the necessity of (a). The necessity of (b) is established by contradiction. Suppose, contrary to (b), that there exists an r -stable graph $\hat{H} \in G - 1e$ for some $r < p - 1$. Then,

$$\begin{aligned}
 C_p(G) &= \max \gamma_s(G - pe) - \gamma_s(G) \\
 &= \max \gamma_s((G - 1e) - (p - 1)e) - \gamma_s(G) \\
 &\geq \max \gamma_s(\hat{H} - (p - 1)e) - \gamma_s(\hat{H}) \\
 &= C_{p-1}(\hat{H}) \\
 &\geq 1,
 \end{aligned}$$

contradicting the p -stability of G . This shows that all graphs in the class $G - 1e$ are r -stable for some $r \geq p - 1$. Note, however, that by Proposition 2 there exists an r -stable graph $H' \in G - 1e$ for some $r < p$. Clearly, $r = p - 1$ in this case, thereby establishing the necessity of (b).

For the sufficiency of (a) and (b), suppose, to the contrary, that at least one member $H^* \in G - 1e$ for which $\gamma_s(H^*) = \gamma_s(G)$ is $(p - 1)$ -stable and that each member $H \in G - 1e$ for which $\gamma_s(H) = \gamma_s(G)$ is r -stable for some $r \geq p - 1$, but that G is not p -stable. Then $\max \gamma_s(G - pe) = \max \gamma_s(H - (p - 1)e) = \gamma_s(H) = \gamma_s(G)$, where the maximum is taken over all graphs $H \in G - 1e$ for which $\gamma_s(H) = \gamma_s(G)$. But $\max \gamma_s(G - (p + 1)e) \geq \gamma_s(H^* - pe) > \gamma_s(H^*) = \gamma_s(G)$, contradicting the supposition that G is not p -stable. \square

If the class \mathcal{S}_n^0 can be characterised and constructed, then the result of Proposition 3 may be used to compute the class \mathcal{S}_n^p inductively from the class \mathcal{S}_n^{p-1} for all $p \in \mathbb{N}$ and all $n \geq 2$, using the class \mathcal{S}_n^0 as the base case. We therefore pose the following open problem.

Problem 1 Characterise the class \mathcal{S}_n^0 of 0-stable graphs of order n .

While the above problem seems hard, it is easy to prove that \mathcal{S}_n^0 is nonempty for all $n \geq 2$. The next result follows immediately from a realisation that the complete graph \mathcal{K}_n is the only graph of order n with secure domination number 1 [5, Proposition 1].

Proposition 4 $\mathcal{K}_n \in \mathcal{S}_n^0$ for all $n \geq 2$.

In fact, it follows from Proposition 4 that any graph of order n which contains a nontrivial, complete component is a member of \mathcal{S}_n^0 . The seven graphs of order 5 in Figure 2 are, for example, all members of the graph class \mathcal{S}_5^0 by Proposition 4.

Furthermore, each member of the graph class \mathcal{S}_n^0 has the following interesting property.

Proposition 5 If $G \in \mathcal{S}_n^0$ for some $n \geq 2$, then some vertex in every minimum secure dominating set X of G has private neighbours external to X .

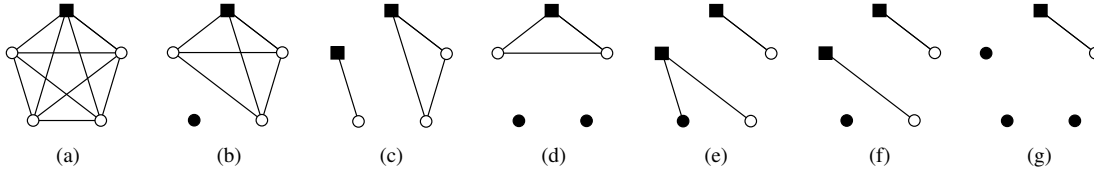


Fig. 2: A subset of the graph class \mathcal{S}_5^0 . Minimum secure dominating sets are denoted by solid vertices in each case. Square solid vertices denote members of the minimum secure dominating set which have external private neighbours.

Proof: Suppose G is 0-stable, but suppose, to the contrary, that G possesses a minimum secure dominating set X in which no vertex has private neighbours external to X . Let $e = uv$ be any edge of G . Then there are three cases to consider:

Case i: $u, v \in X$. In this case, clearly, X remains a secure dominating set of $G - e$, showing that $\gamma_s(G - e) \leq |X| = \gamma_s(G)$. But since $\gamma_s(G - e) \geq \gamma_s(G)$ by Proposition 1, it follows that $\gamma_s(G - e) = \gamma_s(G)$.

Case ii: $u, v \notin X$. Since u and v are not external private neighbours of any vertex in X , it follows from [9, Proposition 2] that they are not uniquely defended by a common vertex in X . Hence X remains a secure dominating set of $G - e$, and so $\gamma_s(G - e) = \gamma_s(G)$, as above.

Case iii: $u \in X$ and $v \notin X$. Since no vertex outside X is an external private neighbour of any vertex in X , v has another neighbour in X which does not defend any vertex outside X uniquely. Hence X remains a secure dominating set of $G - e$, and so $\gamma_s(G - e) = \gamma_s(G)$ yet again.

In all of the above cases, removal of the arbitrary edge e from G does not increase the domination number of the resulting graph, contradicting the 0-stability of G . \square

The property in Proposition 5 is, however, not sufficient to characterise the graph class \mathcal{S}_n^0 , as illustrated by the counter example in Figure 1. The graph G_1 in the figure is not a member of \mathcal{S}_5^0 ; removal of any of its edges other than v_2v_3 will cause an increase in the secure domination number. Yet every minimum secure dominating set of G_1 has at least one member which possesses private neighbours external to the set, as shown in Table 1.

Minimum secure dominating set X	Members of the set X	Private neighbours external to X
in Figure 1(a)	v_1	None
	v_2	v_3
in Figure 1(b)	v_1	v_4, v_5
	v_3	None
in Figure 1(c)	v_2	v_1, v_4, v_5
	v_3	None

Tab. 1: At least one member of any secure dominating set of G_1 possesses private neighbours external to the set.

If Problem 1 can be solved and if the resulting characterisation can be used to derive an iterative or recursive construction for the graph class \mathcal{S}_n^0 , then the inductive process of computing the graph classes $\mathcal{S}_n^1, \mathcal{S}_n^2, \mathcal{S}_n^3, \dots$ from \mathcal{S}_n^0 can be achieved by Algorithm 1. The algorithm commences by systematically considering each graph $H \in \mathcal{S}_n^{p-1}$ and proceeding to add a single edge $e \notin E(H)$ to H in Step 3, upon which the result of Proposition 3 is used to test whether $H + e$ is, in fact, p -stable. If $H + e$ is p -stable, it

is included in the class \mathcal{S}_n^p . This process is repeated for each edge $e \notin E(H)$.

Algorithm 1: The class \mathcal{S}_n^p of p -stable graphs of order n for $p > 0$

Input : The classes $\mathcal{S}_n^0, \dots, \mathcal{S}_n^{p-1}$.
Output: The class \mathcal{S}_n^p of p -stable graphs of order n .
1 **for** each $H \in \mathcal{S}_n^{p-1}$ **do**
2 **for** each $e \notin E(H)$ **do**
3 **if** p-Stable($H + e, p$) **then** $\mathcal{S}_n^p \leftarrow \mathcal{S}_n^p \cup \{H + e\}$

In Step 3 of Algorithm 1, another algorithm, Algorithm 2, is called to test whether the graph $G = H + e$ is p -stable. In Algorithm 2, each member of $G - 1e$ is examined. If a member I is found for which $\gamma_s(I) \neq \gamma_s(G)$, then G is not p -stable. Furthermore, if $G - e \notin \mathcal{S}_n^r$ for $r \geq p - 1$, then again G is not p -stable by Proposition 3.

