

Uniform star-factors of graphs with girth three*

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Abstract

A *star-factor* of a graph G is a spanning subgraph of G each component of which is a star. Recently, Hartnell and Rall studied a family \mathcal{U} of graphs satisfying the property that every star-factor of a member graph has the same number of edges. They determined the family \mathcal{U} when the girth is at least five. In this paper, we investigate the family of graphs of girth three but without leaves and determine all members of this family.

1 Introduction

Throughout this paper, all graphs considered are simple. We refer the reader to [2] for standard graph theoretic terms not defined in this paper.

Let $G = (V, E)$ be a graph with vertex set $V(G)$ and edge set $E(G)$. If G is not a forest, the length of a shortest cycle in G is called the *girth* of G . We say that a forest has an infinite girth. We shall often construct new graphs from old ones by deleting some vertices or edges. If $W \subset V(G)$, then $G - W = G[V - W]$ is the subgraph of G obtained by deleting the vertices in W and all edges incident with them. Similarly, if $E' \subset E(G)$, then $G - E' = (V(G), E(G) - E')$. We denote the degree of a vertex x

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in G by $d_G(x)$, and the set of vertices adjacent to x in G by $N_G(x)$. A *leaf* is a vertex of degree one and a *stem* is a vertex which has at least one leaf as its neighbor. A *star* is a tree isomorphic to $K_{1,n}$ for some $n \geq 1$, and the vertex of degree n is called the *center* of the star. A *star-factor* of a graph G is a spanning subgraph of G such that each component of which is a star. Clearly a graph with isolated vertices has no star-factors. It is not hard to see that every graph without isolated vertices admits a star-factor. If one limits the size of the star used, the existence of such a star-factor is non-trivial. In [1], Amahashi and Kano presented a criterion for the existence of a star-factor, i.e., $\{K_{1,1}, \dots, K_{1,n}\}$ -factor. Yu [4] obtained an upper bound on the number of edges in a graph with unique star-factor.

An *edge-weighting* of a graph G is a function $w : E(G) \rightarrow \mathbb{N}^+$, where \mathbb{N}^+ is the set of positive integers. For a subgraph H , the *weight* of H under w is the sum of all the weight values for edges belonging to H , i.e., $w(H) = \sum_{e \in E(H)} w(e)$. Motivated by the minimum cost spanning tree and the optimal assignment problems, Hartnell and Rall posed an interesting general question: for a given graph, does there exist an edge-weighting function w such that a certain type of spanning subgraphs always has the same weights. In particular, they investigated the following narrow version of the problem in which the spanning subgraph is a star-factor.

Star-Weighting Problem (Hartnell and Rall [3]): For a given graph $G = (V, E)$, is there an edge-weighting w of G such that every star-factor of G has the same weights under w ?

To start the investigation, one may consider the special case that w is a constant function, i.e., all edges in G are assigned with the same weights. In this case, every star-factor of G has the same weights if and only if all star-factors have the same number of edges. For simplicity, we assume that all edges are assigned with weight one.

We denote by \mathcal{U} the family of all graphs G such that if S_1 and S_2 are any two star-factors of G , then S_1 and S_2 have the same number of edges. Clearly, S_1 and S_2 have the same number of edges is equivalent to that they have the same number of components. Hartnell and Rall classified the family \mathcal{U} when graphs in \mathcal{U} have girth at least five and minimum degree at least two.

Theorem 1. (Hartnell and Rall [3]) *Let G be a connected graph of girth at least five and minimum degree at least two. Then all star-factors of G have the same weights if and only if G is a 5-cycle or 7-cycle.*

In this paper, we investigate the family \mathcal{U} with girth three and minimum degree at least two, and we are able to determine this family completely. The main theorem is as follows.

