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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# *Eulerian and Hamiltonian Directed Hypergraphs.*

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## Eulerian and Hamiltonian Directed Hypergraphs.

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**Abstract:** Let  $H = (\mathcal{V}, \mathcal{E})$  be a directed hypergraph, sometimes called a dihypergraph. Each vertex  $v \in \mathcal{V}$  is incident to some hyperarcs in  $\mathcal{E}$ . Conversely, each hyperarc  $E \in \mathcal{E}$  is incident to some vertices in  $\mathcal{V}$ .  $H$  is Eulerian if there is a circuit  $C$  such that each hyperarc  $E \in \mathcal{E}$  appears exactly once in  $C$ . Similarly,  $H$  is Hamiltonian if there is a circuit  $C'$  such that every vertex  $v \in \mathcal{V}$  appears exactly once in  $C'$ .

We show that both of the problems are NP-complete. Some necessary conditions for a dihypergraph to be Eulerian are presented. We exhibit some families of hypergraphs for which those are sufficient conditions. We also generalize a part of the properties of the Eulerian digraphs to the uniform and regular directed hypergraphs. Stronger generalizations of *Eulerianity* to dihypergraphs are also studied.

Finally, we show that the de Bruijn and Kautz dihypergraphs are Eulerian and Hamiltonian in most cases. We also study some properties of their bipartite representation digraph.

**Key-words:** directed hypergraphs, Eulerian and Hamiltonian circuits, de Bruijn and Kautz dihypergraphs

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## Hypergraphes Orientés Eulériens et Hamiltoniens.

**Résumé :** Soit un hypergraphe orienté  $H = (\mathcal{V}, \mathcal{E})$ , qu'on appelle aussi un dihypergraphe. Chaque sommet  $v \in \mathcal{V}$  est relié à des hyperarcs dans  $\mathcal{E}$ . Réciproquement, chaque hyperarc  $E \in \mathcal{E}$  est relié à des sommets dans  $\mathcal{V}$ .  $H$  est Eulérien s'il existe un circuit  $C$  tel que chaque hyperarc  $E \in \mathcal{E}$  n'apparaisse qu'une et une seule fois dans  $C$ . De même  $H$  est Hamiltonien s'il existe un circuit  $C'$  tel que chaque sommet  $v \in \mathcal{V}$  n'apparaisse qu'une et une seule fois dans  $C'$ .

Nous montrons que ces deux problèmes sont NP-complets. Des conditions nécessaires pour qu'un hypergraphe orienté soit Eulérien sont présentées. Nous exhibons des familles d'hypergraphes pour lesquelles elles sont suffisantes. Nous généralisons aussi certaines propriétés des graphes orientés Eulériens aux hypergraphes orientés uniformes et réguliers. D'autres généralisations plus fortes de l'*Eulerianité* aux dihypergraphes sont aussi étudiées.

Enfin nous montrons que les hypergraphes de de Bruijn et de Kautz sont Eulériens et Hamiltoniens dans la plupart des cas. Nous étudions également certaines propriétés de leur représentation bipartite.

**Mots-clés :** hypergraphes orientés, circuits Eulériens et Hamiltoniens, hypergraphes de de Bruijn et de Kautz

## 1 Introduction

Two concepts that are well-known and studied in Graph Theory are: Eulerian and Hamiltonian (di)cycles. An *Eulerian* (di)cycle in a (di)graph is a (di)cycle  $C$  such that an *edge* (resp. an *arc*) appears exactly once in  $C$ . A close notion is the *Hamiltonian* (di)cycle: where a *vertex* appears exactly once (see [8]).

A graph is Eulerian iff every vertex has an even degree, and a digraph is Eulerian iff every vertex has equal indegree and outdegree. Therefore deciding if there is an Eulerian (di)cycle in a (di)graph  $G$  can be done in polynomial time; but deciding if there is a Hamiltonian (di)cycle is an NP-complete problem [13].

A recent work generalizes the *graph*-theoretic concept of an Euler cycle to *undirected* hypergraphs [25]. We now generalize the *digraph*-theoretic concept of an Eulerian dicycle to *directed* ones. We say that an Eulerian dicycle in a dihypergraph is a dicycle  $C$  such that a *hyperarc* appears exactly once in  $C$ . It is a natural generalization of an Eulerian dicycle in a digraph. We also define and study a generalization of Hamiltonian dicycles to directed hypergraphs. Similarly, a Hamiltonian dicycle in a dihypergraph is a dicycle  $C$  such that a *vertex* appears exactly once in  $C$ . We show that deciding if a dihypergraph is Eulerian is an NP-complete problem. Actually, deciding whether a dihypergraph is Eulerian is as hard as deciding if a dihypergraph is Hamiltonian. However, we show that some results about the Eulerian digraphs can be generalized, in the case when the studied dihypergraphs are *uniform* and *regular*. Finally, we study a special family of regular, uniform dihypergraphs, including Kautz and de Bruijn directed hypergraphs defined in [7]. We show that this family has good Hamiltonian and Eulerian properties.

Definitions and discussion about the proper generalization of an Eulerian dicycle are given in Section 2. In Section 3, the mentioned-above equivalence between Eulerian and Hamiltonian dicycles are presented. Results about Eulerian, uniform, regular dihypergraphs are presented in Section 4. Section 5 deals with the particular subclass of the Consecutive- $(d, s)$  dihypergraphs.

## 2 Definitions and Notations

### 2.1 Directed Hypergraphs

An *undirected hypergraph*  $H$ , simply called a hypergraph, is a pair  $(\mathcal{V}(H), \mathcal{E}(H))$  where  $\mathcal{V}(H)$  is a non-empty set of elements (called *vertices*) and  $\mathcal{E}(H)$  is a collection of subsets (or *edges*) of  $\mathcal{V}(H)$ . If we replace  $\mathcal{E}(H)$  by a set of ordered pairs of subsets of  $\mathcal{V}(H)$  (called *hyperarcs*),  $H$  is a *directed hypergraph* (or *dihypergraph*).

Let  $E = (E^-, E^+)$  be a hyperarc in  $\mathcal{E}(H)$ . Then the vertex sets  $E^-$  and  $E^+$  are called the *in-set* and the *out-set* of the hyperarc  $E$ , respectively. The sets  $E^-$  and  $E^+$  need not to be disjoint. The hyperarc  $E$  is said to *join* the vertices of  $E^-$  to the vertices of  $E^+$ . Furthermore, the vertices of  $E^-$  are said to be *incident to* the hyperarc  $E$  and the vertices of  $E^+$  are said to be *incident from*  $E$ . The vertices of  $E^-$  are *adjacent to* the vertices of  $E^+$ , and the vertices of  $E^+$  are *adjacent from* the vertices of  $E^-$ .

If  $E$  is a hyperarc in a dihypergraph  $H$ , then  $|E^-|$  is the *in-size* and  $|E^+|$  is the *out-size* of  $E$ . The *maximum in-size* and the *maximum out-size* of  $H$  are respectively:

$$s^-(H) = \max_{E \in \mathcal{E}(H)} |E^-| \quad \text{and} \quad s^+(H) = \max_{E \in \mathcal{E}(H)} |E^+|.$$

The *order* of  $H$  is the number of vertices in  $\mathcal{V}(H)$  and is denoted by  $n(H)$ . The number of hyperarcs in  $H$  is denoted by  $m(H)$ . We note that a *digraph* is a directed hypergraph  $D = (\mathcal{V}(D), \mathcal{E}(D))$  with  $s^-(D) = s^+(D) = 1$ .

Let  $v$  be a vertex in  $H$ . The *in-degree* of  $v$  is the number of hyperarcs that contain  $v$  in their out-set, and is denoted by  $d_H^-(v)$ . Similarly, the *out-degree* of vertex  $v$  is the number of hyperarcs that contain  $v$  in their in-set, and is denoted by  $d_H^+(v)$ .

To a directed hypergraph  $H$ , we associate a **bipartite representation digraph**:

$$R(H) = (\mathcal{V}_1(R) \cup \mathcal{V}_2(R), \mathcal{E}(R)).$$

where:

$$\mathcal{V}_1 = \mathcal{V}(H)$$

$$\mathcal{V}_2 = \mathcal{E}(H)$$

$$\mathcal{E}(R) = \{v_i E_j \setminus v_i \in E_j^-\} \cup \{E_j v_i \setminus v_i \in E_j^+\}$$

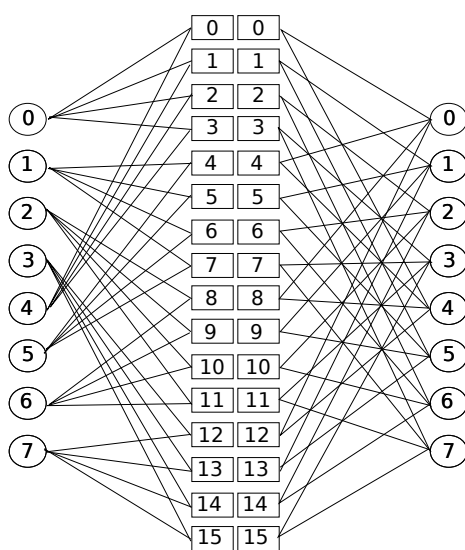


Figure 1: The bipartite representation digraph of the de Bruijn dihypergraph  $GB_1(4, 8, 2, 16)$

This representation digraph is useful for drawing dihypergraphs. Remark that when you inverse the respective roles of  $\mathcal{V}_1(R)$  and  $\mathcal{V}_2(R)$  in  $R(H)$ , you intuitively exchange the role of the vertices with the role of the hyperarcs in  $H$ . That is the informal definition of the **dual dihypergraph**  $H^*$ . Formally:

$$\mathcal{V}(H^*) \approx \mathcal{E}(H)$$

$$\mathcal{E}(H^*) \approx \mathcal{V}(H)$$

such that vertex  $e$  is in  $V^-$  if and only if  $v \in E^+$  and similarly,  $e$  is in  $V^+$  if and only if  $v \in E^-$ .

It is important to notice that a hyperarc  $V \in \mathcal{E}(H^*)$  may have an empty in-set (if  $d_H^-(v) = 0$ ) or an empty out-set (if  $d_H^+(v) = 0$ ).

Other transformations are possible. For example, in the *mirror dihypergraph*  $\tilde{H}$  (sometimes called the symmetric image), the orientation of every hyperarc in  $H$  is inverted.

$$\begin{aligned}\mathcal{V}(\tilde{H}) &= \mathcal{V}(H) \\ \mathcal{E}(\tilde{H}) &= \{(E^+, E^-) \mid (E^-, E^+) \in \mathcal{E}(H)\}\end{aligned}$$

When we replace the hyperarcs by cliques, we get the *underlying multidigraph*  $U(H)$ :

$$\begin{aligned}\mathcal{V}(U(H)) &= \mathcal{V}(H) \\ \mathcal{E}(U(H)) &\supset \{uv \mid \exists E \in \mathcal{E}(H) \text{ such that } u \in E^- \text{ and } v \in E^+\}\end{aligned}$$

We emphasize that  $U(H)$  needs not to be simple: the number of arcs from  $u$  to  $v$  in  $U(H)$  is the number of hyperarcs  $E = (E^-, E^+)$  in  $H$  such that  $u \in E^-$  and  $v \in E^+$ . Thus, the in- and out-degrees of a vertex in  $U(H)$  are

$$d_{U(H)}^-(u) = \sum_{\substack{E \in \mathcal{E}(H) \\ E^+ \ni u}} |E^-| \quad \text{and} \quad d_{U(H)}^+(u) = \sum_{\substack{E \in \mathcal{E}(H) \\ E^- \ni u}} |E^+|.$$

Observe that the underlying multidigraph of a given dihypergraph is unique. However, a given digraph  $D$  can be the underlying digraph of many dihypergraphs  $H$ . In fact, the hyperarcs in  $H$  form a *legitimate* partition of the arcs in  $D$ . A *legitimate* partition means that vertices in the in-set  $E^-$  of a hyperarc must be adjacent to every vertex in  $E^+$ , in  $D$ .

**Remark 1.** *If  $s^- = s^+ = 1$  then  $U(H) = H$ .*

Moreover,  $H$  can always be transformed into a BF-graph:

**Definition 1** ([21]). *A Backward hyperarc, or simply B-arc, is a hyperarc  $E = (E^-, E^+)$  with  $|E^+| = 1$ . A Forward hyperarc, or simply F-arc, is a hyperarc  $E = (E^-, E^+)$  with  $|E^-| = 1$ .*

*A BF-graph is a hypergraph  $H$  whose hyperarcs are either B-arcs or F-arcs. When all the hyperarcs are B-arcs,  $H$  is a B-graph. In the same way, when all the hyperarcs are F-arcs,  $H$  is a F-graph.*

Let  $E = (E^-, E^+)$  be a hyperarc of  $H$  that is neither a B-arc nor a F-arc. First we add a new vertex  $e$  in  $H$ . Then we replace  $E$  by the B-arc  $E_1 = (E^-, \{e\})$  and the F-arc  $E_2 = (\{e\}, E^+)$ . When iterating the process we get a BF-graph, denoted  $\mathbf{BF}(H)$ .

By a dipath in  $H$  we mean a sequence  $P = u_0, E_0, \dots, u_i, E_i, \dots, u_{p-1}, E_{p-1}, u_p$ , such that, for all  $i, j$ , we have  $u_i \in \mathcal{V}(H)$ ,  $E_j \in \mathcal{E}(H)$ , and  $u_i \in E_{i-1}^+ \cap E_i^-$ . We say that  $P$  is a dipath of length  $p$ .