Algorithm 2: p-Stable(G, p)

Input : A graph G of order n , a natural number p and the graph classes $\mathcal{S}_n^0, \dots, \mathcal{S}_n^{p-1}$.
Output: TRUE if $G \in \mathcal{S}_n^p$, or FALSE otherwise.
1 **if** $G \in \mathcal{S}_n^q$ for some $q \leq p$ **then**
2 **return** [FALSE]
3 **for** each $e \in E(G)$ **do**
4 **if** $\gamma_s(G - e) \neq \gamma_s(G)$ **or** $G - e \in \mathcal{S}_n^q$ for some $q < p - 1$ **then**
5 **return** [FALSE]
6 **return** [TRUE]

The graph classes $\mathcal{S}_n^0, \mathcal{S}_n^1, \mathcal{S}_n^2$ and \mathcal{S}_n^3 are shown as an example in Figure 3. The base case, the class \mathcal{S}_5^0 , shown in the outer layer of Figure 3, was found manually (by brute force). Thereafter, Algorithm 1 was used to compute the classes $\mathcal{S}_5^1, \mathcal{S}_5^2$ and \mathcal{S}_5^3 inductively. These classes are shown in the inner layers of the figure.

The cardinalities of the nonempty graph classes \mathcal{S}_n^p are listed in Table 2 for all $p \in \{0, 1, \dots, \binom{n}{2}\}$ and all $n \in \{2, 3, \dots, 9\}$.

4 The largest p for which an order n graph is p -stable

Let ω_n be the largest value of p for which there exists a graph of order n that is p -stable. It follows from Proposition 4 that $\mathcal{S}_n^0 \neq \emptyset$ for all $n \geq 2$. Proposition 3 therefore implies that

$$\mathcal{S}_n^0, \dots, \mathcal{S}_n^{\omega_n} \neq \emptyset \quad \text{and} \quad \mathcal{S}_n^{\omega_n+1}, \dots, \mathcal{S}_n^{\binom{n}{2}} = \emptyset$$

for all $n \geq 2$. It follows from Table 2 that $\omega_n = n - 2$ for all $n \in \{2, \dots, 9\}$. We believe that this linear functional relation holds in general, and hence conjecture as follows.

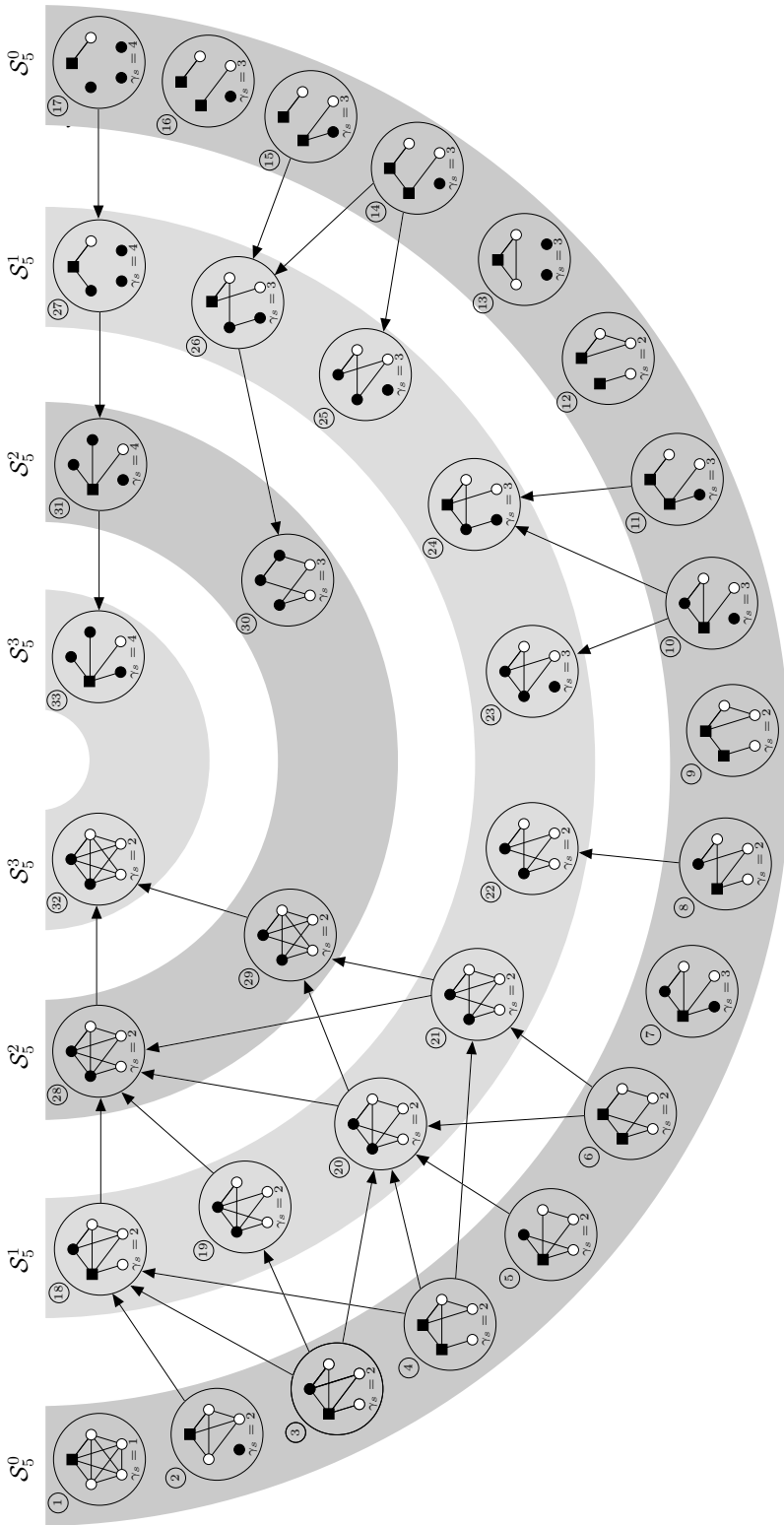


Fig. 3: The graph classes \mathcal{S}_5^0 , \mathcal{S}_5^1 , \mathcal{S}_5^2 and \mathcal{S}_5^3 . Minimum secure dominating sets are denoted by solid vertices in each case. Square vertices in these minimum secure dominating sets have external private neighbours. An arrow from a member of $G - 1e$ to G denotes the p -stability certificate relationship (in terms of graphs that are $(p - 1)$ -stable) described in Proposition 3(b).

$n \rightarrow$	2	3	4	5	6	7	8	9
$ \mathcal{S}_n^0 $	1	2	6	17	81	514	5460	107794
$ \mathcal{S}_n^1 $		1	3	10	51	355	4205	94106
$ \mathcal{S}_n^2 $			1	4	16	136	2050	52502
$ \mathcal{S}_n^3 $				2	5	32	551	16923
$ \mathcal{S}_n^4 $					2	5	70	3081
$ \mathcal{S}_n^5 $						1	6	245
$ \mathcal{S}_n^6 $							3	13
$ \mathcal{S}_n^7 $								3
Total	1	3	10	33	155	1043	12345	274667
Time		$\ll 1$	< 1	1	15	374	15895	1069220

Tab. 2: Cardinalities of the nonempty graph classes $\mathcal{S}_n^1, \dots, \mathcal{S}_n^{\binom{n}{2}}$ of orders $n \in \{2, \dots, 9\}$ computed by a C++ implementation of Algorithms 1–2 on a 3.4 GHz Intel(R) Core(TM) i7-3770 processor with 8 GiB RAM running in Ubuntu 12.04. The Boost graph library [13] was used for isomorphism testing. The classes $\mathcal{S}_2^0, \mathcal{S}_3^0, \dots, \mathcal{S}_9^0$ were found by brute force and the constructions of these classes were not included in the time measurements in the last row of the table (which are measured in seconds).

Conjecture 1 $\omega_n = n - 2$ for all $n \geq 2$.

Although we are unable to prove Conjecture 1, we further substantiate this conjecture and establish bounds on ω_n in this section.

4.1 Upper bounds on ω_n

It is easy to show that ω_n is bounded from above by a linear function of n .

Proposition 6 Suppose u and v are two adjacent vertices of a graph G . Then G is p -stable for some $p \leq \deg(u) + \deg(v) - 2$.