Theorem 2. *Let G be a connected graph of girth three and minimum degree at least two. Then all star-factors of G have the same weights if and only if G is one of the five graphs shown in Figure 1.*

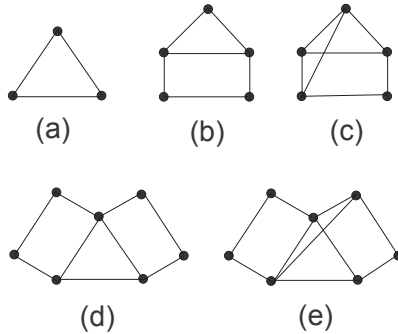


Figure 1: Graphs in \mathcal{U} with girth three and minimum degree at least two

2 Proof of Theorem 2

Note that if H is a spanning subgraph of G , then any star-factor of H is also a star-factor of G . The following lemma will be used frequently in reducing the problem of determining membership in \mathcal{U} to its spanning subgraphs.

Lemma 1. (Hartnell and Rall [3]) *Let F be a subset of $E(G)$ such that $G - F$ has no isolated vertices. If $G - F$ is not in \mathcal{U} , then G is not in \mathcal{U} .*

The above lemma implies that if G is in \mathcal{U} , then so is $G - F$.

The idea to show that a graph does not belong to \mathcal{U} is to decompose G into several components without isolated vertices and then simply find one of them not belonging to \mathcal{U} . For the proof of Theorem 2, we shall also use the following two lemmas.

Lemma 2. *Let G be a graph with a triangle such that two of its vertices are of degree two and the third is a stem, then G does not belong to \mathcal{U} .*

Proof. Let $C_3 = v_1v_2v_3$ be a triangle of G , where v_1 is a stem adjacent to a leaf u . Let S be a star-factor of the graph $G - \{v_2, v_3\}$. Note that v_1 is the center of some star T in S . Let T' be the star formed from T by adding leaves v_2 and v_3 adjacent to v_1 , and let $S' = (S - \{T\}) \cup \{T'\}$, then S' as well as $S \cup \{v_2v_3\}$ are star-factors of G having different weights. Hence $G \notin \mathcal{U}$. \square

Lemma 3. *Let G be a graph in \mathcal{U} with a triangle. If exactly one of the vertices on this triangle has degree at least three, then all of its neighbors that don't belong to this triangle must be stems.*

Proof. Suppose G is a graph satisfying the hypothesis. Let v be a vertex on the triangle of degree at least three and assume v has a neighbor x not on the triangle such that x is not a stem. By Lemma 2, x is not a leaf. Let F be the set of edges not including vx that are incident with x . The graph $G - F$ has no isolated vertices, and

the vertex v is a stem belonging to a triangle of the type that satisfies the hypothesis of Lemma 2, then $G - F$ is not in \mathcal{U} . Thus G does not belong to \mathcal{U} by Lemma 1, a contradiction. \square

Now we proceed to prove our main result.

Proof of Theorem 2. The only star-factor of a triangle C_3 has weight two, so $C_3 \in \mathcal{U}$. Assume G belongs to \mathcal{U} and has girth three and minimum degree at least two but G is not a triangle. Then G contains a triangle C_3 with at least two vertices of degree at least three by Lemma 3.

Let $C_3 = v_1v_2v_3$. We consider the following two cases.

Case 1. $d_G(v_3) = 2, d_G(v_1) \geq 3, d_G(v_2) \geq 3$.

Let F_1 be the set of edges incident with v_1 except v_1v_2 and v_1v_3 . Then $G - F_1 \in \mathcal{U}$ by Lemma 1 since no isolated vertices are created in $G - F_1$, and all neighbors of v_2 not in the triangle C_3 are stems in $G - F_1$ by Lemma 3. Let x be a neighbor of v_2 , then there exists a leaf y incident with x . By the definition of $G - F_1$, y is adjacent to v_1 in G and $d_G(y) = 2$. Let F_2 be the set of edges incident with v_2 except v_2v_1 and v_2v_3 . A similar argument yields that all neighbors of v_1 are stems in $G - F_2$ and so y is a stem in $G - F_2$. However $d_G(y) = 2$, so x is the only leaf of y in $G - F_2$. It follows that $d_G(x) = 2$ and x, y, v_1 and v_2 form a quadrangle in G . From the above discussion, we see that all neighbors of v_1 and v_2 except v_1 and v_2 are of degree two in G . Hence G is isomorphic to the graph shown in Figure 2(a) (dashed line indicates a possible edge).