One can build the *line directed hypergraph*  $L(H)$  (*denoted line dihypergraph of  $H$* ). Vertices are labeled by the dipaths of length 1 in  $H$ , and hyperarcs are labeled by the dipaths of length 1 in  $H^*$ :

$$\begin{aligned}\mathcal{V}(L(H)) &= \bigcup_{E \in \mathcal{E}(H)} \{(uEv) \mid u \in E^-, v \in E^+\}, \\ \mathcal{E}(L(H)) &= \bigcup_{v \in \mathcal{V}(H)} \{(EvF) \mid v \in E^+ \cap F^-\};\end{aligned}$$

where the in-set and the out-set of hyperarc  $(EvF)$  are defined as :



$$\begin{aligned}(EvF)^- &= \{(uEv) \mid u \in E^-\}, \\ (EvF)^+ &= \{(vFw) \mid w \in F^+\}.\end{aligned}$$

Particularly when  $D$  is a digraph,  $L(D)$  is called the *line digraph* of  $D$ .

The following results are used in the next sections:

**Theorem 1** ([6]). *Let  $H$  be a directed hypergraph.*

1. *The digraphs  $R(L(H))$  and  $L^2(R(H))$  are isomorphic.*
2. *The digraphs  $U(L(H))$  and  $L(U(H))$  are isomorphic.*
3. *The digraphs  $(L(H))^*$  and  $L(H^*)$  are isomorphic.*

## 2.2 Eulerian and Hamiltonian Circuits in Dihypergraphs

Let  $H$  be a directed hypergraph. A dipath  $P = u_0, E_0, \dots, u_i, E_i, \dots, u_{p-1}, E_{p-1}, u_p$  is a dicycle, or circuit, in  $H$  if and only if we have  $u_0 = u_p$ .

Dicycles in a digraph are a special case of dicycles in a dihypergraph.

**Remark 2.** *A dicycle in the dihypergraph  $H$  can be seen as a dicycle in its bipartite representation  $R(H)$ .*

In the same way, we can extend the digraph-theoretic notions of *Eulerian* circuits and *Hamiltonian* dicycles, to the dihypergraphs:

**Definition 2.** *Let  $H$  be a dihypergraph. We say that  $H$  is Eulerian (resp.  $H$  is Hamiltonian) if, and only if, there is a dicycle  $C$  in  $H$ , such that a hyperarc of  $H$  (resp. a vertex of  $H$ ) appears in  $C$  exactly once. We call  $C$  an Eulerian dicycle (resp. a Hamiltonian dicycle).*

**Remark 3.** *A dihypergraph  $H$  is Eulerian if and only if there is a dipath  $P = u_0, E_0, \dots, u_i, E_i, \dots, u_{p-1}, E_{p-1}, u_p$ , such that a hyperarc of  $H$  appears exactly once in  $P$ , and  $u_p$  is in  $E_0^-$ .*

Indeed, when  $u_0 \neq u_p$ , we can always replace  $u_0$  by  $u_p$ , and in so doing we have an Eulerian circuit.

Our generalization of an Eulerian circuit to dihypergraphs is close to the extension of an Euler tour to the *undirected* hypergraphs, that was proposed in [25].

**Definition 3** ([25]). *Let  $H_u$  be an undirected hypergraph. A tour is a sequence  $T = v_0, E_0, v_1, \dots, v_{m-1}, E_{m-1}, v_0$  where for all  $i$ ,  $v_i \neq v_{i+1}$  and  $v_i, v_{i+1}$  are in subset  $E_i$ . Particularly,  $T$  is called an Euler tour when every edge appears exactly once in  $T$ .  $H_u$  is an Eulerian hypergraph if there exists an Euler tour  $T$  in  $H_u$ .*

**Remark 4.** *An Eulerian dicycle in  $H$  (resp. a Hamiltonian dicycle in  $H$ ) is a circuit in  $R(H)$ , such that a vertex of  $\mathcal{V}_2(R)$  (resp. of  $\mathcal{V}_1(R)$ ) appears exactly once.*

As a consequence, a necessary and sufficient condition for  $R(H)$  to be Hamiltonian is that there is a dicycle  $C$  in  $H$ , such that  $C$  is simultaneously an Eulerian dicycle and a Hamiltonian dicycle in  $H$ . In reference to the undirected case [5], we call  $C$  a *complete Berge circuit*:

**Definition 4.** *Let  $H$  be a directed hypergraph. A complete Berge circuit in  $H$  is a dicycle  $C$  in  $H$ , such that  $C$  is an Eulerian dicycle and a Hamiltonian dicycle in  $H$ .*

In the following sections, we focus on Eulerian dihypergraphs. We assume that the studied dihypergraphs have no isolated vertex, without any loss of generality.

### 3 First Results

#### 3.1 Some conditions

First we recall the well-known characterization of the Eulerian digraphs:

**Theorem 2** ([4]). *Let  $D$  be a digraph. The following statements are equivalent:*

1.  $D$  is Eulerian.
2.  $D$  is connected, and for all vertex  $v \in \mathcal{V}(D)$   $d^-(v) = d^+(v)$ .
3.  $D$  is connected, and it has a cycle decomposition (that is its arcs can be partitioned into arc-disjoint circuits).

A digraph  $D$  is weakly connected when its underlying multigraph is connected. It is a strongly connected digraph provided for each pair of vertices  $u, v \in \mathcal{V}(D)$  there exists a dipath from  $u$  to  $v$ . These connectivity notions can be extended to dihypergraphs as well [6]. We say that  $H$  is strongly (resp. weakly) connected when its underlying multidigraph  $U(H)$  is strongly (resp. weakly) connected.  $U(H)$  is weakly connected when its *underlying* multigraph  $G_{U(H)}$  is a connected multigraph. The digraph-theoretic notions of vertex-connectivity and arc-connectivity are also generalized by the dihypergraph-theoretic notions of vertex-connectivity and hyperarc-connectivity. Unlike 1-arc connected digraphs, 1-hyperarc connected dihypergraphs are not always 1-vertex connected.

Remark that unlike an Eulerian digraph, an Eulerian dihypergraph does not need to be strongly connected. Indeed, let  $H$  be an Eulerian dihypergraph. If we add a new vertex  $x$  in  $H$ , such that  $x$  is incident to only one hyperarc  $E$  of  $H$ , and  $d^-(x) = 0$ , then  $H$  is still Eulerian, but  $H$  cannot be strongly connected anymore.

On the other hand, we have the following necessary condition:

**Proposition 3.** *Let  $H$  be a dihypergraph. If  $H$  is Eulerian, then  $H$  is weakly connected.*

*Proof.* Let  $H$  be a dihypergraph. Let  $G_{U(H)}$  be the *underlying* multigraph of  $U(H)$ . We want to prove that  $G_{U(H)}$  is connected.

Remark first that for all hyperarc  $E \in \mathcal{E}(H)$ , vertices in the subset  $E^- \cup E^+$  are in the same connected component in  $G_{U(H)}$ , by the definition of  $U(H)$ .

Moreover, let  $E, F$  be two distinct hyperarcs in  $\mathcal{E}(H)$ . Since there is an Eulerian dicycle in  $H$ , therefore,  $\exists u \in E^+, \exists v \in F^-$ , such that there is a dipath in  $H$  from  $u$  to  $v$ . Since there is a dipath from  $u$  to  $v$  in  $H$ , hence a dipath  $P$  from  $u$  to  $v$  in  $U(H)$ . Let  $P_u$  be the *undirected* version of  $P$  in  $G_{U(H)}$ .  $P_u$  is a path from  $u$  to  $v$  (resp. from  $v$  to  $u$ ) in  $G_{U(H)}$ . So subsets  $E^- \cup E^+$  and  $F^- \cup F^+$  are in the same connected component in  $G_{U(H)}$  too. Therefore,  $G_{U(H)}$  is connected.  $\square$

A necessary condition for a uniform, undirected hypergraph  $H_u$  to be Eulerian is presented in [25]. A  $k$ -uniform undirected hypergraph is a hypergraph  $H_u$  such that for all edge  $E$  in  $H_u$ ,  $E$  is a subset of  $\mathcal{V}(H_u)$  with  $k$  elements. An extension of this property to dihypergraphs is presented and studied in the next Section.

**Theorem 4** ([25]). *Let  $H_u$  be a  $k$ -uniform, undirected hypergraph. If  $H_u$  is an Eulerian hypergraph, then*

$$|V_{\text{odd}}(H_u)| \leq (k-2)m(H_u)$$

where  $V_{\text{odd}}(H_u)$  denotes the set of vertices in  $H_u$  that are incident to an odd number of edges, and  $m(H_u)$  is the total number of edges in  $H_u$ .

Using the same idea we prove a necessary condition for a directed hypergraph  $H$  to be Eulerian.

**Theorem 5.** *Let  $H$  be a dihypergraph. If  $H$  is Eulerian then:*

$$\sum_{u \in \mathcal{V}(H)} |d^+(u) - d^-(u)| \leq \sum_{E \in \mathcal{E}(H)} [(|E^+| - 1) + (|E^-| - 1)].$$

*Proof.* Let  $m = m(H)$  be the number of hyperarcs in  $H$ . Let  $C = v_0, E_0, v_1, \dots, v_{m-1}, E_{m-1}, v_0$  be an Eulerian dicycle in  $H$ . By definition, a given vertex may appear many times in  $C$ , but every hyperarc appears only once in the dicycle. Let us find the maximum number of occurrences of a given vertex  $v$  in  $C$ .  $\forall i \neq j$  we may have  $v_i = v_j$ , but we are sure that  $E_i \neq E_j$ . So a vertex  $v$  can appear, at most,  $\min(d^+(v), d^-(v))$  times in  $C$  and, as a consequence, we have the following inequality:

$$\sum_{v \in \mathcal{V}(H)} \min(d^+(v), d^-(v)) \geq m(H)$$

Moreover, we know that:

$$\min(d^+(v), d^-(v)) = \frac{1}{2}(d^+(v) + d^-(v) - |d^+(v) - d^-(v)|)$$

Since

$$\sum_{v \in \mathcal{V}(H)} d^+(v) = \sum_{E \in \mathcal{E}(H)} |E^-|$$

$$\sum_{v \in \mathcal{V}(H)} d^-(v) = \sum_{E \in \mathcal{E}(H)} |E^+|$$

therefore, the following inequalities are all equivalent to the previous one:

$$\begin{aligned} \frac{1}{2} \sum_{v \in \mathcal{V}(H)} (d^+(v) + d^-(v) - |d^+(v) - d^-(v)|) &\geq m(H) \\ \sum_{v \in \mathcal{V}(H)} (d^+(v) + d^-(v) - |d^+(v) - d^-(v)|) &\geq 2m(H) \\ \sum_{v \in \mathcal{V}(H)} d^+(v) + \sum_{v \in \mathcal{V}(H)} d^-(v) - \sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| &\geq \sum_{E \in \mathcal{E}(H)} 2 \\ \sum_{E \in \mathcal{E}(H)} |E^-| + \sum_{E \in \mathcal{E}(H)} |E^+| - \sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| &\geq \sum_{E \in \mathcal{E}(H)} 2 \\ \sum_{u \in \mathcal{V}(H)} |d^+(u) - d^-(u)| &\leq \sum_{E \in \mathcal{E}(H)} [(|E^+| - 1) + (|E^-| - 1)] \end{aligned}$$

□

For a directed graph, Theorem 5 is equivalent to the Euler condition:

**Corollary 1.** *Let  $D$  be a digraph. If  $D$  is Eulerian, then for all  $u \in \mathcal{V}(D)$   $d^+(u) = d^-(u)$ .*

Theorem 5 is not a sufficient condition for a strongly connected dihypergraph  $H$  to be Eulerian: a counterexample is presented in Section 3.3, Figure 6.

Another necessary condition was proposed by N. Cohen (private communication), who transposed the search of an Eulerian circuit to a *flow networks* problem.

**Definition 5.** Let  $N = (\mathcal{V}, \mathcal{E})$  be a directed graph, with vertices  $s$  and  $t$  being the source and the sink, respectively;  $N$  is called a network. Each arc  $uv \in \mathcal{E}$  has a capacity  $c(uv) \in \mathbb{N}^*$ . A flow is a mapping  $f : \mathcal{E} \rightarrow \mathbb{N}$ , such that:

1. for all  $uv \in \mathcal{E}$ ,  $f(uv) \leq c(uv)$  (capacity constraint)
2. for all vertex  $v \neq s, t$   $\sum_{uv \in \mathcal{E}} f(uv) = \sum_{vw \in \mathcal{E}} f(vw)$  (conservation of flows)

The value of the flow is  $|f| = \sum_{v \in \mathcal{V}} f(sv)$ .

Let  $H$  be a directed hypergraph. If there is a hyperarc  $E$  whose in-set (resp. whose out-set) is empty, then  $H$  cannot be Eulerian. Else, let  $\varphi$  be a function from  $\mathcal{E}(H)$  to  $\mathcal{V}(H)^2$ , such that for all  $E$ ,  $\varphi(E) \in E^- \times E^+$ . Actually we transform the hyperarcs into arcs. So we get a digraph, denoted  $D_\varphi[H] = (\mathcal{V}(H), \varphi(\mathcal{E}(H)))$ . Observe that  $D_\varphi[H]$  is a subdigraph of  $U(H)$ . There are  $\prod_{E \in \mathcal{E}(H)} |E^-||E^+|$  possible  $\varphi$  functions.

**Remark 5.** A dihypergraph  $H$  is Eulerian if and only if there exists  $\varphi$  such that  $D_\varphi[H]$  is an Eulerian digraph.

By Theorem 2, a necessary and sufficient condition for a digraph  $D$  to be Eulerian is that for every vertex  $v$ ,  $d^-(v) = d^+(v)$  and  $D$  must be (weakly) connected. When  $D$  satisfies only the first condition, we call it a *balanced* digraph.