Proof: Let u and v be two adjacent vertices in G , and let H be the graph obtained by removing all the edges from G that are incident to u or v , except for the edge uv . Then H contains $\deg(u) + \deg(v) - 2$ edges fewer than G and one component more than G . Furthermore, one of these components is isomorphic to the complete graph \mathcal{K}_2 , which is 0-stable by Proposition 4. Hence it is possible to increase the secure domination number of G by removing more than $\deg(u) + \deg(v) - 2$ edges, and so G is not p -stable for any $p \geq \deg(u) + \deg(v) - 1$. \square

The following three consequences immediately follow from Proposition 6.

Corollary 2 A connected graph with maximum degree Δ is p -stable for some $p \leq 2(\Delta - 1)$.

Corollary 3 A connected graph with minimum degree δ and maximum degree Δ which contains a universal vertex is p -stable for some $p \leq \Delta + \delta - 3$.

Corollary 4 $\omega_n \leq 2n - 4$ for all $n \geq 2$.

When further restrictions are placed on the graph, then improvements on the above bounds, such as the following, may be obtained.

Proposition 7 If G contains a vertex v such that $\gamma_s(G - v) \geq \gamma_s(G)$, then G is p -stable for some $p \leq \deg(v) - 1 \leq \Delta - 1$.

Proof: Let v be a vertex of G such that $\gamma_s(G - v) \geq \gamma_s(G)$ and let H be the graph obtained by removing all edges from G that are incident to v . Then $\gamma_s(H) = \gamma_s(G - v) + 1 \geq \gamma_s(G) + 1 > \gamma_s(G)$. Hence it is possible to increase the secure domination number of G by removing $\deg(v)$ edges from G , and so G is p -stable for some $p \leq \deg(v) - 1 \leq \Delta - 1$. \square

The following corollaries are immediate consequences of Proposition 7.

Corollary 5 *If G contains a vertex v such that $\gamma_s(G - v) \geq \gamma_s(G)$, then G is p -stable for some $p \leq n - 2$.*

Corollary 6 *If G is an $(n - 2)$ -stable graph, then $\gamma_s(G - v) < \gamma_s(G)$ for any non-universal vertex v of G .*

Although a vertex v for which $\gamma_s(G - v) \geq \gamma_s(G)$ may often be found in a graph G , this requirement is not necessary for the result of Corollary 5. For example, the complete bipartite graph $\mathcal{K}_{4,4}$ has no such vertex, yet it is possible to prove the following result.

Proposition 8 $\mathcal{K}_{4,4} \in \mathcal{S}_8^6$.

The proof of Proposition 8 is rather lengthy, consists of many cases and is not particularly instructive. The proof is therefore omitted here, but may be found in Appendix A. The result of Proposition 8 seems to be an isolated instance. The graph in Figure 4, for example, is a member of $\mathcal{K}_{r,r} - 2(r - 1)e$ which has no secure dominating set of cardinality 4. This shows that Proposition 8 cannot be generalised to $\mathcal{K}_{r,r}$ and hence that $\mathcal{K}_{r,r} \notin \mathcal{S}_n^{n-2}$ for all $n = 2r$, where $r > 4$.

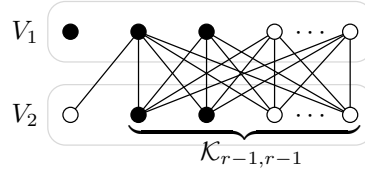


Fig. 4: A member of $\mathcal{K}_{r,r} - 2(r - 1)e$ which has no secure dominating set of cardinality 4. A minimum secure dominating set of cardinality 5 is indicated by the solid vertices.

The following result is a similarly isolated case.

Proposition 9 $\mathcal{K}_{3,3,3} \in \mathcal{S}_9^7$.

The proof of Proposition 9 is again rather lengthy and may be found in Appendix B. The graph in Figure 5 is a member of $\mathcal{K}_{r,r,r} - (3r - 2)e$ which has no secure dominating set of cardinality 3 and hence $\mathcal{K}_{r,r,r} \notin \mathcal{S}_n^{n-2}$ for $n = 3r$, where $r \geq 3$. This shows that the result of Proposition 9 cannot be generalised to $\mathcal{K}_{r,r,r}$.

4.2 A lower bound on ω_n

We next turn our attention to establishing a lower bound on ω_n .

Proposition 10 (Stability of stars) *For any integer $n \geq 2$, $\mathcal{K}_{1,n-1} \in \mathcal{S}_n^{n-2}$.*

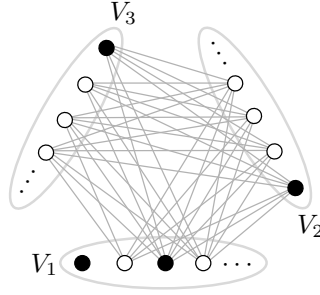


Fig. 5: A member of $\mathcal{K}_{r,r,r} - (3r - 2)e$ which has no secure dominating set of cardinality 3. A minimum secure dominating set of cardinality 4 is indicated by the solid vertices.

Proof: The result is an immediate consequence of [4, Theorem 3], which states that

$$C_p(\mathcal{K}_{1,n-1}) = \begin{cases} 0 & \text{if } 0 \leq p \leq n - 2 \\ 1 & \text{if } p = n - 1 \end{cases}$$

for the star graph $\mathcal{K}_{1,n-1}$ of order n . □

We therefore have the following corollary.

Corollary 7 $\omega_n \geq n - 2$ for all $n \geq 2$.

Our next result disqualifies large partitions of any sufficiently large independent set of a graph from forming part of a minimum secure dominating set of the graph.

Proposition 11 *Let G be a graph for which $\gamma_s(G) = k$. If G contains an independent set S of cardinality at least $k + 1$, then every minimum secure dominating set of G contains at most $k - 2$ vertices of S .*

Proof: By contradiction. Suppose G contains an independent set S of cardinality at least $k + 1$ and let X be a minimum secure dominating set of G . There are two cases to consider:

Case i: $|X \cap S| = k - 1$. In this case X contains a single vertex, x (say), of $V(G) - S$ and there are at least two vertices, y and z (say), in the set $S - X$. Then x is adjacent to both y and z (for otherwise y and z are not dominated). However, since y and z are nonadjacent, they are not defended by x . But clearly y and z are also not defended by any vertex in $X - \{x\}$, a contradiction.

Case ii: $|X \cap S| = k$. In this case $X \subset S$. But then no vertex in $S - X$ is dominated, a contradiction. These contradictions show that $|X \cap S| \leq k - 2$, as required. □

It follows from the contrapositive of the special case where $k = 2$ in Proposition 11 that the secure domination number of the graph

$$H = \mathcal{K}_{1, \underbrace{3, 3, \dots, 3}_{\ell \text{ terms}}}$$

is at least 3. But since $H \in \mathcal{K}_n - 3\ell e = \mathcal{K}_n - (n - 1)e = (\mathcal{K}_n - e) - (n - 2)e$, for $n = 3\ell + 1$, it follows that $\mathcal{K}_n - e$ is not p -stable for any $p \geq n - 2$ if $n \equiv 1 \pmod{3}$. Therefore, $\mathcal{K}_n - e \notin \mathcal{S}_n^{n-2}$ if $n \equiv 1 \pmod{3}$.

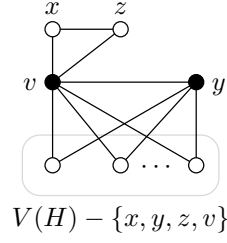


Fig. 6: A subgraph of H for which x, y, z are three consecutive vertices on a cycle of \overline{H} .

Despite this counter example, we next show that the graph class \mathcal{S}_n^{n-2} nevertheless contains the graph $\mathcal{K}_n - e$ if $n \equiv 0, 2 \pmod{3}$.

Proposition 12

If $n \geq 3$ is a natural number such that $n \equiv 0, 2 \pmod{3}$, then $\mathcal{K}_n - e \in \mathcal{S}_n^{n-2}$.