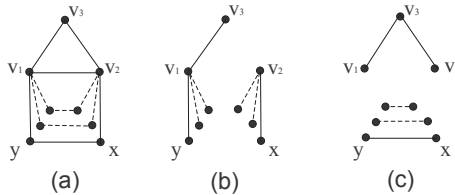


Figure 2

If $d_G(v_1) = d_G(v_2) = 3$, then $G \in \mathcal{U}$. Otherwise $d_G(v_1) = d_G(v_2) = k$ ($k \geq 4$), then G contains two star-factors shown in Figure 2(b) and 2(c), with the weights $2k - 3$ and k , respectively. However, we see $2k - 3 \neq k$ for $k \geq 4$, a contradiction to $G \in \mathcal{U}$. Hence there is exactly one quadrangle using the edge v_1v_2 in G , and G is shown in Figure 1(b).

Case 2. $d_G(v_i) \geq 3, i = 1, 2, 3$.

Claim 1. Let $X = \{x \in V(G) \mid N_G(x) \subseteq \{v_1, v_2, v_3\}\}$, then $X = \emptyset$.

Suppose $X \neq \emptyset$. Let $F_3 = \{u_1u_2 \mid u_1 \in \{v_1, v_2, v_3\}, u_2 \in V(G) - X - \{v_1, v_2, v_3\}\}$. Then $G - F_3$ has no isolated vertices, so $G - F_3 \in \mathcal{U}$ by Lemma 1. Assume

$$N_G(v_1) \cap N_G(v_2) = \{x_1, \dots, x_i\},$$

$$N_G(v_2) \cap N_G(v_3) = \{y_1, \dots, y_j\},$$

$$N_G(v_1) \cap N_G(v_3) = \{z_1, \dots, z_k\},$$

$$N_G(v_1) \cap N_G(v_2) \cap N_G(v_3) = \{u_1, \dots, u_l\}.$$

Then $G - F_3$ contains a component H with vertices in X and the triangle $\Delta v_1v_2v_3$ shown in Figure 3(a). Since $X \neq \emptyset$, without loss of generality, we assume $l = 0$ and at least one of i, j, k that is nonzero.

Subcase 1.1. There is exactly one of i, j, k that is nonzero. Then H can be decomposed into one or two stars.

Subcase 1.2. There are exactly two of i, j, k that are nonzero. Assume, without loss of generality, that $i = 0, j \neq 0$ and $k \neq 0$. If $j = k = 1$, then H can be decomposed into one or two stars. Otherwise H can be decomposed into one or two or three stars.

Subcase 1.3. i, j, k are all nonzero. Then H can be decomposed into two or three stars.

So in all three subcases it contradicts to $G - F_3 \in \mathcal{U}$.

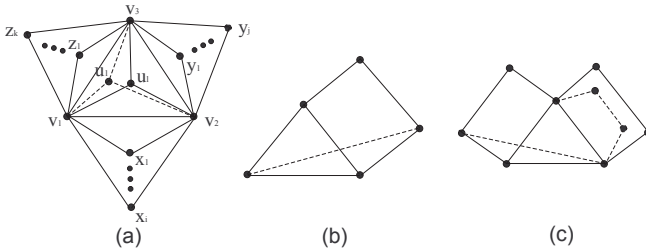


Figure 3

Let $F_4 = \{u_1u_2 \mid u_1 \in \{v_1, v_2\}, u_2 \in V(G) - \{v_1, v_2, v_3\}\}$. Then, by Claim 1, no isolated vertices are created in $G - F_4$, and all the neighbors of v_3 other than v_1 and v_2 are stems in graph $G - F_4$ by Lemma 3. Suppose u is a stem which is adjacent to v_3 in $G - F_4$, and m is a leaf adjacent to u in $G - F_4$. It is obvious that m can only be adjacent to v_1 or v_2 besides u in G .

Claim 2. $N_G(u) - \{m, v_3\} \subseteq \{v_1, v_2\}$ and $N_G(u) \cap N_G(m) = \emptyset$.