Let  $s, t \notin \mathcal{V}(H)$  be two vertices. Consider the network  $N_f(H) = (\mathcal{V}_f(H), \mathcal{E}_f(H))$ , such that:

$$\mathcal{V}_f(H) = \mathcal{V}(H) \cup \mathcal{E}(H)^{\{-,+\}} \cup \{s, t\}$$

$$\mathcal{E}_f(H) = \{sE_j^+ : E_j \in \mathcal{E}(H)\} \cup \{E_j^-t : E_j \in \mathcal{E}(H)\} \cup \{E_j^+v : v \in E_j^+\} \cup \{vE_j^- : v \in E_j^-\}$$

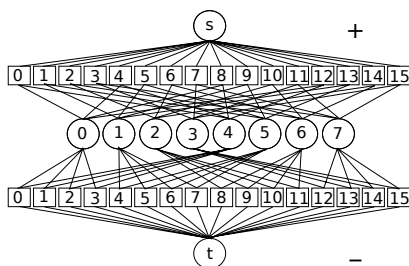


Figure 2: The flow networks  $N_f(GB_1(4, 8, 2, 16))$ .

Each arc  $uv \in \mathcal{E}_f(H)$  has a capacity of 1. In those conditions, by the max-flow min-cut Theorem, the maximum value of an  $s-t$  flow in  $N_f(H)$  is the greatest number of pairwise arc-disjoint dipaths between  $s$  and  $t$  in  $N_f(H)$ . An upper bound of this value is  $m(H)$ .

**Lemma 1.** *Let  $H$  be a dihypergraph. If  $H$  is Eulerian, then the maximum value of an  $s-t$  flow in  $N_f(H)$  is  $m(H)$ . More precisely, there exists  $\varphi$  such that  $D_\varphi[H]$  is a balanced digraph if and only if this condition is verified.*

*Proof.* If  $H$  is Eulerian, by Remark 5, there exists  $\varphi$  such that  $D_\varphi[H]$  is a balanced digraph. As a consequence, we only need to show the second part of the lemma.

Let us assume the maximum value of the flow is  $m(H)$ , that is there are  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . Let  $P_1, \dots, P_{m(H)}$  be  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . By construction those dipaths are of the form  $s, E_x^+, v_i, E_y^-, t$ , such that every  $E_x^+$  (resp. every  $E_y^-$ ) appears in only one dipath  $P_l$ . We define the function  $\varphi$  as follows: if  $s, E_x^+, v_i, E_y^-, t$  and  $s, E_y^+, v_i', E_z^-, t$  are among the  $m(H)$  pairwise arc-disjoint dipaths between  $s$  and  $t$ , then  $\varphi(E_y^-) = (v_i, v_i')$ . Clearly,  $D_\varphi[H]$  is a balanced digraph.

Now, let us suppose there exists  $\varphi$  such that  $D_\varphi[H]$  is a balanced digraph. Let  $v$  be a vertex of  $D_\varphi[H]$ . Since  $d_{D_\varphi[H]}^-(v) = d_{D_\varphi[H]}^+(v)$  one can define a bijection between the out-links and the in-links of  $v$ . Those arcs are all associated to a different hyperarc by  $\varphi$ . Therefore we can build  $d_{D_\varphi[H]}^-(v)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . Since  $\sum_{v \in \mathcal{V}(H)} d_{D_\varphi[H]}^-(v) = m(H)$  by construction of  $D_\varphi[H]$ , therefore there are  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . □

There is a condition allowing a dihypergraph  $H$  to have a balanced digraph  $D_\varphi[H]$  for some  $\varphi$ . It is easier to show the characterization if we transpose the flow networks problem to a *perfect matching* problem. The relation between both of these problems is well known. Let  $B(H) = (\mathcal{V}_1(B), \mathcal{V}_2(B), \mathcal{E}(B))$  be a bipartite graph, with:

$$\begin{aligned} \mathcal{V}_1(B) &= \{E_j^+ : E_j \in \mathcal{E}(H)\} \\ \mathcal{V}_2(B) &= \{E_j^- : E_j \in \mathcal{E}(H)\} \\ \mathcal{E}(B) &= \{E_j^+ E_j^- : E_j^+ \cap E_j^- \neq \emptyset\} \end{aligned}$$

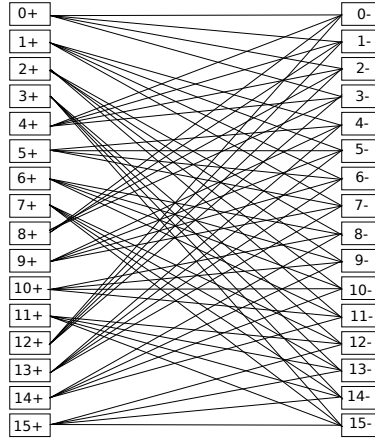


Figure 3: The bipartite graph  $B(GB_1(4, 8, 2, 16))$ .

**Lemma 2.** *Let  $H$  be a directed hypergraph. There is a perfect matching in  $B(H)$  if and only if the maximum value of an  $s - t$  flow in  $N_f(H)$  is  $m(H)$ .*

*Proof.* Let  $e, f$  be two vertex-disjoint edges in  $B(H)$ :  $e = E_x^+ E_y^-$  and  $f = E_z^+ E_r^-$ . By construction of  $B(H)$   $E_x^+ \cap E_y^- \neq \emptyset$  and  $E_z^+ \cap E_r^- \neq \emptyset$ . Therefore we can select a vertex  $u \in E_x^+ \cap E_y^-$  and a vertex  $v \in E_z^+ \cap E_r^-$ . Clearly,  $P_1 = s, E_x^+, u, E_y^-, t$  and  $P_2 = s, E_z^+, v, E_r^-, t$  are two dipaths in  $N_f(H)$  between  $s$  and  $t$ . Furthermore, since  $e$  and  $f$  are vertex-disjoint, therefore  $E_x \neq E_z$  and  $E_y \neq E_r$ . As a consequence,  $P_1$  and  $P_2$  are arc-disjoint.

Reciprocally, let  $P_1 = s, E_x^+, u, E_y^-, t$  and  $P_2 = s, E_z^+, v, E_r^-, t$  be two arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . By construction of  $N_f(H)$ ,  $u$  is in  $E_x^+ \cap E_y^-$  and  $v$  is in  $E_z^+ \cap E_r^-$ . Therefore  $e = E_x^+ E_y^-$  and  $f = E_z^+ E_r^-$  are edges in  $B(H)$ . Moreover, since  $P_1$  and  $P_2$  are arc-disjoint, therefore  $E_x \neq E_z$  and  $E_y \neq E_r$ . As a consequence,  $e$  and  $f$  are vertex-disjoint.

Let us assume there is a perfect matching in  $B(H)$ . That means there are  $m(H)$  pairwise vertex-disjoint edges in  $B(H)$ . So there are  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . Reciprocally, if there are  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  then there are  $m(H)$  pairwise vertex-disjoint edges in  $B(H)$  - that is a perfect matching.  $\square$

A well-known condition allowing a bipartite graph to have a perfect matching is the Hall's Theorem. We use the following result so that we can prove a necessary and sufficient condition for a dihypergraph to have a balanced digraph.

**Theorem 6** (Hall, Wikipedia). *Let  $G = (\mathcal{V}_1 \cup \mathcal{V}_2, \mathcal{E})$  be a bipartite graph such that  $|\mathcal{V}_1| = |\mathcal{V}_2|$ . There is a perfect matching in  $B$  if and only if for every subset  $S \subset \mathcal{V}_1$ ,  $|Adj(S)| \geq |S|$ , where  $Adj(S)$  denotes the set of vertices adjacent to some vertex of  $S$ .*

Let  $X$  be a subset of  $\mathcal{V}(H)$ . Let  $d^+(X)$  (also denoted  $d_H^+(X)$ ) be the number of hyperarcs  $E \in \mathcal{E}(H)$  such that  $E^- \cap X \neq \emptyset$ , and  $d_s^-(X)$  (also denoted  $d_{s,H}^-(X)$ ) be the number of hyperarcs  $E$  such that  $E^+ \subseteq X$ . We are now able to prove the following result:

**Theorem 7.** *Let  $H$  be a dihypergraph. There exists  $\phi$  such that  $D_\phi[H]$  is a balanced digraph if and only if for every subset  $X \subseteq \mathcal{V}(H)$   $d_s^-(X) \leq d^+(X)$ .*

*Proof.* Let us assume there exists  $\phi$  such that  $D_\phi[H]$  is a balanced digraph. For every subset  $X \subseteq \mathcal{V}(H)$ , for every hyperarc  $E$  such that  $E^+ \subseteq X$ , we necessarily have  $(u, v) = \phi(E) \in \mathcal{V}(H) \times X$ . Since  $D_\phi[H]$  is balanced, hence there must be the image  $\phi(F)$  of some hyperarc  $F$  whose origin is  $v$ . Clearly,  $F^- \cap X$  is not empty. Hence  $d_s^-(X) \leq d^+(X)$ .

Reciprocally, let us assume that for every subset  $X \subseteq \mathcal{V}(H)$ ,  $d_s^-(X) \leq d^+(X)$ . Let  $S = \{E_{j_1}^+, E_{j_2}^+, \dots, E_{j_{|S|}}^+\}$  be a subset of  $\mathcal{V}_1(B)$ , and  $X = \bigcup_{k=1}^{|S|} E_{j_k}^+$ . Observe that  $|Adj(S)| = d^+(X)$ . Since  $d_s^-(X) \geq |S|$ , therefore  $|Adj(S)| \geq |S|$ . Furthermore,  $\mathcal{V}_1(B)$  and  $\mathcal{V}_2(B)$  obviously have the same cardinality. By Theorem 6, there is a perfect matching in  $B(H)$ . Therefore by Lemma 2, there are  $m(H)$  pairwise arc-disjoint dipaths in  $N_f(H)$  between  $s$  and  $t$ . So, by Lemma 1, there exists  $\phi$  such that  $D_\phi[H]$  is a balanced digraph.  $\square$

Observe that we may define  $d^-(X)$  and  $d_s^+(X)$  in the same way as  $d^+(X)$  and  $d_s^-(X)$ . Another formulation of Theorem 7 is: there exists  $\phi$  such that  $D_\phi[H]$  is a balanced digraph if and only if for every subset  $X \subseteq \mathcal{V}(H)$   $d_s^+(X) \leq d^-(X)$ .

**Proposition 8.** *Let  $H$  be a  $B -$  graph (resp. a  $F -$  graph). If for all subset  $X \subseteq \mathcal{V}(H)$ ,  $d_s^-(X) \leq d^+(X)$ , then:*

$$\sum_{u \in \mathcal{V}(H)} |d^+(u) - d^-(u)| = \sum_{E \in \mathcal{E}(H)} [(|E^+| - 1) + (|E^-| - 1)].$$

*Proof.* By symmetry, if Proposition 8 is true for B-graphs, then it is true for F-graphs. Let  $H$  be a B-graph. Observe that, for every subset  $X$ ,  $d_s^-(X) = d^-(X) = \sum_{x \in X} d^-(x)$ . If, for every subset  $X$ ,  $d^-(X) \leq d^+(X)$ , then, for every vertex  $v$ ,  $d^-(v) \leq d^+(v)$ . Therefore:

$$\begin{aligned} \sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| &= \sum_{v \in \mathcal{V}(H)} d^+(v) - d^-(v) = \sum_{v \in \mathcal{V}(H)} d^+(v) - \sum_{v \in \mathcal{V}(H)} d^-(v) = \sum_{E \in \mathcal{E}(H)} |E^-| - \sum_{E \in \mathcal{E}(H)} |E^+| \\ &= \sum_{E \in \mathcal{E}(H)} |E^-| - \sum_{E \in \mathcal{E}(H)} 1 = \sum_{E \in \mathcal{E}(H)} |E^-| - 1 = \sum_{E \in \mathcal{E}(H)} [|E^+| - 1 + |E^-| - 1] \end{aligned}$$

□

Consequently, Theorem 7 is stronger than Theorem 5 for B-graphs and F-graphs.

**Remark 6.** *Deciding whether there exists  $\varphi$  such that  $D_\varphi[H]$  is a balanced digraph can be done in polynomial time. But the connectivity of  $D_\varphi[H]$  cannot be guaranteed.*

Actually, deciding whether there exists  $\varphi$  such that  $D_\varphi[H]$  is strongly connected is an NP-complete problem [24]. But the condition of Theorem 7 is sufficient if we impose that for every  $\varphi$ ,  $D_\varphi[H]$  is connected.

**Proposition 9.** *Let  $H$  be a dihypergraph. We denote  $\lambda = \sum_{E \in \mathcal{E}(H)} |E^+||E^-| - 1$ . Let  $G_{U(H)}$  be the underlying multigraph of the underlying multidigraph  $U(H)$ . If  $G_{U(H)}$  is  $\lambda + 1$ -edge connected, then  $H$  is Eulerian if and only if for every subset  $X$ ,  $d_s^-(X) \leq d^+(X)$ .*

*Proof.* Let  $E$  be a hyperarc in  $H$ . By construction of  $U(H)$ , there are  $|E^-||E^+|$  arcs of  $U(H)$  that are associated to  $E$ . The transformation of  $E$  into an arc requires the deletion of  $|E^-||E^+| - 1$  of these arcs. Therefore, if  $G_{U(H)}$  is  $\lambda + 1$ -edge connected, then every  $D_\varphi[H]$  is weakly-connected. □

This solution appears very restrictive. Another approach is the *skeleton-connectivity*. Let  $H$  be a BF-graph. We know that for all hyperarc  $E \in \mathcal{E}(H)$ ,  $E^-$  or  $E^+$  is a singleton, denoted  $\{e\}$ . The choice of  $e$  is not unique when  $E$  is an arc. Observe that for all  $\varphi$ ,  $\{e\}$  is in  $\{\varphi(E)^-, \varphi(E)^+\}$ . Consequently, we have a better control over the possible values of  $\varphi(E)$  than in the general case.

We define a graph  $S(H) = (\mathcal{V}(S), \mathcal{E}(S))$  such that  $\mathcal{V}(S)$  is isomorphic to  $\mathcal{E}(H)$ , and if  $E, F$  are two hyperarcs in  $H$ , then  $EF$  is in  $\mathcal{E}(S)$  if and only if they share a singleton. Formally, the edge exists if and only if there is  $X \in \{E^+, E^-\}$ , there is  $Y \in \{F^+, F^-\}$ , such that  $X = Y$  and  $|X| = 1$ . We call  $H$  a skeleton-connected dihypergraph when  $S$  is a connected graph.