Proof: For any integer $n \geq 3$, the graph $\mathcal{K}_n - e$ contains a vertex v of degree $n - 1$. Removal of the $n - 1$ edges incident to v yields the graph $\mathcal{K}_1 \cup \mathcal{K}_{n-1} - e$. Since $\gamma_s(\mathcal{K}_n - e) = \gamma_s(\mathcal{K}_{n-1} - e) = 2$, but $\gamma_s(\mathcal{K}_1 \cup \mathcal{K}_{n-1} - e) = 1 + 2 = 3$, it therefore follows that

$$\mathcal{K}_n - e \text{ is not } p\text{-stable for any integer } p \geq n - 1. \quad (1)$$

Suppose now that $H \in \mathcal{K}_n - (n - 1)e$. Then it follows by the pigeonhole principle that there is one vertex of H with degree at least $n - 2$ and another vertex of H of degree at least $n - 3$. We consider three cases:

Case i: *At least one vertex of H has degree $n - 1$.* There are three further subcases to consider.

Case i(a): *At least two vertices of H have degree $n - 1$ each.* In this case any two universal vertices form a secure dominating set of H .

Case i(b): *Exactly one vertex of H has degree $n - 1$ and at least one vertex of H has degree $n - 2$.* In this case the universal vertex and any vertex of degree $n - 2$ form a secure dominating set of H .

Case i(c): *Exactly one vertex of H , v (say), has degree $n - 1$, and no vertex of H has degree $n - 2$.* In this case each vertex in $H - v$ has degree $n - 3$. Since every vertex of \overline{H} other than v therefore has degree 2, each component of $\overline{H} - v$ is a cycle. But since $n \not\equiv 1 \pmod{3}$, at least one of these cycles, C (say), is not a triangle. Let x, y and z be three consecutive vertices on C . Then x and z are adjacent in H and y is adjacent to neither x nor z in H . But since the degree of y in H is $n - 3$, y is therefore adjacent to all the vertices in $V(H) - \{x, y, z\}$. Hence the graph in Figure 6 is a subgraph of H and so $\{v, y\}$ is a secure dominating set of H , with v defending itself as well as x and z , and y defending itself and all the vertices in $V(H) - \{x, y, z, v\}$.

Case ii: *No vertex of H has degree $n - 1$.* In this case \overline{H} has size $n - 1$ and $\delta(\overline{H}) \geq 1$. Therefore at least one component of \overline{H} is a nontrivial tree T . Since all trees are bipartite, let V_1 and V_2 be the partite sets of T . Then the set $\{x, y\}$, where $x \in V_1$ and $y \in V_2$, is a secure dominating set of H , since x defends all the vertices in V_1 , y defends all the vertices in V_2 , and both x and y defend the vertices in $V(H) - V_1 - V_2$.

In both the above cases $\gamma_s(H) = 2$ and hence $\mathcal{K}_n - e$ is p -stable for some $p \geq n - 2$. The result therefore follows from (1). \square

It follows from Propositions 8–12 that the class of graphs

$$\Lambda_n = \begin{cases} \{\mathcal{K}_{1,7}, \mathcal{K}_8 - e, \mathcal{K}_{4,4}\} & \text{if } n = 8 \\ \{\mathcal{K}_{1,8}, \mathcal{K}_9 - e, \mathcal{K}_{3,3,3}\} & \text{if } n = 9 \\ \{\mathcal{K}_{1,n-1}\} & \text{if } n \equiv 1 \pmod{3} \\ \{\mathcal{K}_{1,n-1}, \mathcal{K}_n - e\} & \text{otherwise} \end{cases} \quad (2)$$

is a subset of \mathcal{S}_n^{n-2} for all $n \geq 3$. We are unaware of any graphs in the class $\mathcal{S}_n^{n-2} \setminus \Lambda_n$ and conjecture as follows.

Conjecture 2 $\mathcal{S}_n^{n-2} = \Lambda_n$ for all $n \geq 3$.

Our final result of this section shows that the validity of Conjecture 2 would imply the validity of Conjecture 1.

Proposition 13 *If $\Lambda_n = \mathcal{S}_n^{n-2}$, then $\omega_n = n - 2$.*

Proof: By contradiction. Suppose $\Lambda_n = \mathcal{S}_n^{n-2}$, but assume, to the contrary, that $\mathcal{S}_n^{n-1} \neq \emptyset$. Let $G \in \mathcal{S}_n^{n-1}$. Then it follows from Proposition 3 that there is a member $H \in G - 1e$ of the class \mathcal{S}_n^{n-2} such that $\gamma_s(G) = \gamma_s(H)$. There are three cases to consider:

Case i: $n \neq 8, 9$. In this case $H \not\cong \mathcal{K}_{1,n-1}$, because $\gamma_s(\mathcal{K}_{1,n-1}) = n - 1 > n - 2 = \gamma_s(\mathcal{K}_{1,n-1} + e)$ as a result of the triangle in $\mathcal{K}_{1,n-1} + e$. Furthermore, $H \not\cong \mathcal{K}_n - e$, because $\gamma_s(\mathcal{K}_n - e) = 2 > 1 = \gamma_s(\mathcal{K}_n)$. We therefore have a contradiction in this case.

Case ii: $n = 8$. In this case, additionally $H \not\cong \mathcal{K}_{4,4}$, because $\gamma_s(\mathcal{K}_{4,4}) = 4$ by [9, Proposition 11], yet $\Psi'(2, 1, 4, 0, 0)$ is a certificate showing that $\gamma_s(\mathcal{K}_{4,4} + e) \leq 3$ [5, Proposition 3]. This is again a contradiction.

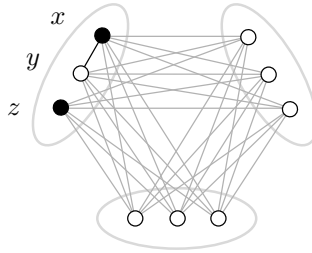


Fig. 7: The graph $\mathcal{K}_{3,3,3} + e$, which admits $\{x, y\}$ as secure dominating set.

Case iii: $n = 9$. In this case, additionally $H \not\cong \mathcal{K}_{3,3,3}$, because $\gamma_s(\mathcal{K}_{3,3,3}) = 3$ by [9, Proposition 11], yet $\mathcal{K}_{3,3,3} + e$ is isomorphic to the graph in Figure 7, which admits $\{x, y\}$ as secure dominating set, showing that $\gamma_s(\mathcal{K}_{3,3,3} + e) \leq 2$, yet again a contradiction.

The above contradictions show that $\mathcal{S}_n^{n-1} = \emptyset$ and hence that $\omega_n \leq n - 2$. The desired result therefore follows from Corollary 7. \square

5 Paths and Cycles

In this section we consider the stability of paths and cycles. We start with paths.

Proposition 14 (Stability of paths)

The only paths that are 1-stable are \mathcal{P}_3 and paths of the form $\mathcal{P}_{5+7\ell}$ for some $\ell \in \mathbb{N}_0$. All other paths are 0-stable.

Proof: It is easily verified exhaustively that the paths \mathcal{P}_2 and \mathcal{P}_4 are 0-stable, and that the paths \mathcal{P}_3 and \mathcal{P}_5 are 1-stable. Suppose, therefore, that $n \geq 6$. It follows from [9, Theorem 12(d)] that $\gamma_s(\mathcal{P}_n) = \lceil 3n/7 \rceil$. Removal of the fifth edge from \mathcal{P}_n yields the forest $\mathcal{P}_5 \cup \mathcal{P}_{n-5}$ for which

$$\gamma_s(\mathcal{P}_5 \cup \mathcal{P}_{n-5}) = \left\lceil \frac{3(5)}{7} \right\rceil + \left\lceil \frac{3(n-5)}{7} \right\rceil = 3 + \left\lceil \frac{3n}{7} - 2 - \frac{1}{7} \right\rceil = 1 + \left\lceil \frac{3n-1}{7} \right\rceil,$$

again by [9, Theorem 12(d)]. Therefore $\gamma_s(\mathcal{P}_5 \cup \mathcal{P}_{n-5}) > \gamma_s(\mathcal{P}_n)$, unless $3n \equiv 1 \pmod{7}$, which has the unique solution $n \equiv 5 \pmod{7}$. For any $n \neq 7\ell + 5$, the path \mathcal{P}_n is therefore 0-stable.