Subcase 2.1. m is adjacent to exactly one of v_1 and v_2 in G . Assume, without loss of generality, that m is adjacent to v_1 , and u has other neighbors other than v_1, v_2, v_3 and m . Let $F_5 = \{u_1u_2 \mid u_1 \in \{v_2, v_3\}, u_2 \in V(G) - \{v_1, v_2, v_3\}\}$, then u is not a leaf

in $G - F_5$. But the neighbors of m in $G - F_5$ are v_1 and u , so m is not a stem in $G - F_5$. However, m should be a stem in $G - F_5$ by Lemma 3, a contradiction. Hence $N_G(u) - \{m, v_3\} \subseteq \{v_1, v_2\}$. If u is also adjacent to v_1 , then m and u are stems in graph $G - F_5$ by Lemma 3, a contradiction.

Subcase 2.2. m is adjacent to both v_1 and v_2 in G . One may obtain a contradiction by a similar argument as in Subcase 2.1.

Hence v_1, v_2, v_3, m and u form at most two quadrangles with common edge mu by Claim 2, and an induced subgraph of G with the vertices v_1, v_2, v_3, m and u is isomorphic to the graph shown in Figure 3(b) (dashed line indicates a possible edge). So the subgraph H induced by all the vertices in the component, in $G - F_4$, which contains the 3-cycle $C_3 = v_1v_2v_3$ is isomorphic to the graph shown in Figure 3(c).

Let $F_6 = \{u_1u_2 \mid u_1 \in \{v_1, v_3\}, u_2 \in V(G) - \{v_1, v_2, v_3\}\}$. By the similar argument above, both subgraphs induced by the vertices in the component of $G - F_5$ and $G - F_6$, respectively, which contain the 3-cycle $C_3 = v_1v_2v_3$ are also isomorphic to the graph shown in Figure 3(c). So G is isomorphic to the graph shown in Figure 4(a). If we delete some edges from G such that all vertices in $G - \{v_1, v_2, v_3\}$ are of degree two, then the spanning subgraph G' of G will be the graph shown in Figure 4(b).

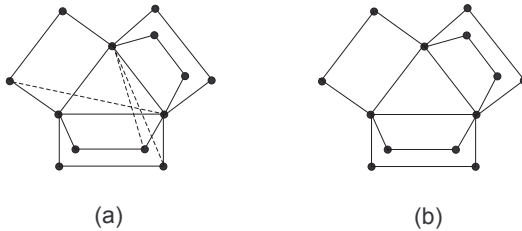


Figure 4

Claim 3. For each edge on the triangle $\Delta v_1v_2v_3$, there exists at most one quadrangle in G' containing it.

Let Y denote the vertices that are contained in a quadrangle which use the edge v_1v_2 and $F_7 = \{u_1u_2 \mid u_1 \in \{v_1, v_2, v_3\}, u_2 \in V(G) - Y - \{v_3\}\}$. Then a component containing the triangle $\Delta v_1v_2v_3$ of $G - F_7$ is either the triangle $\Delta v_1v_2v_3$ itself or a triangle satisfying the conditions in Case 1. So v_1v_2 is contained in at most one quadrangle in G . The same argument can be applied to edges v_2v_3 and v_1v_3 .

Now we know that G' could be the graphs shown in Figure 5. However, the graph shown in Figure 5(c) can be decomposed into three or four stars. Hence, by Lemma 1, $G \notin \mathcal{U}$. So the only possible graph G' are the graphs shown in Figure 5(a) and 5(b). We add the edges back following the principle of Claim 2, then G can only be the graphs shown in Figure 1(c), 1(d) and 1(e) since every vertex in the triangle $\Delta v_1v_2v_3$ has degree at least three in G .

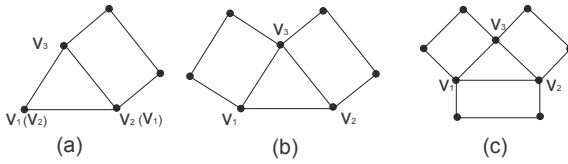


Figure 5

This completes the proof of Theorem 2. \square

The main theorem has classified all graphs in \mathcal{U} with girth three and minimum degree at least two. Combining with Theorem 1, the two families remaining to be determined are those of girth three with leaves and all those of girth four. It seems that the structures of both families are much more complicated and new techniques are required in order to determine them completely.

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