**Lemma 3.** *Let  $H$  be a BF-graph. If  $H$  is skeleton-connected then for every  $\varphi$ ,  $D_\varphi[H]$  is weakly connected.*

*Proof.* Let  $E, F$  be two hyperarcs in  $H$ , such that  $EF$  is an edge of  $S(H)$ . By definition, there exists  $X \in \{E^+, E^-\}$ , there exists  $Y \in \{F^+, F^-\}$ , such that  $X = Y$  and  $|X| = 1$ . Since  $|X| = 1$ , therefore  $X$  is in  $\{\varphi(E)^+, \varphi(E)^-\}$  and in  $\{\varphi(F)^+, \varphi(F)^-\}$ . So  $\varphi(E)\varphi(F)$  is still an edge of  $S(D_\varphi[H])$ .

Consequently,  $S(H)$  connected implies  $S(D_\varphi[H])$  connected. Clearly, skeleton-connectivity implies weakly-connectivity for a digraph. Therefore,  $D_\varphi[H]$  is weakly connected. □

We generalize the Euler's Theorem to BF-graphs:

**Theorem 10.** *Let  $H$  be a skeleton-connected BF-graph.  $H$  is Eulerian if and only if for every subset  $X$  of  $\mathcal{V}(H)$   $d_s^-(X) \leq d^+(X)$ .*

*Proof.* It follows from Lemma 3 and Theorem 7. □

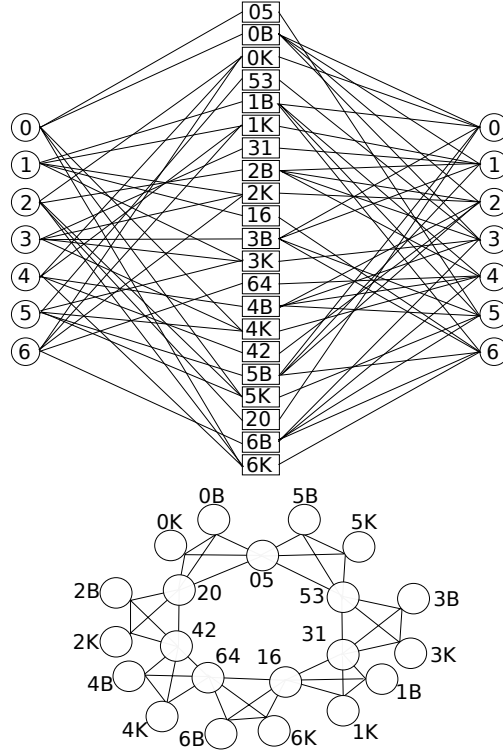


Figure 4: A skeleton-connected dihypergraph.

In Section 2.1, we detail the method of construction of a BF-graph  $BF(H)$  from any given dihypergraph  $H$ . So we may imagine using the method and combining it with Theorem 10, in order to get Eulerian dihypergraphs. Unfortunately,  $BF(H)$  may be skeleton-connected if and only if  $H$  is already a BF-graph (hence  $H = BF(H)$ ), or  $m(H) = 1$ .

From any dihypergraph  $H$ , such that for each hyperarc  $E$ ,  $E^- \neq \emptyset$  and  $E^+ \neq \emptyset$ , one can obtain a B-graph  $B(H)$  in the following way: let  $E \in \mathcal{E}(H)$  be a hyperarc that is not a B-arc. Then we order the elements of  $E^+$ , denoted  $e_1, e_2, \dots, e_{|E^+|}$ , and we replace  $E$  by the  $|E^+|$  B-arcs  $Ee_1, Ee_2, \dots, Ee_{|E^+|}$ , such that for all  $j$ , with  $1 \leq j \leq |E^+|$ :

$$(Ee_j)^- = E^-,$$

$$(Ee_j)^+ = \{e_j\}.$$

In the same way,  $H$  could be transformed into a F-graph, denoted  $F(H)$ . We present a sufficient condition for  $B(H)$  and  $F(H)$  to be Eulerian.

**Proposition 11.** *Let  $H$  be a directed hypergraph, having no hyperarc  $E$  such that  $E^- = \emptyset$  or  $E^+ = \emptyset$ . If  $R(H)$  is Eulerian, then both  $B(H)$  and  $F(H)$  are Eulerian.*

*Proof.* By construction of the bipartite representation digraph  $R(H)$ ,  $\mathcal{E}(R(H)) = \mathcal{E}_1 \cup \mathcal{E}_2$ , where  $\mathcal{E}_1 = \{u_i E_j : u_i \in E_j^-\}$  and  $\mathcal{E}_2 = \{E_j u_i : u_i \in E_j^+\}$ . One can easily check that there is a natural bijection  $f$  between  $\mathcal{E}_1$  and the F-arcs in  $F(H)$ , plus another one  $b$  between  $\mathcal{E}_2$  and the B-arcs of  $B(H)$ . Let us assume that  $R(H)$  is Eulerian.

Let  $C = u_0, u_0 E_0, E_0, E_0 u_1, u_1, \dots, u_k, u_k E_k, E_k, E_k u_0, u_0$  be an Eulerian circuit in  $R(H)$ . Then  $C_F = u_0, f(u_0 E_0), u_1, f(u_1 E_1), \dots, u_k, f(u_k E_k), u_0$  is an Eulerian circuit in  $F(H)$ , and  $C_B = u_0, b(E_0 u_1), u_1, b(E_1 u_2), \dots, u_k, b(E_k u_0), u_0$  is an Eulerian dicycle in  $B(H)$ .  $\square$



### 3.2 Equivalences and Complexity

We know that from a dihypergraph  $H$ , we can build other dihypergraphs that are related to  $H$  (see Section 2.1). The search of an Eulerian dicycle in  $H$  is equivalent to the search of other dicycles in those directed hypergraphs:

**Proposition 12.** *Let  $H$  be a dihypergraph. The following statements are equivalent:*

1.  $H$  is Eulerian.
2.  $H^*$  is Hamiltonian.
3.  $\tilde{H}$  is Eulerian.
4.  $BF(H)$  is Eulerian.

*Proof.* **Let us prove that  $H$  is Eulerian if, and only if,  $H^*$  is Hamiltonian.** To a dicycle  $C = v_0, E_0, v_1, \dots, v_p, E_p, v_0$  of  $H$  we associate in  $H^*$  a dicycle  $C^* = e_0, v_1, e_2, \dots, e_p, v_0, e_0$ . If  $C$  is an Eulerian dicycle in  $H$  (i.e.  $C$  contains each edge exactly once) then  $C^*$  contains each vertex of  $H^*$  exactly once, and so  $C^*$  is a Hamiltonian dicycle of  $H^*$ . Conversely, if  $C^*$  is a Hamiltonian dicycle of  $H^*$  (each vertex appears exactly once),  $C$  is an Eulerian dicycle.

**We prove now that  $H$  is Eulerian if, and only if,  $\tilde{H}$  is Eulerian.** Since  $\tilde{\tilde{H}} = H$  we only need to prove the implication. For a given hyperarc  $E = (E^-, E^+) \in \mathcal{E}(H)$  we call  $\tilde{E} = (E^+, E^-)$  the associated hyperarc in  $\mathcal{E}(\tilde{H})$ . Let  $C = v_0, E_0, \dots, v_{m-1}, E_{m-1}, v_0$  be an Eulerian dicycle in  $H$ . Then, by definition of  $\tilde{H}$ ,  $\tilde{C} = v_0, \tilde{E}_{m-1}, \dots, v_1, \tilde{E}_0, v_0$  is an Eulerian dicycle in  $\tilde{H}$ .

**Finally, let us show that  $H$  is Eulerian if and only if  $BF(H)$  is Eulerian.** Let  $C = v_0, E_0, v_1, \dots, v_{m(H)-1}, E_{m(H)-1}, v_0$  be an Eulerian dicycle in  $H$ . For all  $j$ , if  $E_j$  is neither a B-arc nor a F-arc,  $E_j$  is replaced in  $BF(H)$  by a B-arc  $E_{j,1}$  and a F-arc  $E_{j,2}$ , that are linked by a new vertex  $e_j$ ; in order to obtain an Eulerian circuit  $C_{BF}$  of  $BF(H)$ , we replace  $E_j$  by the sequence  $E_{j,1}, e_j, E_{j,2}$  in  $C$ . Conversely, assume that  $C_{BF}$  is an Eulerian dicycle in  $BF(H)$ . Let  $E_j$  be a hyperarc in  $H$  that is neither a B-arc nor a F-arc; let  $E_{j,1}$  be the associated B-arc and  $E_{j,2}$  be the associated F-arc in  $BF(H)$ . By construction of  $BF(H)$ ,  $E_{j,1}$  only shares a common vertex with  $E_{j,2}$ . Consequently,  $E_{j,1}, e_j, E_{j,2}$  is a subsequence of  $C_{BF}$ , where  $e_j$  is the vertex of  $BF(H)$  by which  $E_{j,1}$  and  $E_{j,2}$  are linked. So we may replace this subsequence by  $E_j$  for every such  $E_j$ , and we get a circuit  $C$  that is an Eulerian dicycle in  $H$ .  $\square$

**Remark 7.** *Since  $(H^*)^* = H$ ,  $H$  is Hamiltonian if, and only if,  $H^*$  is Eulerian.*

These equivalences may help to prove that some given dihypergraphs are Eulerian. Remark that because of Proposition 12, searching an Eulerian dicycle in a directed hypergraph  $H$  is as hard as searching a Hamiltonian dicycle in its dual. Since it is already the case when the studied dihypergraphs are digraphs [2], deciding whether a dihypergraph  $H$  is Hamiltonian is an NP-complete problem. So the following result is not that surprising:

**Theorem 13.** *Deciding if a dihypergraph  $H$  is Eulerian is NP-complete.*

*Proof.* Let  $C$  be a dipath. One can verify, in  $O(|\mathcal{E}(H)|)$  operations, whether  $C$  is an Eulerian circuit in  $H$ . Consequently, the problem is in NP.

Now, assume that  $H$  is an instance for the Hamiltonian problem: *Given a dihypergraph  $H$ . Is there a Hamiltonian circuit in  $H$ ?* This problem is NP-complete. Moreover, the dual of  $H$  can be built in  $O(|\mathcal{E}(H)| + |\mathcal{V}(H)|)$  operations. By Proposition 12,  $H$  is Hamiltonian if and only if  $H^*$  is Eulerian. Hence, the Eulerian problem is NP-complete too.  $\square$

Finding Hamiltonian dihypergraphs is useful to build Eulerian dihypergraphs. The following lemma is used in the next sections:

**Lemma 4.** *Let  $H$  be a directed hypergraph.  $H$  is Hamiltonian if, and only if, its underlying multidigraph  $U(H)$  is Hamiltonian.*

*Proof.* By definition of  $U(H)$ , any circuit in  $H$  is a circuit in  $U(H)$ , and reciprocally.  $\square$

This lemma, and its proof, have a direct application. Let  $\mathcal{G}$  be a family of Hamiltonian digraphs. Let  $D$  be a digraph in  $\mathcal{G}$ . Using a *legitimate* partition of the arcs in  $\mathcal{E}(D)$ , we can build a dihypergraph  $H$ , whose underlying digraph is  $D$ . Consequently, we build a set  $\mathcal{H}$  of Hamiltonian dihypergraphs. Let  $\mathcal{H}^* = \{H : H^* \in \mathcal{H}\}$ . Then  $\mathcal{H}^*$  is a set of Eulerian dihypergraphs, by Proposition 12.

Here is another application: let  $D$  be a digraph. From  $D$  we build a dihypergraph  $H_D$  such that:

$$\mathcal{V}(H_D) = \mathcal{V}(D)$$

and for every vertex  $v$  we associate a hyperarc  $V$  defined as follows:

$$\begin{aligned} V^- &= \{v\} \\ V^+ &= \{w \in \mathcal{V}(D) : vw \in \mathcal{E}(D)\} \end{aligned}$$

An Eulerian circuit in  $H_D$  (resp. a Hamiltonian circuit) is always a complete Berge circuit. Therefore  $H_D$  is Eulerian if and only if  $D$  is Hamiltonian.

### 3.3 Line Dihypergraphs Properties

For a given digraph  $D$ , the line digraph  $L(D)$  is Hamiltonian if, and only if,  $D$  is Eulerian [13]. First, we give a new proof of this result.

**Lemma 5.** *Let  $D$  be a digraph. Its line digraph  $L(D)$  is isomorphic to  $U(D^*)$ .*

*Proof.* Let  $D$  be a digraph. By construction of its dual dihypergraph,  $\mathcal{V}(U(D^*))$  is isomorphic to  $\mathcal{E}(D)$ . Since every arc in  $D$  is represented by a vertex in  $L(D)$ , therefore  $\mathcal{V}(L(D))$  and  $\mathcal{V}(U(D^*))$  are isomorphic.