If $n = 7\ell + 5$ for some $\ell \in \mathbb{N}$, then $\gamma_s(\mathcal{P}_n) = \lceil 3n/7 \rceil = 3\ell + 3$. Removal of the k -th edge from \mathcal{P}_n yields the forest $\mathcal{P}_k \cup \mathcal{P}_{n-k}$ for which

$$\gamma_s(\mathcal{P}_k \cup \mathcal{P}_{n-k}) = \left\lceil \frac{3k}{7} \right\rceil + \left\lceil \frac{3(7\ell+5-k)}{7} \right\rceil = \left\lceil \frac{3k}{7} \right\rceil + 3\ell + 2 + \left\lceil \frac{1-3k}{7} \right\rceil.$$

Since $\gamma_s(\mathcal{P}_n) \leq \gamma_s(\mathcal{P}_k \cup \mathcal{P}_{n-k})$, it follows that $\lceil 3k/7 \rceil + \lceil (1-3k)/7 \rceil \geq 1$. But by taking $a = 3k$ and $b = 7$ in the identity $\lceil a/b \rceil + \lceil (1-a)/b \rceil \leq 1$, which holds for any $a, b \in \mathbb{Z}$ with $b \neq 0$, it follows that $\lceil 3k/7 \rceil + \lceil (1-3k)/7 \rceil \leq 1$, so that, in fact, $\lceil 3k/7 \rceil + \lceil (1-3k)/7 \rceil = 1$. We conclude that $\gamma_s(\mathcal{P}_n) = \gamma_s(\mathcal{P}_k \cup \mathcal{P}_{n-k})$ for any $k \in \{1, \dots, n-1\}$ if $n = 7\ell + 5$, showing that \mathcal{P}_n is p -stable for some $p \geq 1$ in this case.

However, removal of the first and second edges from $\mathcal{P}_{7\ell+5}$ yields the forest $2\mathcal{P}_1 \cup \mathcal{P}_{7\ell+3}$ for which $\gamma_s(2\mathcal{P}_1 \cup \mathcal{P}_{7\ell+3}) = 2\lceil 3/7 \rceil + \lceil 3(7\ell+3)/7 \rceil = 3\ell + 4 > \gamma_s(\mathcal{P}_n)$, showing that $\mathcal{P}_{7\ell+5}$ is not p -stable for any $p > 1$. We therefore conclude that $\mathcal{P}_{7\ell+5}$ is 1-stable. \square

The stability results for cycles other than \mathcal{C}_3 follow immediately from Proposition 14 upon realisation that any edge removal from such a cycle produces a path of the same order. The cycle \mathcal{C}_3 is an exception merely because it is also a complete graph.

Proposition 15 (Stability of cycles)

The only cycles that are 2-stable are cycles of the form $\mathcal{C}_{5+7\ell}$ for some $\ell \in \mathbb{N}_0$. All other cycles, except \mathcal{C}_3 , are 1-stable. Finally, \mathcal{C}_3 is 0-stable.

6 Further work

We propose the following three problems for future work:

1. In §3 we showed how the graph classes $\mathcal{S}_n^1, \dots, \mathcal{S}_n^{\omega_n}$ can be computed inductively from the class \mathcal{S}_n^0 for all $n \geq 2$. We therefore propose the design of a construction process for the graph class \mathcal{S}_n^0 (Problem 1) as further work.
2. In §4 we showed that the graph class Λ_n in (2) is a subclass of \mathcal{S}_n^{n-2} for all $n \geq 2$. We believe that $\mathcal{S}_n^{n-2} = \Lambda_n$ for all $n \geq 2$ (Conjecture 2), but are unable to prove this. We therefore propose the proof of Conjecture 2 or, alternatively, demonstration of a graph in the class $\mathcal{S}_n^{n-2} \setminus \Lambda_n$ as a problem for future research.
3. Although the proof of Conjecture 2 would establish the truth of Conjecture 1 (by Proposition 13), it may of course be possible that Conjecture 1 is true even if Conjecture 2 is false. We therefore propose the resolution of Conjecture 1 as an independent problem.

Acknowledgements

The anonymous referees are thanked for their constructive criticism which has improved the quality of the paper. Research towards this paper was financially supported by the South African National Research Foundation (GUNs 70593, 77248 and 81558). The last author was additionally supported by a grant from Sub-committee A of Stellenbosch University's Research Committee.

References

- [1] AP BURGER, EJ COCKAYNE, WR GRÜNDLINGH, CM MYNHARDT, JH VAN VUUREN & W WINTERBACH, 2004. *Finite order domination in graphs*, Journal of Combinatorial Mathematics and Combinatorial Computing, **49**, 159–175.
- [2] AP BURGER, EJ COCKAYNE, WR GRÜNDLINGH, CM MYNHARDT, JH VAN VUUREN & W WINTERBACH, 2004. *Infinite order domination in graphs*, Journal of Combinatorial Mathematics and Combinatorial Computing, **50**, 179–194.
- [3] AP BURGER, AP DE VILLIERS & JH VAN VUUREN. *Edge criticality in secure graph domination*, Discrete Applied Mathematics, submitted.
- [4] AP BURGER, AP DE VILLIERS & JH VAN VUUREN, 2014. *The cost of edge failure with respect to secure graph domination*, Utilitas Mathematica, **95**, 329–339.
- [5] AP BURGER, AP DE VILLIERS & JH VAN VUUREN. *On minimum secure dominating sets of graphs*, Quaestiones Mathematicae, submitted.
- [6] AP BURGER, MA HENNING & JH VAN VUUREN, 2008. *Vertex covers and secure domination in graphs*, Quaestiones Mathematicae, **31(2)**, 163–171.
- [7] EJ COCKAYNE, 2007. *Irredundance, secure domination and maximum degree in trees*, Discrete Mathematics, **307**, 12–17.
- [8] EJ COCKAYNE, O FAVARON & CM MYNHARDT, 2003. *Secure domination, weak roman domination and forbidden subgraphs*, Bulletin of the Institute of Combinatorics and its Applications, **39**, 87–100.
- [9] EJ COCKAYNE, PJP GROBLER, WR GRÜNDLINGH, J MUNGANGA & JH VAN VUUREN, 2005. *Protection of a graph*, Utilitas Mathematica, **67**, 19–32.

- [10] PJP GROBLER & CM MYNHARDT, 2009. *Secure domination critical graphs*, *Discrete Mathematics*, **309**, 5820–5827.
- [11] TW HAYNES, ST HEDETNIEMI & PJ SLATER, 1998. *Fundamentals of domination in graphs*, Marcel Dekker, New York (NY).
- [12] CM MYNHARDT, HC SWART & E UNGERER, 2005. *Excellent trees and secure domination*, *Utilitas Mathematica*, **67**, 255–267.
- [13] J SIEK, LQ LEE & A LUMSDAINE, 2014. *Boost graph library*, [Online], [Cited: April 10th, 2014], Available from <http://www.boost.org/libs/graph/>.

Appendix A: Proof of Proposition 8

Suppose V_1 and V_2 are the partite sets of $\mathcal{K}_{4,4}$ and let H be a subgraph of $\mathcal{K}_{4,4}$ that is isomorphic to a member of $\mathcal{K}_{4,4} - 6e$. Since $H \subseteq \mathcal{K}_{4,4}$ and $\gamma_s(\mathcal{K}_{4,4}) = 4$ [9, Proposition 10],

$$\gamma_s(H) \geq 4. \quad (3)$$

We show, by considering a number of cases, that, in fact, $\gamma_s(H) = 4$.

The largest subgraph of $\mathcal{K}_{4,4}$ containing a vertex $v \in V_1$ with $d \in \{0, 1, 2, 3, 4\}$ private neighbours $u_1, \dots, u_d \in V_2$ is obtained by joining v to all vertices in V_2 and joining each of the three vertices in $V_1 - \{v\}$ to each of the $4 - d$ vertices in $V_2 - \{u_1, \dots, u_d\}$. Because this subgraph has size $4 + 3(4 - d) = 16 - 3d$ and H has size 10, it follows that $d \leq 2$ (i.e. H has no vertex with more than two private neighbours). Moreover, if H has a vertex with two private neighbours, then it has exactly one such vertex, v (say), and H is necessarily isomorphic to the graph in Figure 8(a). In this case H has the secure dominating set of cardinality 4 indicated by the solid vertices in the figure, showing that $\gamma_s(H) = 4$ by (3).