Let  $v$  be a vertex in  $D$ . Let  $E_v = (E_v^-, E_v^+)$  be the associated hyperarc in  $D^*$ .  $E_v^-$  is the set of the arcs  $uv \in \mathcal{E}(D)$ , and  $E_v^+$  is the set of the arcs  $vw \in \mathcal{E}(D)$ . As a consequence, for each vertex  $uv$  in  $U(D^*)$ ,  $uv$  is incident to the vertices  $vw \in \mathcal{V}(U(D^*))$ . Those are the relations of incidence in  $L(D)$ . Moreover, in  $D^*$  the vertex  $uv$  is only incident to the hyperarc  $E_v$ . Therefore,  $U(D^*)$  is a simple digraph.  $\square$

**Corollary 2.** *Let  $D$  be a digraph.  $D$  is Eulerian if and only if its line digraph  $L(D)$  is Hamiltonian.*

*Proof.* Let  $D$  be a digraph.

$$\begin{aligned} D \text{ is Eulerian} &\iff \\ D^* \text{ is Hamiltonian, by Proposition 12} &\iff \\ U(D^*) \text{ is Hamiltonian, by Lemma 4} &\iff \\ L(D) \text{ is Hamiltonian, by Lemma 5} &\iff \end{aligned}$$

$\square$

This property is useful for some special families of digraphs, such that Kautz and de Bruijn digraphs, that are stable by line digraph operation [13]. Using induction, one can prove every digraph of the family is Hamiltonian. It was shown in [6] that de Bruijn and Kautz dihypergraphs are also stable by line dihypergraph operation. So it is natural to wonder whether Corollary 2 can be generalized to dihypergraphs. Unfortunately, that is not exactly the case.

**Proposition 14.** *Let  $H$  be a directed hypergraph.*

$$L(H) \text{ is Hamiltonian} \iff U(H) \text{ is Eulerian.}$$

*Proof.*

$$\begin{aligned} U(H) \text{ Eulerian} &\iff \\ L(U(H)) \text{ Hamiltonian by Corollary 2} &\iff \\ U(L(H)) \text{ Hamiltonian by Theorem 1} &\iff \\ L(H) \text{ Hamiltonian, by Lemma 4.} & \end{aligned}$$

□

When  $H$  is a digraph, we have  $U(H) = H$ , and the digraph property holds.

We show with two counter-examples that both implications do not hold: there are dihypergraphs  $H$  Eulerian such that  $L(H)$  is not Hamiltonian, and there are dihypergraphs  $H$  not Eulerian such that  $L(H)$  is Hamiltonian. By Proposition 14, we only need to study the relation between  $H$  Eulerian and  $U(H)$  Eulerian.

Consider the following dihypergraph  $H_1 = (\mathcal{V}(H_1), \mathcal{E}(H_1))$ :

$$\mathcal{V}(H_1) = \{1, 2, 3, 4, 5\} \text{ and } \mathcal{E}(H_1) = \{E, F\}$$

The bipartite representation digraph of  $H_1$  is in the following Figure.

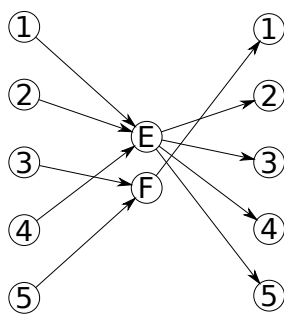


Figure 5: An example of  $H$  Eulerian and  $U(H)$  not Eulerian.

$1, E, 3, F, 1$  is an Eulerian dicycle in  $H_1$ . But  $d_{U(H_1)}^+(2) = \sum_{2 \in E^-} |E^+| = 4$ , that is different than  $d_{U(H_1)}^-(2) = \sum_{2 \in E^+} |E^-| = 3$ . As a consequence,  $U(H_1)$  cannot be Eulerian, by Corollary 1.

**On the other hand, there exist dihypergraphs  $H$  that are not Eulerian such that  $U(H)$  is Eulerian and so  $L(H)$  is Hamiltonian:** let  $H_2 = (\mathcal{V}(H_2), \mathcal{E}(H_2))$  be the following dihypergraph:

$$\mathcal{V}(H_2) = \{1, 2, 3, 4\} \text{ and } \mathcal{E}(H_2) = \{E, F, G\}$$

The bipartite representation of  $H_2$  is in the following Figure:

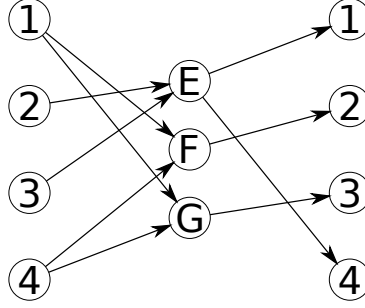


Figure 6: An example of  $H$  not Eulerian and  $U(H)$  Eulerian.

Remark that  $H_2$  verifies the necessary condition of Theorem 5. Furthermore,  $H_2$  is strongly connected. One may observe that its underlying multidigraph  $U(H_2)$  is Eulerian. However,  $H_2$  is not Eulerian because it does not verify the condition of Theorem 7.

We show in the next sections there are dihypergraphs  $H$ , that are not digraphs, that are Eulerian and such that  $U(H)$  is Eulerian.

Nonetheless, Corollary 2 could be generalized in this way:

**Proposition 15.** *Let  $H$  be a dihypergraph. If  $H$  is Eulerian, then there is a circuit  $C$  in  $L(H)$ , whose length is  $m(H)$ , and such that a vertex in  $\mathcal{V}(L(H))$  appears at most once in  $C$ .*

*Proof.* Let  $u_0, E_0, u_1, \dots, u_{m(H)-1},$

$E_{m(H)-1}, u_0$  be an Eulerian circuit in  $H$ . Let  $C = (u_0 E_0 u_1), [E_0 u_1 E_1], (u_1 E_1 u_2), \dots, (u_{m(H)-1} E_{m(H)-1} u_0), [E_{m(H)-1} u_0 E_0], (u_0, E_0, u_1)$ .

$C$  is a circuit in  $L(H)$  whose length is  $m(H)$ . Moreover, for all  $j \neq j'$  vertex  $u_j E_j u_{j+1}$  is different than vertex  $u_{j'} E_{j'} u_{j'+1}$  because  $H$  is Eulerian and consequently  $E_j \neq E_{j'}$ .  $\square$

Hence, if there are enough Eulerian circuits in  $H$ , whose associated circuits in  $U(H)$  are arc-disjoint, then there may be a Hamiltonian dicycle in  $L(H)$ . Based on this intuition, we now present a stronger notion of Eulerian dihypergraphs. Let  $c$  be a positive integer. We assume that  $H$  is a dihypergraph such that for every hyperarc  $E$ ,  $|E^-||E^+| = c$ .

**Definition 6.** *A digraph partition of  $H$  is a collection of functions  $\varphi_1, \varphi_2, \dots, \varphi_c$ , such that for all  $i \neq j$  for every hyperarc  $E$ ,  $\varphi_i(E) \neq \varphi_j(E)$ . Formally:  $\mathcal{E}(D_{\varphi_1}[H]), \mathcal{E}(D_{\varphi_2}[H]), \dots, \mathcal{E}(D_{\varphi_c}[H])$  is a partition of  $\mathcal{E}(U(H))$ .*

We now introduce the notion of *strongly Eulerian dihypergraphs*. A directed hypergraph  $H$  is strongly Eulerian if there is a digraph-partition  $\varphi_1, \varphi_2, \dots, \varphi_c$ , such that for every  $j$ ,  $D_{\varphi_j}[H]$  is an Eulerian digraph.

By Remark 5, a strongly Eulerian dihypergraph is an Eulerian dihypergraph. Furthermore, a digraph is strongly Eulerian iff it is an Eulerian digraph. Non-trivial examples of strongly Eulerian dihypergraphs are presented in the Appendix.

**Lemma 6.** *Let  $H$  be a dihypergraph. If  $H$  is strongly Eulerian, then there is a cycle decomposition in  $U(H)$ .*

*Proof.* Let  $\varphi_1, \varphi_2, \dots, \varphi_c$  be a digraph-partition of  $H$ . Observe that an arc in  $U(H)$  is also an arc in one and only one  $D_{\varphi_j}[H]$ , where  $1 \leq j \leq c$ .

Let us assume that for every  $1 \leq j \leq c$   $D_{\varphi_j}[H]$  is an Eulerian digraph. Let  $C_j$  be an Eulerian circuit in  $D_{\varphi_j}[H]$ . Then  $C_1, C_2, \dots, C_c$  is a cycle decomposition of  $U(H)$ .  $\square$

We now show the following result:

**Theorem 16.** *Let  $H$  be a dihypergraph. If  $H$  is strongly Eulerian, then  $L(H)$  is Hamiltonian.*

*Proof.* Since  $H$  is strongly Eulerian, therefore  $H$  is Eulerian. By Proposition 3,  $H$  is weakly connected. Consequently,  $U(H)$  is also weakly connected. By Lemma 6, there is a cycle decomposition in  $U(H)$ . Therefore, by Theorem 2,  $U(H)$  is Eulerian. If  $U(H)$  is Eulerian, then  $L(H)$  is Hamiltonian by Proposition 14.  $\square$

### 3.4 Kronecker Product of Dihypergraphs

Eulerian and Hamiltonian properties of the digraph products have been intensively studied. We propose a brief study of a dihypergraph product. Let  $\mathcal{H}$  be a family of Eulerian (resp. Hamiltonian) dihypergraphs. We want to know whether the product of two elements of  $\mathcal{H}$  is still an Eulerian (resp. Hamiltonian) dihypergraph. The studied dihypergraph product is a generalization of a digraph product:

**Definition 7.** *Let  $G_1 = (\mathcal{V}_1, \mathcal{E}_1)$ ,  $G_2 = (\mathcal{V}_2, \mathcal{E}_2)$ , be two digraphs. Their Kronecker product  $G_1 \otimes G_2$  is a digraph  $G = (\mathcal{V}, \mathcal{E})$  such that:*

1.  $\mathcal{V} = \mathcal{V}_1 \times \mathcal{V}_2$
2.  $\mathcal{E} = \{(\langle u_1, u_2 \rangle, \langle v_1, v_2 \rangle) : (u_1, v_1) \in \mathcal{E}_1 \text{ and } (u_2, v_2) \in \mathcal{E}_2\}$

Among the properties of Kronecker product, we are interested in its Hamiltonian properties:

**Proposition 17** ([12]). *Let  $C_1, C_2$  be two dicycles whose respective sizes are  $n_1$  and  $n_2$ . Then  $G = C_1 \otimes C_2$  is the union of  $\gcd(n_1, n_2)$  disjoint dicycles, whose size is  $\text{lcm}(n_1, n_2)$ .*

We define the Kronecker product of two dihypergraphs  $H_1, H_2$ , denoted  $H = H_1 \otimes H_2$ , as follows:

$$\begin{aligned}\mathcal{V}(H) &= \mathcal{V}(H_1) \times \mathcal{V}(H_2) \\ \mathcal{E}(H) &\approx \mathcal{E}(H_1) \times \mathcal{E}(H_2)\end{aligned}$$

such that if  $E$  is in  $\mathcal{E}(H_1)$  and  $F$  is in  $\mathcal{E}(H_2)$ , then:

$$\begin{aligned}(E, F)^- &= E^- \times F^- \\ (E, F)^+ &= E^+ \times F^+\end{aligned}$$

**Lemma 7.** *Let  $H_1, H_2$  be two dihypergraphs.*

$$U(H_1 \otimes H_2) \text{ and } U(H_1) \otimes U(H_2) \text{ are isomorphic.}$$

*Proof.* One may easily check that  $\mathcal{V}(U(H_1 \otimes H_2))$  and  $\mathcal{V}(U(H_1) \otimes U(H_2))$  are isomorphic. Let  $u, v$  be two vertices of  $H_1$  and  $x, y$  be two vertices of  $H_2$ . Let us suppose there are  $k_1$  arcs in  $U(H_1)$  from  $u$  to  $v$ . They are associated to  $k_1$  different hyperarcs of  $H_1$ , denoted  $E_1, E_2, \dots, E_{k_1}$ . Similarly, let us suppose there are  $k_2$  arcs in  $U(H_2)$  from  $x$  to  $y$ , associated to hyperarcs  $F_1, F_2, \dots, F_{k_2}$ . Then there are  $k_1 k_2$  arcs in  $U(H_1 \otimes H_2)$  from  $(u, x)$  to  $(v, y)$ , that are associated to hyperarcs  $(E_1, F_1), \dots, (E_1, F_{k_2}), \dots, (E_{k_1}, F_1), \dots, (E_{k_1}, F_{k_2})$ . That is the same number of arcs from  $(u, x)$  to  $(v, y)$  as in  $U(H_1) \otimes U(H_2)$ .  $\square$

**Lemma 8.** *Let  $H_1, H_2$  be two dihypergraphs.*

$$(H_1 \otimes H_2)^* \text{ and } H_1^* \otimes H_2^* \text{ are isomorphic.}$$

*Proof.* Vertices in  $H_1^* \otimes H_2^*$  and in  $(H_1 \otimes H_2)^*$  are labeled by  $\mathcal{E}(H_1) \times \mathcal{E}(H_2)$ . Hyperarcs in  $H_1^* \otimes H_2^*$  are labeled by  $\mathcal{V}(H_1) \times \mathcal{V}(H_2)$ , such that, if  $v$  is a vertex of  $H_1$  and  $x$  is a vertex of  $H_2$ :

$$(V, X)^- = \{(e, f) : v \in E^+ \text{ and } x \in F^+\} = \{(e, f) : (v, x) \in (E, F)^+\}$$

$$(V, X)^+ = \{(e, f) : v \in E^- \text{ and } x \in F^-\} = \{(e, f) : (v, x) \in (E, F)^-\}$$

Those are the same relations of incidence as in  $(H_1 \otimes H_2)^*$ . Therefore  $H_1^* \otimes H_2^*$  and  $(H_1 \otimes H_2)^*$  are isomorphic.  $\square$

We deduce from these lemmas the following theorem:

**Theorem 18.** *Let  $H_1, H_2$  be two dihypergraphs.*

1. *If  $n(H_1)$  is coprime to  $n(H_2)$  and  $H_1, H_2$  are Hamiltonian, then  $H_1 \otimes H_2$  is Hamiltonian.*
2. *If  $m(H_1)$  is coprime to  $m(H_2)$  and  $H_1, H_2$  are Eulerian, then  $H_1 \otimes H_2$  is Eulerian.*

*Proof.* Let us assume that  $H_1, H_2$  are Hamiltonian. Then  $U(H_1), U(H_2)$  are Hamiltonian, by Lemma 4. Furthermore, if  $n(H_1)$  is coprime to  $n(H_2)$ , then  $U(H_1) \otimes U(H_2)$  is Hamiltonian, by Proposition 17.  $U(H_1) \otimes U(H_2)$  is isomorphic to  $U(H_1 \otimes H_2)$ , by Lemma 7. Therefore,  $H_1 \otimes H_2$  is Hamiltonian, by Lemma 4.

Now let us assume that  $H_1, H_2$  are Eulerian. That means that  $H_1^*, H_2^*$  are Hamiltonian by Proposition 12. If  $m(H_1) = n(H_1^*)$  is coprime to  $m(H_2) = n(H_2^*)$ , then  $H_1^* \otimes H_2^*$  is Hamiltonian.  $H_1^* \otimes H_2^*$  is isomorphic to  $(H_1 \otimes H_2)^*$ , by Lemma 8. Therefore,  $(H_1 \otimes H_2)^*$  is Hamiltonian. By Proposition 12,  $H_1 \otimes H_2$  is Eulerian.  $\square$

## 4 The Properties of $d$ -regular, $s$ -uniform Dihypergraphs

Let  $(s^-, s^+)$  be a couple of positive integers. A  $(s^-, s^+)$ -uniform dihypergraph  $H$  is a dihypergraph such that the in-size (resp. the out-size) of every hyperarc in  $H$  equals  $s^-$  (resp. equals  $s^+$ ). When  $s^- = s^+ = s$  we also say that  $H$  is a  $s$ -uniform dihypergraph.

Regular dihypergraphs generalize regular digraphs. Let  $(d^-, d^+)$  be a couple of positive integers. A  $(d^-, d^+)$ -regular dihypergraph  $H$  is a dihypergraph such that the in-degree (resp. the out-degree) of every vertex in  $H$  equals  $d^-$  (resp.  $d^+$ ). When  $d^- = d^+ = d$  we also say that  $H$  is a  $d$ -regular dihypergraph. Remark that a dihypergraph  $H$  is  $(p, q)$ -uniform if, and only if, its dual dihypergraph  $H^*$  is  $(p, q)$ -regular, for some positive integers  $p, q$ .

When the studied dihypergraphs are uniform, Theorem 5 can be reformulated, in a very similar way to [25]:

**Corollary 3.** *Let  $H$  be an Eulerian dihypergraph. If  $H$  is  $(s^-, s^+)$ -uniform, then :*

$$\sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| \leq (s^+ + s^- - 2)m(H)$$

Observe that even though  $d$ -regular dihypergraphs always verify the necessary condition of Theorem 5, they are not always Eulerian.

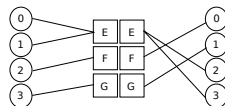


Figure 7: A regular dihypergraph that is not Eulerian.

The next result is a generalization of a property that disjoint unions of circuits have:

**Proposition 19.** *Let  $H$  be a 1-regular dihypergraph.  $H$  is Hamiltonian if and only if  $H$  is connected, and for all hyperarc  $E \in \mathcal{E}(H)$ ,  $|E^-| = |E^+|$ . Consequently, deciding whether  $H$  is Hamiltonian can be done in polynomial time.*

*Proof.* Let  $H$  be a 1-regular dihypergraph. Remark that its dual  $H^*$  is a digraph. By Theorem 2,  $H^*$  is Eulerian if and only if it is connected and, for every vertex  $v \in \mathcal{V}(H^*)$ ,  $d^-(v) = d^+(v)$ . Moreover, by Proposition 12,  $H$  is Hamiltonian if and only if  $H^*$  is Eulerian.  $\square$

This does not mean that deciding whether a uniform dihypergraph is Eulerian is an easier task than in the general case. We recall the following result about regular digraphs:

**Theorem 20** ([2]). *Deciding whether a 2-regular digraph  $D$  is Hamiltonian is an NP-complete problem.*

In [25], the authors use a similar result about 3-regular graphs, for proving that deciding whether a  $k$ -uniform hypergraph,  $k \geq 3$ , is Eulerian is an NP-complete problem. We do the same for uniform dihypergraphs. First observe that when the studied dihypergraphs are 1-uniform, that is they are digraphs, we know that:

Deciding whether a digraph is Eulerian can be done in polynomial time. [13]

**Theorem 21.** *Let  $(s^-, s^+)$  be a couple of positive integers. If  $s^- \geq 2$ , or  $s^+ \geq 2$ , then deciding whether a  $(s^-, s^+)$ -uniform dihypergraph is Eulerian is an NP-complete problem.*

*Proof.* By Proposition 12, we only need to prove the case when  $s^+ \geq 2$ . Indeed, the mirror dihypergraph of a  $(s^-, s^+)$ -uniform dihypergraph is a  $(s^+, s^-)$ -uniform dihypergraph. Furthermore, by Theorem 13, we already know that the problem is in the NP-class. The idea is to start from a 2-regular digraph  $D$ , to build with it a dihypergraph  $H_D$  in polynomial time, then we add useless vertices in  $H_D$  to have the expected uniformity. Finally, we prove that  $D$  Hamiltonian if and only if  $H_D$  Eulerian.

Let  $D = (\mathcal{V}(D), \mathcal{E}(D))$  be a 2-regular digraph. We define the dihypergraph  $H_D$  with the following rules:

1.  $\mathcal{V}(H_D) = \mathcal{V}(D) \cup [A \times \mathcal{V}(D)] \cup [B \times \mathcal{V}(D)]$ , where  $A$  and  $B$  are two sets satisfying  $|A| = s^- - 1$  and  $|B| = s^+ - 2$ .

2. To each vertex  $v \in \mathcal{V}(D)$  we associate a hyperarc  $V \in \mathcal{E}(H_D)$ , such that  $V^- = \{v\} \cup [A \times \{v\}]$ , and  $V^+ = \{w_v, w'_v\} \cup [B \times \{v\}]$ , where  $w_v$  and  $w'_v$  are the out-neighbors of  $v$  in  $D$ .

By construction,  $H_D$  is a  $(s^-, s^+)$ -uniform dihypergraph. Suppose that  $D$  is Hamiltonian. Let  $C = v_0, v_0v_1, v_1, \dots, v_{n-1}, v_{n-1}v_0, v_0$  be a Hamiltonian dicycle in  $D$ . From  $C$ , we build a dicycle  $C_D$  in  $H_D$ ,  $C_D = v_0, V_0, v_1, V_1, \dots, v_{n-1}, V_{n-1}, v_0$ , where  $V_i$  is the hyperarc that is induced by  $v_i$ . By definition of a Hamiltonian dicycle,  $\forall v \in \mathcal{V}(D)$ ,  $v$  appears only once in  $C$ . Therefore, by construction of  $H_D$ ,  $\forall V \in \mathcal{E}(H_D)$ ,  $V$  appears exactly once in  $C_D$ . So  $C_D$  is an Eulerian dicycle in  $H_D$ .

Moreover, remark that  $\forall E, F \in \mathcal{E}(H_D)$ , by construction of  $H_D$  we have  $E^+ \cap F^- \subset 2^{\mathcal{V}(D)}$ . Let  $C_D = v_0, E_0, v_1, \dots, v_{m-1}, E_{m-1}, v_0$  be an Eulerian dicycle in  $H_D$ . Because of the previous remark, we know that  $\forall i, v_i \in \mathcal{V}(D)$ . But a vertex  $v \in \mathcal{V}(D)$  is incident to only one hyperarc in  $H_D$ . As a consequence, for all  $i$ ,  $E_i$  is the hyperarc that is induced by  $v_i$ . So  $C = v_0, v_0v_1, v_1, \dots, v_{m-1}, v_{m-1}v_0, v_0$  is a Hamiltonian dicycle in  $D$ .  $\square$

Nonetheless, we are able to prove more results than in the general case, when the studied dihypergraphs are uniform and also regular. When  $H$  is a digraph, we know that:

**Theorem 22** ([13]). *Let  $D$  be a weakly-connected digraph. If  $D$  is regular, then all its iterated line digraphs  $L^n(D)$ ,  $n \geq 1$ , are Hamiltonian.*

Observe that a digraph is a 1-uniform dihypergraph, and that every  $L^n(D)$  is also Eulerian, because it is obvious when  $D$  is a regular digraph. We are able to prove that, more generally:

**Theorem 23.** *Let  $H$  be a weakly-connected,  $d$ -regular,  $s$ -uniform directed hypergraph. Then  $\forall n \geq 1$ ,  $L^n(H)$  is Eulerian and Hamiltonian.*

*Proof.* Since  $H$  is  $d$ -regular and  $s$ -uniform, then  $U(H)$  is a  $ds$ -regular multidigraph. As a consequence,  $\forall n$   $L^n(U(H))$  is also  $ds$ -regular. Using that  $L^0(U(H)) = U(H)$  for the basic step, and Theorem 1 for the induction step, we show by induction that  $\forall n$   $U(L^n(H))$  is isomorphic to  $L^n(U(H))$ . So  $\forall n$ ,  $U(L^n(H))$  is Eulerian (because it is a regular multidigraph), that is equivalent, by Proposition 14, to  $L(L^n(H)) = L^{n+1}(H)$  Hamiltonian.

Moreover,  $H^*$  is  $s$ -regular,  $d$ -uniform. Therefore,  $\forall n \geq 1$   $L^n(H^*)$  is also Hamiltonian. Using that  $L^0(H) = H$  (resp.  $L^0(H^*) = H^*$ ) for the basic step, and Theorem 1 for the induction step again, we prove by induction that  $\forall n$   $(L^n(H))^*$  is isomorphic to  $L^n(H^*)$ . Therefore, by Proposition 12,  $\forall n \geq 1$   $L^n(H)$  is Eulerian.  $\square$

**Remark 8.** *Theorem 23 holds when  $H$  is  $(d^-, d^+)$ -regular;  $H$  is  $(s^-, s^+)$ -uniform, if we add the extra-condition:  $d^-s^- = d^+s^+$ .*

In the case when  $s = d$  we are able to prove slightly more than Theorem 23:

**Proposition 24.** *Let  $H$  be a  $d$ -regular,  $d$ -uniform dihypergraph. There is a complete Berge dicycle in  $L(H)$ . In other words, the bipartite representation digraph  $R(L(H))$  is Hamiltonian.*

*Proof.* Because of the  $d$ -regularity,  $d$ -uniformity of  $H$ , its own bipartite representation digraph  $R(H)$  is  $d$ -regular. Therefore,  $\forall i \geq 1$   $L^i(R(H))$  is Hamiltonian. Particularly when  $i = 2$ . By Theorem 1, we know that  $L^2(R(H))$  and  $R(L(H))$  are isomorphic. Therefore,  $R(L(H))$  is Hamiltonian.  $\square$

Uniform B-graphs and F-graphs also have an interesting property. When their line dihypergraph  $L(H)$  is Hamiltonian, they are not necessarily Eulerian, but they verify the necessary condition of Theorem 7:

**Proposition 25.** *Let  $H$  be a  $(1, s^+)$ -uniform dihypergraph (resp. a  $(s^-, 1)$ -uniform dihypergraph). If  $L(H)$  is Hamiltonian, then for all subset  $X \subset \mathcal{V}(H)$ ,  $d_s^-(X) \leq d^+(X)$ .*



*Proof.* By symmetry, we only show the property for B-graphs.

Let  $H$  be a  $(s^-, 1)$ -uniform dihypergraph, such that its line dihypergraph  $L(H)$  is Hamiltonian. By Proposition 14, its underlying multidigraph  $U(H)$  is Eulerian. Therefore, for all subset  $X \subset \mathcal{V}(H)$ , we have

$$d_{U(H)}^-(X) = \sum_{x \in X} d_{U(H)}^-(x) = \sum_{x \in X} d_{U(H)}^+(x) = d_{U(H)}^+(X)$$

Since  $H$  is a  $(s^-, 1)$ -uniform dihypergraph, therefore  $d_{U(H)}^-(X) = s^- \cdot d_H^-(X)$ . Furthermore:

$$d_{U(H)}^+(X) = \sum_{E \in \mathcal{E}(H) \text{ s.t. } E^- \cap X \neq \emptyset} |E^- \cap X| \leq \sum_{E \in \mathcal{E}(H) \text{ s.t. } E^- \cap X \neq \emptyset} |E^-| = s^- \cdot d_H^+(X)$$

Consequently:

$$d_{s,H}^-(X) = d_H^-(X) = \frac{d_{U(H)}^-(X)}{s^-} = \frac{d_{U(H)}^+(X)}{s^-} \leq d_H^+(X)$$

□

#### 4.1 A Particular Subfamily

One can find a family of uniform dihypergraphs for which the condition of Theorem 5 is a sufficient condition. But that imposes very restrictive conditions over this family.

Let  $\mathcal{H}$  be a set of dihypergraphs, such that for all  $H \in \mathcal{H}$ :

1.  $H$  is  $(s^-, s^+)$ -uniform, for some couple of positive integers  $(s^-, s^+)$ .
2. for all hyperarc  $E \in \mathcal{E}(H)$ ,  $E^- \cap E^+ = \emptyset$ .
3. for all hyperarcs  $E, F \in \mathcal{E}(H)$ , such that  $E \neq F$ , if  $E \cap F \neq \emptyset$  then  $E^+ \cap F^- \neq \emptyset$  and  $F^+ \cap E^- \neq \emptyset$ .