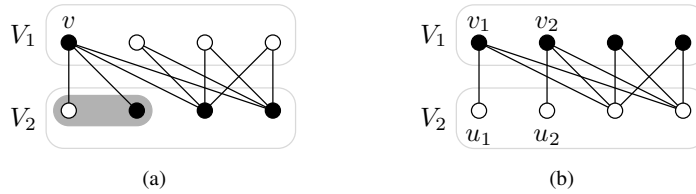


Fig. 8: The graph H (a) with a vertex with two private neighbours, and (b) two vertices, each with exactly one private neighbour.

Suppose, therefore, that no vertex in H has more than one private neighbour and let the number of vertices of H with exactly one private neighbour be $k \in \{0, 1, 2, 3, 4\}$. The largest subgraph of $\mathcal{K}_{4,4}$ containing k vertices $v_1, \dots, v_k \in V_1$, each with one private neighbour, is obtained by joining v_i to a private neighbour $u_i \in V_2$ for each $i = 1, \dots, k$ and by joining each vertex in $V_1 - \{v_1, \dots, v_k\}$ to all vertices in $V_2 - \{u_1, \dots, u_k\}$. Because this subgraph of $\mathcal{K}_{4,4}$ has size $k + 4(4 - k) = 16 - 3k$ and H has size 10, it follows that $k \leq 2$. Furthermore, if H has exactly two vertices, each with exactly one private neighbour, then H is necessarily isomorphic to the graph in Figure 8(b). In this case H again has a secure dominating set of cardinality 4, as indicated by the solid vertices in the figure, showing that $\gamma_s(H) = 4$ by (3).

We may therefore assume that exactly one vertex of H , w (say), has at most one private neighbour and that the remaining vertices of H have no private neighbours. Furthermore, since it requires at least $4 + 3 = 7$ edge removals from $\mathcal{K}_{4,4}$ to isolate two vertices of the graph, H has at most one isolated vertex. Hence we have four final cases to consider:

Case i: H has one isolated vertex, x (say), and w has one private neighbour w' . In this case x and w' cannot be in the same partite set, because the largest subgraph satisfying these conditions has size 9, as shown in Figure 9(a). There is, however, only one subgraph of size 10 of $\mathcal{K}_{4,4}$ in which x and w' are in different partite sets, as shown in Figure 9(b). In this case H yet again has a secure dominating set of cardinality 4, as indicated by the solid vertices in the figure, showing that $\gamma_s(H) = 4$ in view of (3).

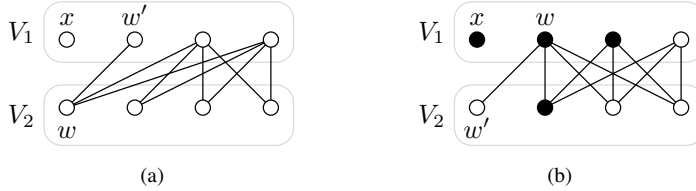


Fig. 9: The graph H with one isolated vertex x , and one vertex w which has one private neighbour w' , where (a) x and w' are in the same partite set, and (b) x and w' are in different partite sets.

Case ii: H has one isolated vertex, (x say), but no vertex with a private neighbour. Suppose $x \in V_1$ and let v_1, v_2 and v_3 be the other vertices in V_1 . Since $\deg(v_1) + \deg(v_2) + \deg(v_3) = 10$, it follows by the pigeonhole principle that at least one vertex in V_1 has degree 4; suppose this vertex is v_1 . Then, since $\deg(v_2) + \deg(v_3) = 6$, it follows by the pigeonhole principle that at least one of v_2 or v_3 has degree at least 3; suppose this vertex is v_2 and let the common neighbours of v_1 and v_2 be w_1, w_2 and w_3 . Then the remaining vertex w_4 in V_2 is adjacent to either v_2 or v_3 , for otherwise it would be a private neighbour of v_1 . If w_4 is adjacent to v_2 , then H contains the subgraph in Figure 10(a), in which case v_3 is adjacent to exactly two vertices in V_2 , w_i and w_j (say). But then H has the secure dominating set $\{x, v_1, w_i, w_j\}$ of cardinality 4. If, however, w_4 is adjacent to v_3 , then H contains the subgraph in Figure 10(b) which also has a secure dominating set of cardinality 4, as indicated by the solid vertices in the figure. In both cases, therefore, $\gamma_s(H) = 4$ by (3).

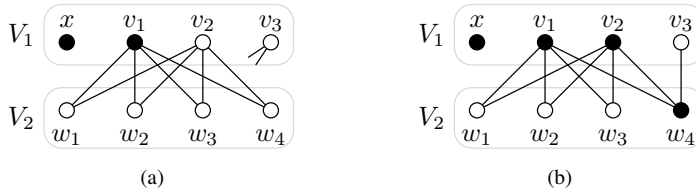


Fig. 10: Subgraphs of H with an isolated vertex, (x say), but where no vertex has a private neighbour and where (a) v_3 is adjacent to w_i and w_j , and (b) v_3 is adjacent to w_4 .

Case iii: H has no isolated vertices, and w has one private neighbour w' . Suppose $w \in V_1$ and let v_1, v_2 and v_3 be the other vertices in V_1 . Since $\deg(w) + \deg(v_1) + \deg(v_2) + \deg(v_3) = 10$, it follows by the pigeonhole principle that at least two vertices in V_1 have degree at least 3. If w has degree at least 3, let v_1 be another vertex in V_1 with degree at least 3. Then H contains the subgraph in Figure 11(a), in which case some vertex $u \in V_2$, which is adjacent to v_1 , must be adjacent to at least one other vertex in V_1 , v_3 (say). But then H has the secure dominating set $\{w, v_1, v_2, v_3\}$ of cardinality 4. If, however, w has degree 2, then two other vertices in V_1 , v_1 and v_2 (say), have degree at least 3. Then H contains the subgraph in Figure 11(b) which also has a secure dominating set of cardinality 4, as indicated by the solid vertices in the figure. In both cases, therefore, $\gamma_s(H) = 4$ by (3).

Case iv: H has no isolated vertices and no vertices with private neighbours. Let v_1, v_2, v_3 and v_4 be the vertices in V_1 . Since $\delta(H) \geq 2$, it follows by the pigeonhole principle that at least two vertices in V_1 , v_1 and v_2 (say), have

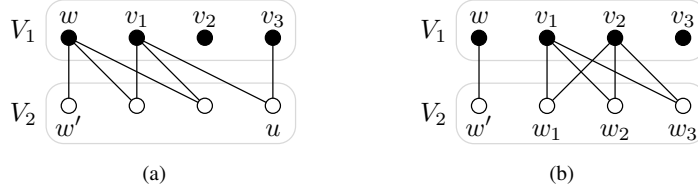


Fig. 11: The graph H with no isolated vertices, where w has one private neighbour w' and where (a) w has degree at least 3, and (b) w does not have degree at least 3.

degree 2. Furthermore, without loss of generality, either v_3 has degree 2 and v_4 has degree 4, or else both v_3 and v_4 have degree 3. If v_3 has degree 2 and v_4 has degree 4, then H contains the subgraph in Figure 12(a), in which case H has the secure dominating set $\{v_1, v_2, v_3, v_4\}$, because $N(v_1) \cup N(v_2) \cup N(v_3) = V_2$ in order to avoid private neighbours in H . In this case, therefore, $\gamma_s(H) = 4$ by (3).

Finally, if both v_3 and v_4 have degree 3, then $N(v_3) = N(v_4)$ or $N(v_3) \neq N(v_4)$. If $N(v_3) = N(v_4)$, then there is a vertex $u \in V_2$ that is adjacent to neither v_3 nor v_4 , in order to avoid private neighbours in H . Since $\delta(H) \geq 2$, u is adjacent to v_1 and v_2 , as shown in Figure 12(b), in which case H has the secure dominating set $\{v_1, v_2, v_3, v_4\}$ of cardinality 4, showing that $\gamma_s(H) = 4$ by (3). If, however, $N(v_3) \neq N(v_4)$, then some vertex $u \in V_2$ is adjacent to v_3 but not to v_4 . Since $\delta(H) \geq 2$, u is adjacent to at least one other vertex in V_1 . Assume, without loss of generality, that u is adjacent to v_1 . Then H contains the subgraph in Figure 12(c), in which case H has the secure dominating set $\{v_1, v_2, v_3, v_4\}$ of cardinality 4, showing that $\gamma_s(H) = 4$ by (3).