We associate to  $H \in \mathcal{H}$  an *undirected* hypergraph  $H_u$ , whose set of vertices is  $\mathcal{V}(H)$ , and whose set of edges is  $\mathcal{E}_u = \{E^- \cup E^+ : E \in \mathcal{E}(H)\}$ .  $H_u$  is called the *underlying hypergraph* of  $H$ . By construction,  $H_u$  is a  $k$ -uniform hypergraph, where  $k = s^- + s^+$ . The Eulerian properties of the undirected uniform hypergraphs have been studied in [25]. Particularly, the authors of this paper define the *strongly connectivity* of an *undirected* uniform hypergraph:

**Definition 8** ([25]). *Let  $H_u$  be a  $k$ -uniform, undirected hypergraph. Let  $G$  be a graph, whose vertices are the edges of  $H_u$ , such that an edge  $E$  is linked to another edge  $F$  if and only if  $|E \cap F| = k - 1$ .  $H_u$  is called a *strongly connected hypergraph* when  $G$  is a connected graph.*

**Theorem 26** ([25]). *Let  $H_u$  be a  $k$ -uniform, undirected hypergraph. If  $H_u$  is strongly connected, then  $H_u$  is Eulerian iff*

$$|V_{\text{odd}}(H_u)| \leq (k - 2)m(H_u)$$

This theorem generalizes the Euler condition for a graph  $G$  to be Eulerian:  $G$  is Eulerian if and only if it is connected and all its vertices have an even degree.

**Theorem 27.** *Let  $H \in \mathcal{H}$  be a  $(s^-, s^+)$ -uniform dihypergraph, and  $H_u$  be the underlying hypergraph of  $H$ . If  $H_u$  is strongly connected, then  $H$  is Eulerian if and only if*

$$\sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| \leq (s^- + s^+ - 2)m(H)$$

*Proof.* By Corollary 3, if  $H$  is Eulerian then  $\sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)| \leq (s^- + s^+ - 2)m(H)$ . Let us assume this condition is verified.

Let  $v$  be a vertex in  $H$ . Since for all hyperarc  $E$ ,  $E^- \cap E^+ = \emptyset$ , therefore the degree of  $v$  in  $H_u$ , that is the number of edges that contain  $v$ , denoted  $d(v)$ , is equal to  $d_H^-(v) + d_H^+(v)$ . Consequently, when  $d(v)$  is odd,  $d_H^-(v) \neq d_H^+(v)$ . Therefore  $\sum_{v \in \mathcal{V}(H)} |d^+(v) - d^-(v)|$  is an upper bound of  $|V_{\text{odd}}(H_u)|$ . We recall that by construction,

$H_u$  is a  $s^- + s^+$ -uniform hypergraph. Moreover,  $H_u$  is strongly connected. Since  $|V_{\text{odd}}(H_u)| \leq (s^- + s^+ - 2)m(H)$ , and  $m(H) = |\mathcal{E}_u|$ , therefore  $H_u$  is Eulerian by Theorem 26.

We denote  $E_j$  the edge in  $H_u$  that is associated to hyperarc  $E_j$ . Let  $T = u_0, E_0, u_1, \dots, u_{m-1}, E_{m-1}, u_0$  be an Euler tour in  $H_u$ . For all  $j$ , we have  $u_{j+1} \in E_j \cap E_{j+1}$  by definition of an Euler tour. Consequently,  $E_j \cap E_{j+1} \neq \emptyset$ . By definition of  $\mathcal{H}$ , there exists a vertex  $v_{j+1} \in E_j^+ \cap E_{j+1}^-$  because  $E_j^+ \cap E_{j+1}^- \neq \emptyset$ . As a consequence,  $C = v_0, E_0, v_1, \dots, v_{m-1}, E_{m-1}, v_0$  is an Eulerian circuit in  $H$ .  $\square$

**Remark 9.** Actually, the property " $H$  is in  $\mathcal{H} \implies H$  is uniform" could be replaced by the following one: if  $H$  is a dihypergraph in  $\mathcal{H}$ , then there exists an integer  $k$  such that for all hyperarc  $E \in \mathcal{E}(H)$ ,  $|E^-| + |E^+| = k$ .

## 4.2 Universal Cycles and Universally Eulerian Dihypergraphs

Finally, we present another kind of so-called Eulerian circuits. Let  $\mathcal{F}$  be a set of  $N$  combinatorial objects, and  $A$  be an alphabet. An element of  $\mathcal{F}$  is associated to one or many words of length  $n$  over  $A$ .

**Definition 9** ([26]). A universal cycle (or ucycle) of  $\mathcal{F}$  is a word  $u_0 u_2 \dots u_{N-1}$  over  $A$ , with each  $F \in \mathcal{F}$  represented by exactly one subword  $u_i u_{i+1} \dots u_{i+n}$  (index addition is interpreted modulo  $N$ ).

Observe that a same word of length  $n$  could represent many elements in  $\mathcal{F}$ . So there are possibly more than one bijection between  $\mathcal{F}$  and the subwords of length  $n$  in a ucycle.

It was suggested in [1] to use universal cycles as an extension of the Eulerian cycles to the uniform hypergraphs. This can be done with the uniform dihypergraphs too. Indeed, let  $H = (\mathcal{V}(H), \mathcal{E}(H))$  be a  $(s^-, s^+)$ -uniform dihypergraph. A hyperarc  $E \in \mathcal{E}(H)$  could be represented as a word of length  $k = s^- + s^+$  over the alphabet  $A = \mathcal{V}(H)$ , denoted  $w = v_0 v_1 \dots v_{k-1}$ , where  $\{v_0, v_1, \dots, v_{s^- - 1}\}$  and  $\{v_{s^-}, v_{s^- + 1}, \dots, v_{k-1}\}$  are the in-set and the out-set of  $E$  respectively. In so doing, a hyperarc is associated to  $s^- ! s^+ !$  words of length  $k$  over the alphabet  $A$ .

**Definition 10.** Let  $H$  be a  $(s^-, s^+)$ -uniform dihypergraph.  $H$  is universally Eulerian if there is a ucycle of  $\mathcal{E}(H)$  over the alphabet  $\mathcal{V}(H)$ .

Observe that an Eulerian digraph  $D$  is a universally Eulerian digraph. Indeed, let  $v_0, v_0 v_1, v_1, \dots, v_{m-1}, v_{m-1} v_0, v_0$  be an Eulerian circuit in  $D$ . Then  $v_0 v_1 v_2 \dots v_{m-1}$  is a ucycle of  $\mathcal{E}(D)$  over the alphabet  $\mathcal{V}(D)$ .

**Proposition 28.** A universally Eulerian dihypergraph is an Eulerian dihypergraph.

*Proof.* Let  $H$  be a  $(s^-, s^+)$ -uniform dihypergraph. Let us assume that  $H$  is universally Eulerian, and let  $C_U = v_0 v_1 \dots v_{m-1}$  be a universal cycle of  $\mathcal{E}(H)$  over the alphabet  $\mathcal{V}(H)$ . We denote by  $E_i$  the hyperarc that is represented by  $v_i v_{i+1} \dots v_{i+k-1}$ , where  $k = s^- + s^+$ . Remark that  $v_{i+s^-}$  is in  $E_i^+ \cap E_{i+1}^-$ . As a consequence,  $C = v_{m-1+s^-}, E_0, v_{s^-}, E_1, \dots, E_i, v_{i+s^-}, E_{i+1}, \dots, v_{m-2+s^-}, E_{m-1}, v_{m-1+s^-}$  is an Eulerian circuit in  $H$ .  $\square$

Proposition 28 shows that universal Eulerianity is a stronger notion than simple Eulerianity. Like strongly Eulerian dihypergraphs, universally Eulerian dihypergraphs verify the following property:

**Theorem 29.** Let  $H$  be a  $(s^-, s^+)$ -uniform dihypergraph. if  $H$  is universally Eulerian, then  $L(H)$  is Hamiltonian.

We prove Theorem 29 with two Lemmas:

**Lemma 9.** *Let  $H$  be a universally Eulerian dihypergraph. Let  $C_U$  be a ucycle of  $\mathcal{E}(H)$  over  $\mathcal{V}(H)$ . For all vertex  $v$ :*

$$d^-(v) = s^+ \cdot |C_U|_v$$

$$d^+(v) = s^- \cdot |C_U|_v$$

where  $|C_U|_v$  denotes the number of occurrences of  $v$  in  $C_U$ .

*Proof.* First observe that there are at least  $\max(s^-, s^+)$  hyperarcs, and that  $\max(s^-, s^+)$  vertices in  $C_U$  are pairwise different. Indeed,  $s^-$  consecutive vertices in  $C_U$  are the in-set of a given hyperarc, and  $s^+$  consecutive vertices are the out-set of a given hyperarc.

Let  $v$  be a vertex in  $H$ . When  $d^-(v) = d^+(v) = 0$ , Lemma 9 holds. Else  $v$  is necessarily in  $C_U$ , and so  $d^-(v), d^+(v) \neq 0$ . Let us assume that  $C_U = v_0v_1, \dots, v_{m-1}$ , and  $v = v_i$  for some  $i \in \{0, \dots, m-1\}$ . Then  $v$  is in the in-set of  $E_i, E_{i-1}, \dots, E_{i-s^-+1}$  and in the out-set of  $E_{i+1-k}, E_{i+2-k}, \dots, E_{i+s^+-k}$ , where  $k = s^- + s^+$ . Consequently, any occurrence of  $v$  in  $C_U$  increases the in-degree  $d^-(v)$  of  $s^+$  (resp. the out-degree  $d^+(v)$  of  $s^-$ ).  $\square$

**Lemma 10.** *Let  $H$  be a  $(s^-, s^+)$ -uniform dihypergraph. If  $H$  is universally Eulerian, then  $U(H)$  is Eulerian.*

*Proof.* Let  $v$  be a vertex in  $H$ . Observe that  $d_{U(H)}^-(v) = s^- d_H^-(v)$  and  $d_{U(H)}^+(v) = s^+ d_H^+(v)$ . Therefore, by Lemma 9, for all vertex  $v$ ,  $d_{U(H)}^-(v) = d_{U(H)}^+(v)$ . In other words,  $U(H)$  is a balanced digraph.

Furthermore, since  $H$  is universally Eulerian, therefore  $H$  is Eulerian by Proposition 28. By Proposition 3,  $H$ , and so  $U(H)$  is weakly connected. Therefore  $U(H)$  is Eulerian by Theorem 2.  $\square$

Theorem 29 is now a direct consequence of Lemma 10 and Proposition 14.

## 5 Consecutive - $(d, s)$ Dihypergraphs

### 5.1 Presentation

We show in the previous sections that:

1. The stability by the dual operation for a family of dihypergraphs may help to find Eulerian dihypergraphs in this family.
2. Dihypergraphs, the underlying multidigraphs of which are Hamiltonian, are Hamiltonian.
3. Some Eulerian dihypergraphs can be constructed from uniform, regular dihypergraphs, by line dihypergraph operation.

In this section, we present a special family of dihypergraphs that are constructed following a similar idea to the ones presented in [7]. We use the above-mentioned properties for proving this family has good Eulerian and Hamiltonian properties.

### 5.2 Definitions

#### 5.2.1 Consecutive - $d$ Digraphs

**Definition 11.** *A generalized de Bruijn digraph (sometimes called Reddy-Pradhan-Khul digraph), is a digraph  $GB(d, n)$  whose vertices are labeled by the residues modulo  $n$ ; there is an arc from vertex  $i$  to vertex  $j$  if, and only if,  $j \equiv di + \alpha \pmod{n}$ , for some  $\alpha$  with  $0 \leq \alpha \leq d - 1$ .*

If  $n = d^D$ ,  $GB(d, n)$  is nothing else than the *de Bruijn digraph*  $B(d, D)$ .

**Definition 12.** A generalized Kautz digraph (sometimes called *Imase-Itoh digraph*), is a digraph  $GK(d, n)$  the vertices of which are labeled by the residues modulo  $n$ ; there is an arc from vertex  $i$  to vertex  $j$  if, and only if,  $j \equiv -di - d + \alpha \pmod{n}$ , for some  $\alpha$  with  $0 \leq \alpha \leq d - 1$ .

If  $n = d^D + d^{D-1}$ ,  $GK(d, n)$  is nothing else than the *Kautz digraph*  $K(d, D)$ .

More generally, a *Consecutive- $d$  digraph* is a digraph  $G(d, n, q, r)$ , the  $n$  vertices of which are labeled by the residues modulo  $n$ ; there is an arc from vertex  $i$  to vertex  $j$  if, and only if,  $j \equiv qi + r + \alpha \pmod{n}$ , for some  $\alpha$  with  $0 \leq \alpha \leq d - 1$ . We assume that  $1 \leq d, q \leq n - 1$ , and  $0 \leq r \leq n - 1$ .

When  $q = d$  and  $r = 0$ ,  $G(d, n, d, 0)$  is a Reddy-Pradhan-Khul digraph [14]. If  $q = r = n - d$ ,  $G(d, n, n - d, n - d)$  is a Imase-Itoh digraph [14].

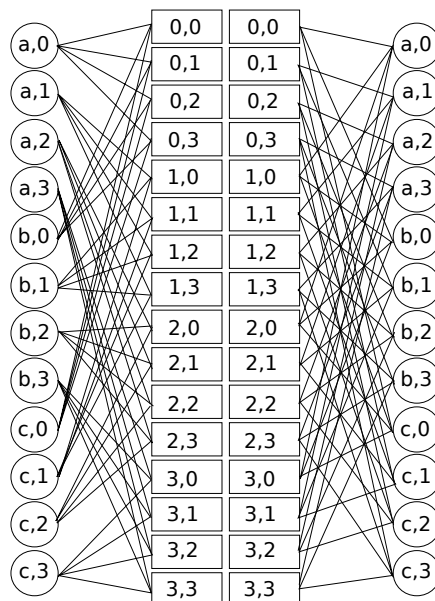
Finally, we present a subfamily that was introduced in [18]: Let  $\lambda$  be a positive integer, with  $1 \leq \lambda \leq d$ . Then  $GB_\lambda(d, n)$  is the subdigraph of  $GB(d, n)$  such that there is a link from  $i$  to  $j$  if, and only if,  $j \equiv di + \alpha \pmod{n}$ , for some  $\alpha$  with  $0 \leq \alpha \leq \lambda - 1$ . Note that  $GK_\lambda(d, n)$  also exists, and it is defined in a similar way.