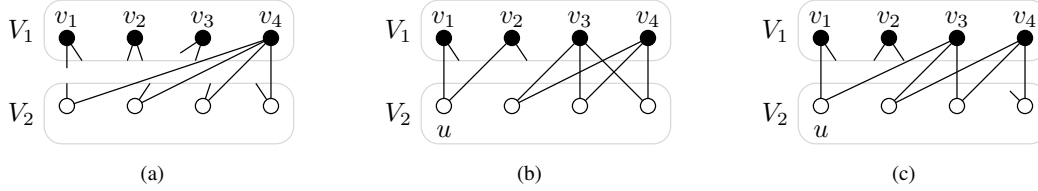


Fig. 12: The graph H with no isolated vertices and no vertices with private neighbours, where (a) $\deg(v_3) = 2$ and $\deg(v_4) = 4$, (b) $\deg(v_3) = \deg(v_4) = 3$ and $N(v_3) = N(v_4)$, and (c) $\deg(v_3) = \deg(v_4) = 3$ and $N(v_3) \neq N(v_4)$.

From the above cases we conclude that $\gamma_s(H) = 4$ and hence that $\mathcal{K}_{4,4}$ is p -stable for some $p \geq 6$. The subgraph $2\mathcal{K}_1 \cup \mathcal{K}_{3,3}$ of size $16 - 7 = 9$ of $\mathcal{K}_{4,4}$, however, has secure domination number $2 + 3 = 5$ [9, Proposition 10], showing that $\mathcal{K}_{4,4}$ is not p -stable for any $p \geq 7$. \square

Appendix B: Proof of Proposition 9

Suppose V_1, V_2 and V_3 are the partite sets of $\mathcal{K}_{3,3,3}$ and let H be a subgraph of $\mathcal{K}_{3,3,3}$ that is isomorphic to a member of $\widehat{\mathcal{K}}_{3,3,3} - 7e$. Since $H \subseteq \mathcal{K}_{3,3,3}$ and $\gamma_s(\mathcal{K}_{3,3,3}) = 3$ by Proposition [9, Proposition 11],

$$\gamma_s(H) \geq 3. \tag{4}$$

It is shown, by considering a number of cases, that, in fact, $\gamma_s(H) = 3$.

Let $V_1 = \{u_1, u_2, u_3\}$, $V_2 = \{v_1, v_2, v_3\}$ and $V_3 = \{w_1, w_2, w_3\}$. It follows from the pigeonhole principle that at least four vertices in H have degree at least 5. Furthermore, two vertices of the same partite set of H , $u_1, u_2 \in V_1$ (say), have degree at least 5. Two cases are considered.

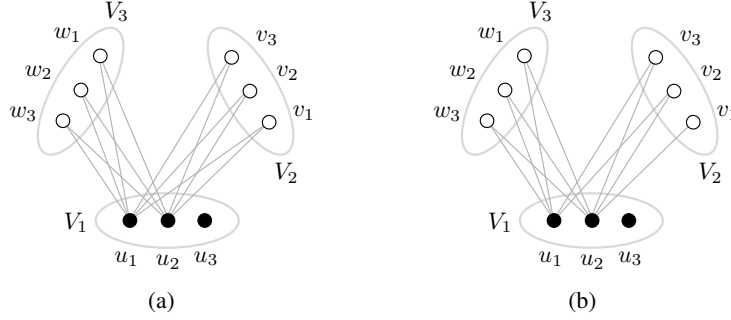


Fig. 13: Subgraphs of H with $\Delta(H) = 6$, where (a) $\deg(u_1) = \deg(u_2) = 6$, with both u_1 and u_2 defending $V_1 \cup V_2$, and (b) $\deg(u_2) = 6$ and $\deg(u_1) = 5$, with u_2 defending v_1 , and u_1 defending $(V_2 - \{v_1\}) \cup V_3$. A minimum secure dominating set is indicated by the solid vertices in each case.

Case i: $\Delta(H) = 6$. If both u_1 and u_2 have degree 6, then H contains the subgraph in Figure 13(a), in which case the partite set V_1 is a secure dominating set of H (of cardinality 3). Suppose then that only one vertex, u_2 (say), has degree 6, while u_1 has degree 5. Then H contains the subgraph in Figure 13(b), in which case the partite set V_1 is yet again a secure dominating set of H (of cardinality 3). In both cases, therefore, $\gamma_s(H) = 3$ by (4).

Case ii: $\Delta(H) \leq 5$. In this case at least two vertices, u_1 and u_2 (say), of V_1 have degree 5. It follows by the pigeonhole principle that $\delta(H) \geq 1$. However, if $\delta(H) = 1$, then H is isomorphic to either the graph in Figure 14(a), the graph in Figure 14(b) or the graph in Figure 14(c). In all of these cases $\gamma_s(H) = 3$. Assume, therefore, that $\delta(H) \geq 2$. There are two subcases to consider:

Case ii(a): $N(u_1) = N(u_2)$. In this case exactly one vertex, v_1 (say), in $V_2 \cup V_3$ is adjacent to neither u_1 nor u_2 . If v_1 and u_3 are adjacent, then H contains the subgraph in Figure 15(a), in which case V_1 is a secure dominating set of H . Suppose, therefore, that v_1 and u_3 are not adjacent. Since v_1 is not adjacent to any vertex in $V_1 \cup V_2$ and u_3 is not adjacent to any vertex in $V_1 \cup \{v_1\}$, and since $\deg(v_1) + \deg(u_3) \geq 7$, it follows that u_3 and v_1 share at least two common neighbours, w_1 and w_2 (say), in V_3 , as shown in Figure 15(b). Furthermore, since $\deg(v_1) + \deg(u_3) \leq 8$, there are at least eight edges between the vertices in V_2 and V_3 . Hence, v_2 and v_3 are both adjacent to at least one of

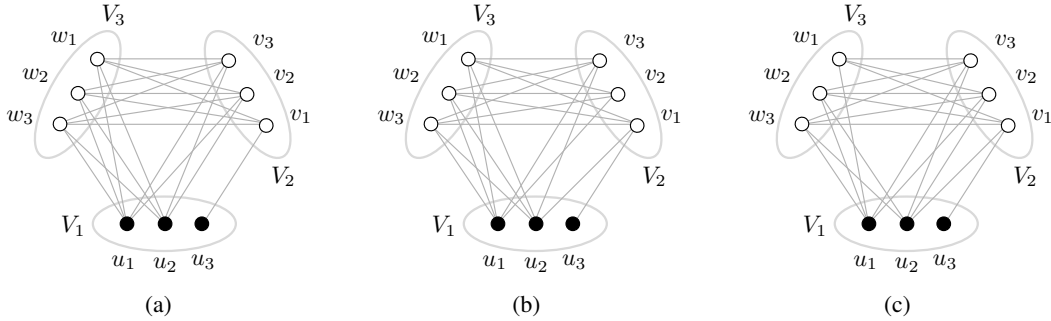


Fig. 14: The graph H with $\Delta(H) = 5$ and $\delta(H) = 1$, with (a) $\deg(v_1) = 4$, where u_3 defends v_1 and u_1 defends $V_1 \cup (V_2 - \{v_1\})$, (b) $\deg(v_1) = 5$ and $\deg(v_2) = 4$, where u_1 defends v_3 and u_1 defends $V_1 \cup (V_2 - \{v_1\})$, and (c) $\deg(v_1) = 5$ and $\deg(w_1) = 4$, where u_3 defends v_1 and u_1 defends $V_1 \cup (V_2 - \{v_1\})$. A minimum secure dominating set is indicated by the solid vertices in each case.

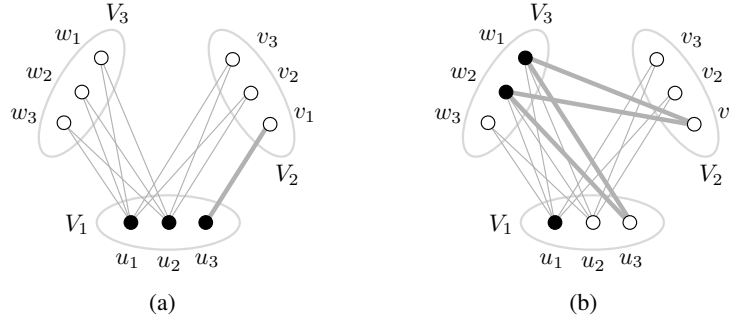


Fig. 15: Subgraphs of H with $\Delta(H) = 5$ and $\delta(H) = 2$, where u_1 and u_2 have identical neighbourhoods and where (a) u_3 and v_1 are neighbours, with u_3 defending v_1 , and both u_1 and u_2 defending the vertices in $(V_2 - \{v_1\}) \cup V_3$, and (b) u_3 and v_1 are not neighbours, with u_1 defending w_3 , and w_1 and w_2 both defending $\{u_2, u_3, v_1, v_2, v_3\}$. A minimum secure dominating set is indicated by the solid vertices in each case.

w_1 or w_2 . In this case, $\{u_1, w_1, w_2\}$ is a secure dominating set of H . In this subcase, therefore, $\gamma_s(H) = 3$ by (4).

Case ii(b): $N(u_1) \neq N(u_2)$. In this case u_1 is adjacent to a vertex, x (say), in $V_2 \cup V_3$ to which u_2 is not adjacent and, similarly, u_2 is adjacent to a vertex, y (say), in $V_2 \cup V_3$ to which u_1 is not adjacent.

Suppose first that x and y are in the same partite set. It may be assumed, without loss of generality, that $x = v_1$ and $y = v_2$. Since $\delta(H) \geq 2$, u_3 is adjacent to at least two vertices in $V_2 \cup V_3$. If u_3 is adjacent to either v_1 or v_2 , then V_1 is a secure dominating set of H , as shown in Figure 16(a). If u_3 is adjacent to neither v_1 nor v_2 , but u_3 shares a neighbour, w_1 (say), with either v_1 or v_2 , then $\{u_1, u_2, w_1\}$ is a secure dominating set of H , as shown in Figure 16(b). Finally, if u_3 is adjacent to neither v_1 nor v_2 , and u_3 shares no common neighbours with v_1 and v_2 , then u_3, v_1 and v_2 are all adjacent to distinct vertices in V_3 and u_3 is also adjacent to w_3 . It may be assumed, without loss of generality, that v_1 is adjacent to w_2 and that v_2 is adjacent to w_1 . Then V_1 is a secure dominating set of H , as

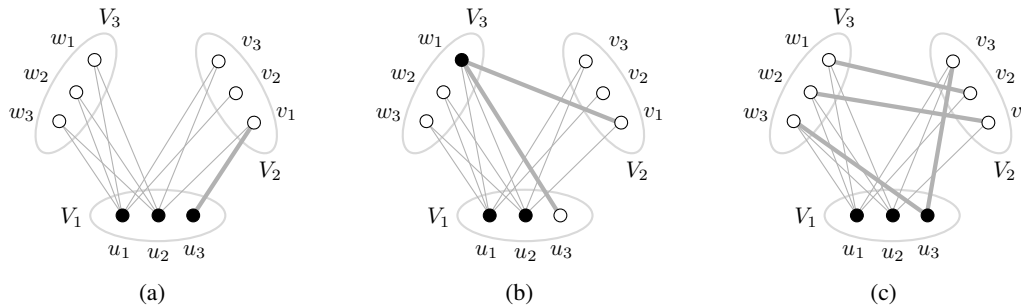


Fig. 16: Subgraphs of H with $\Delta(H) = 5$ and $\delta(H) = 2$, where u_1 and u_2 do not have identical neighbourhoods and where (a) u_3 is adjacent to v_1 , with u_3 defending v_1 and u_2 defending $(V_2 - \{v_1\}) \cup V_3$, (b) u_3 is not adjacent to v_1 or v_2 , but shares w_1 as common neighbour with them, in which case w_1 defends u_3 , while u_2 defends $(V_2 - \{v_2, w_1\}) \cup V_3$ and u_2 defends v_2 , and (c) u_3 is adjacent to neither v_1 nor v_2 and shares no common neighbour with v_1 or v_2 , in which case u_3 defends $\{v_3, w_3\}$, u_2 defends $\{v_1, w_2\}$ and u_1 defends $\{v_2, w_1\}$. A minimum secure dominating set is indicated by the solid vertices in each case.

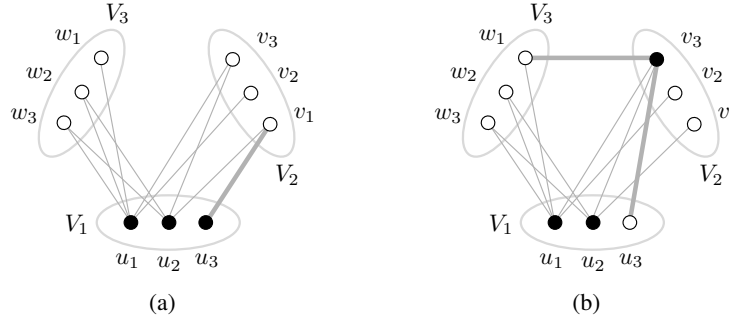


Fig. 17: Subgraphs of H with $\Delta(H) = 5$ and $\delta(H) = 2$, where u_1 and u_2 do not have identical neighbourhoods and where (a) u_3 is adjacent to v_1 , in which case u_3 defends v_1 and u_2 defends $(V_2 - \{v_1, v_2\}) \cup V_3$, while u_1 defends v_2 , and (b) u_3 is adjacent to neither v_1 nor w_1 , but u_3 shares a neighbour v_3 with w_1 , in which case v_3 defends u_3 , u_2 defends v_1 and u_1 defends $(V_2 - \{v_1, v_3\}) \cup V_3$. A minimum secure dominating set is indicated by the solid vertices in each case.

shown in Figure 16(c). In all of these cases, therefore, $\gamma_s(H) = 3$ by (4).

Suppose $x \in V_2$ and $y \in V_3$. It may be assumed, without loss of generality, that $x = v_1$ and $y = w_1$. If u_3 is adjacent to either v_1 or w_1 , or to both v_1 and w_1 , then V_1 is a secure dominating set of H , as shown in Figure 17(a). Suppose, therefore, that u_3 is adjacent to neither v_1 nor w_1 , but that u_3 shares a neighbour, z (say), with either v_1 or w_1 . It may be assumed, without loss of generality, that $z = v_3$, in which case $\{u_1, u_2, v_3\}$ is a secure dominating set of H , as shown in Figure 17(b). If u_3 is adjacent to neither v_1 nor w_1 , and u_3 shares no common neighbours with v_1 and w_1 , but v_1 and w_1 are adjacent, then $\deg(v_1) + \deg(w_1) \leq 6$, in which case $\Delta(H) = 6$, a contradiction. Finally, suppose that u_3 is adjacent to neither v_1 nor w_1 , u_3 shares no common neighbours with v_1 and w_1 , and that v_1 and w_1 are not adjacent. It may be assumed, without loss of generality, that v_1 is adjacent to w_2 and that w_1 is adjacent to w_2 . Then $\deg(v_1) + \deg(w_1) = 4$, in which case $\Delta(H) = 6$, again a contradiction. In both of the cases that did not lead to contradictions, however, $\gamma_s(H) = 3$ by (4).

From all of the above cases it is concluded that $\gamma_s(H) = 3$ and hence that $\mathcal{K}_{3,3,3}$ is p -stable for some $p \geq 7$. Finally, the subgraph of $\mathcal{K}_{3,3,3}$ in Figure 18 has size $27 - 8 = 19$ and secure domination number 4, showing that $\mathcal{K}_{3,3,3}$ is not stable for any $p \geq 8$. \square

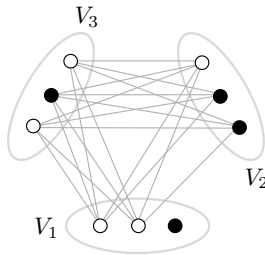


Fig. 18: A graph $H \subseteq \mathcal{K}_{3,3,3} - 8e$ for which $\gamma_s(H) = 4$. A minimum secure dominating set is indicated by the solid vertices in each case.