## 5.2.2 Kautz and De Bruijn Dihypergraphs

In [7] de Bruijn and Kautz digraphs have been generalized to dihypergraphs. Two distinct definitions were proposed for de Bruijn Dihypergraphs. First scheme is a generalization for the alphabetical definition of a de Bruijn digraph. In the dihypergraph  $B_1(d, D, s)$ ,  $d$  is the size of a first alphabet  $A$ , and  $s$  is the size of a second alphabet  $B$ . Vertex labels are of the form  $[BA]^D$ , and hyperarc labels are of the form  $[A][BA]^{D-1}[A]$ .

Vertex  $(b_1, a_1, b_2, a_2, \dots, b_{D-1}, a_{D-1}, b_D, a_D)$  belongs to the in-set of hyperarcs  $(a_1, b_2, a_2, \dots, a_{D-1}, b_D, a_D, \alpha)$ , with  $\alpha \in A$ .

Hyperarc  $(a_0, b_1, a_1, \dots, b_{D-1}, a_{D-1}, a_D)$  has as out-set all the vertices  $(b_1, a_1, \dots, b_{D-1}, a_{D-1}, \beta, a_D)$ , with  $\beta \in B$ .

Figure 8: The de Bruijn dihypergraph  $B_1(4, 1, 3)$ .

An arithmetical extension of the latest definition, denoted by  $GB_1(d, n, s, m)$ , exists, when  $d, n, s, m$  verify some particular conditions detailed in [7]. With this definition,  $GB_1(d, (ds)^D, s, d^2(ds)^{D-1})$  and  $B_1(d, D, s)$  are isomorphic. However there is another arithmetical definition for the de Bruijn dihypergraphs:

**Definition 13** ([7]). *Let  $(d, n, s, m)$  be four positive integers, such that:  $dn \equiv 0 [m]$  and  $sm \equiv 0 [n]$ . The de Bruijn dihypergraph  $GB_2(d, n, s, m)$  can be defined as follows. Vertex labels (resp. hyperarc labels) are the residues modulo  $n$  (resp. modulo  $m$ ). Any vertex  $i$  belongs to the out-set of hyperarcs  $di + \alpha \pmod{m}$ , for every  $0 \leq \alpha \leq d - 1$ . Any hyperarc  $j$  has for in-set the vertices  $sj + \beta \pmod{n}$ , for every  $0 \leq \beta \leq s - 1$ .*

The incidence relations between vertices and hyperarcs (resp. between hyperarcs and vertices) are the same as in  $GB(d, n)$  (resp. in  $GB(s, m)$ ).

It was remarked in [12] these relations can be simultaneously *inversed*. Indeed, we can transform the labels of each hyperarc, labeling hyperarc  $i$  with label  $m - 1 - i$ . If we keep the previously established relations of incidence, then we now have the respective incidence relations of  $GK(d, n)$  and  $GK(s, m)$ :

**Definition 14** ([12]). *Let  $(d, n, s, m)$  be four positive integers, such that:  $dn \equiv 0 [m]$  and  $sm \equiv 0 [n]$ . The de Bruijn dihypergraph  $GB_2(d, n, s, m)$  can be defined as follows. Vertex labels (resp. hyperarc labels) are the residues modulo  $n$  (resp. modulo  $m$ ). Any vertex  $i$  is incident to hyperarcs  $-di - d + \alpha \pmod{m}$ , for every  $0 \leq \alpha \leq d - 1$ . Any hyperarc  $j$  has for in-set the vertices  $-sj - s + \beta \pmod{n}$ , for every  $0 \leq \beta \leq s - 1$ .*

Definition 14 is useful for some proofs, but unless we say that we use Definition 14, it is implied that we use Definition 13. Note that when  $n = (ds)^D$ , and  $m = d^2(ds)^{D-1}$ , those de Bruijn dihypergraphs are also isomorphic to a subfamily of alphabetically-defined dihypergraphs, noted  $B_2(d, D, s)$ .

In the same way, we can define the Kautz dihypergraph with an arithmetical definition:

**Definition 15** ([7]). Let  $(d, n, s, m)$  be four positive integers, such that:  $dn \equiv 0 [m]$  and  $sm \equiv 0 [n]$ . The Kautz dihypergraph, denoted by  $GK(d, n, s, m)$ , is the dihypergraph whose vertices (resp. hyperarcs) are labeled by the residues modulo  $n$  (resp. modulo  $m$ ), such that a vertex  $i$  is incident to hyperarcs  $di + \alpha \pmod{m}$ , for every  $0 \leq \alpha \leq d - 1$ , and hyperarc  $j$  has for out-set the vertices  $-sj - s + \beta \pmod{n}$ , for every  $0 \leq \beta \leq s - 1$ .

Inversing the labeling of the hyperarcs, as it is done for the de Bruijn hypergraphs in Definition 14, it has been proposed in [7] an equivalent definition for Kautz dihypergraphs:

**Definition 16** ([7]). Let  $(d, n, s, m)$  be four positive integers, such that:  $dn \equiv 0 [m]$  and  $sm \equiv 0 [n]$ . The Kautz dihypergraph, denoted by  $GK(d, n, s, m)$ , is the dihypergraph whose vertices (resp. hyperarcs) are labeled by the residues modulo  $n$  (resp. modulo  $m$ ), such that a vertex  $i$  belongs to the out-set of hyperarcs  $-di - d + \alpha \pmod{m}$ , for every  $0 \leq \alpha \leq d - 1$ , and hyperarc  $j$  is incident to vertices  $sj + \beta \pmod{n}$ , for every  $0 \leq \beta \leq s - 1$ .

When  $GB_1(d, n, s, m)$  and  $GB_2(d, n, s, m)$  have a property in common, we refer to them by  $GB(d, n, s, m)$ . Moreover, for preventing the lector from confusing vertices with hyperarcs, we denote by  $i$  the vertex  $i$ , but by  $E_j$  the hyperarc labeled by  $j$ .

### 5.2.3 Generalization

As in the digraph case, Kautz and de Bruijn dihypergraphs are particular cases of a larger class of dihypergraphs. Let  $(d, n, q, r, s, m, p, t)$  be eight positive integers, such that  $qn \equiv 0 [m]$  and  $pm \equiv 0 [n]$ . We call *Consecutive- $(d, s)$  dihypergraph* a dihypergraph  $G([d, n, q, r], [s, m, p, t])$ , whose vertices (resp. whose hyperarcs) are labeled by the residues modulo  $n$  (resp. modulo  $m$ ). Vertex  $i$  belongs to the out-set of hyperarc  $E_j$  if, and only if,  $j \equiv qi + r + \alpha \pmod{m}$ , for some  $\alpha$  with  $0 \leq \alpha \leq d - 1$ . Those are the incidence relations of the Consecutive- $d$  digraph  $G(d, n, q, r)$ . In the same way, the in-set of hyperarc  $E_j$  contains vertex  $k$  if, and only if,  $k \equiv pj + t + \beta \pmod{n}$ , for some  $\beta$  with  $0 \leq \beta \leq s - 1$ . Those are the relations of incidence in the Consecutive- $s$  digraph  $G(s, m, p, t)$ .

**Remark 10.** This definition allows empty in-sets. Clearly, a hyperarc whose in-set is empty is useless. So we may imagine a way to modify Consecutive- $(d, s)$  dihypergraphs such that there is no hyperarc whose in-set is empty.

This idea is not experimented in this paper.

Particularly when both  $G(d, n, q, r)$  and  $G(s, m, p, t)$  are generalized de Bruijn digraphs (resp. are generalized Kautz digraphs), we recognize de Bruijn dihypergraphs. If one of the two digraphs is a generalized de Bruijn digraph, whereas the other is a generalized Kautz digraph, we recognize Kautz dihypergraphs.

Remark that for every couple of positive integers  $(\lambda, \mu)$ , with  $1 \leq \lambda \leq d$  and  $1 \leq \mu \leq s$ , we can define  $GB_{(\lambda, \mu)}(d, n, s, m) = G([\lambda, n, d, 0], [\mu, m, s, 0])$ , a subdihypergraph of  $GB_2(d, n, s, m)$  defined in the same way that  $GB_\lambda(d, n)$  with digraph  $GB(d, n)$ .

## 5.3 Properties of the Consecutive- $(d, s)$ Dihypergraphs

### 5.3.1 Properties of the Consecutive- $d$ digraphs: a brief survey

Consecutive- $d$  digraphs have been intensively studied, especially in [17], [14], [23], [10], [11], [20], [16], [19], and [9]. Particularly, the characterization of the Hamiltonian Consecutive- $d$  digraphs is nearly complete:

**Theorem 30** ([17], [14], [23], [11]). Let  $G = G(d, n, q, r)$  be a Consecutive- $d$  digraph.

If  $d = 1$ , then  $G$  is Hamiltonian if and only if:

1.  $\gcd(n, q) = 1$ .
2. For every prime number  $p$  such that  $p|n$ ,  $p$  divides  $q - 1$ .
3. If  $n$  is a multiple of 4, then  $q - 1$  is also divisible by 4.
4.  $\gcd(n, q - 1, r) = 1$ .

When  $d = 2$ ,  $G$  is Hamiltonian if and only if one of the following conditions is verified:

1.  $\gcd(n, q) = 2$
2.  $\gcd(n, q) = 1$  and either  $G(1, n, q, r)$  or  $G(1, n, q, r + 1)$  is Hamiltonian.

Else, if  $d \geq 4$ , then  $G$  is Hamiltonian if and only if  $d \geq \gcd(n, q)$ .

The only remaining case is when  $d = 3$ . A partial characterization of Hamiltonian Consecutive-3 digraphs can be found in [17] and [10]. Particularly, when  $\gcd(n, q) \geq 2$ ,  $G(3, n, q, r)$  is Hamiltonian if and only if  $3 \geq \gcd(n, q)$ . If  $1 \leq |q| \leq 3$ , and  $n$  is coprime to  $q$ , then  $G(3, n, q, r)$  is always Hamiltonian.

Furthermore, the characterization of the Hamiltonian generalized de Bruijn digraphs (resp. the Hamiltonian generalized Kautz digraphs) is complete:

**Theorem 31** ([18], [15]). *Let  $G_1 = GB(d, n)$  be a generalized de Bruijn digraph. If  $\lambda = \gcd(n, d) \geq 2$  then  $GB_\lambda(d, n)$ , hence  $G_1$ , is Hamiltonian. Else,  $d$  is coprime to  $n$ , and  $G_1$  is Hamiltonian if and only if  $d \geq 3$ .*

*In the same way, let  $G_2 = GK(d, n)$  be a generalized Kautz digraph. If  $\lambda = \gcd(n, d) \geq 2$  then  $GK_\lambda(d, n)$ , hence  $G_2$ , is Hamiltonian. Else,  $d$  is coprime to  $n$ , and  $G_2$  is Hamiltonian if and only if  $d \geq 3$ , or  $d = 2$  and  $n$  is a power of 3.*

$GB(d, n)$  and  $GK(d, n)$  are also Eulerian [18].

Finally, consecutive- $d$  digraphs have interesting line digraph properties. We use the following relations [18]:

**Proposition 32.** *If  $\gcd(n, d) = \lambda \geq 2$  then*

$$L(GB_\lambda(d, \frac{n}{\lambda})) = GB_\lambda(d, n)$$

$$L(GK_\lambda(d, \frac{n}{\lambda})) = GK_\lambda(d, n)$$

Particularly, we have for all  $n$ :

$$L(GB(d, n)) = GB(d, dn) \text{ and } L(GK(d, n)) = GK(d, dn).$$

A possible mapping from the arcs of  $GB_\lambda(d, \frac{n}{\lambda})$  to the vertices in  $GB_\lambda(d, n)$  is this one: let  $(x, y)$  be an arc of  $GB_\lambda(d, \frac{n}{\lambda})$  such that  $y \equiv dx + r \pmod{\frac{n}{\lambda}}$ , then  $(x, y)$  is the vertex  $f(x, y) \equiv dx + r \pmod{n}$  in  $GB_\lambda(d, n)$ . Since  $\gcd(n, d) = \lambda$  it is easy to see that  $f$  is a one-to-one mapping. Furthermore, if  $y \equiv dx + r \pmod{\frac{n}{\lambda}}$  then  $\lambda y \equiv \lambda(dx + r) \pmod{n}$ . Consequently:

$$d.f(x, y) + \alpha \equiv d.(dx + r) + \alpha \equiv \frac{d}{\lambda}\lambda(dx + r) + \alpha \equiv \frac{d}{\lambda}\lambda.y + \alpha \equiv dy + \alpha \pmod{n}$$

So we have  $\{d.f(x, y) + \alpha : 0 \leq \alpha \leq \lambda - 1\} = \{f(y, z) : (y, z) \text{ is an arc of } GB_\lambda(d, \frac{n}{\lambda})\}$

### 5.3.2 General Properties of the Consecutive- $(d, s)$ Dihypergraphs

We generalize to the consecutive- $(d, s)$  dihypergraphs some useful properties of the Kautz and de Bruijn dihypergraphs. An obvious property is the stability by the dual operation:

$$(G([d, n, q, r], [s, m, p, t]))^* = G([s, m, p, t], [d, n, q, r])$$

Particularly:

$$(GB_2(d, n, s, m))^* = GB_2(s, m, d, n) \text{ and } (GK(d, n, s, m))^* = GK(s, m, d, n) \text{ [7].}$$

First, we study the underlying multidigraph of a consecutive- $(d, s)$  dihypergraph.

**Proposition 33.** *Let  $G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. Its underlying multidigraph is a union of Consecutive- $s$  digraphs. More precisely:*

$$U(G([d, n, q, r], [s, m, p, t])) = \bigcup_{\alpha=0}^{d-1} G(s, n, pq, p(r+\alpha)+t) \subset G_r(p(d-1)+s, n, pq, pr+t)$$

where  $G_r(p(d-1)+s, n, pq, pr+t)$  is a version of the consecutive digraph  $G(p(d-1)+s, n, pq, pr+t)$  such that some of the arcs may be repeated.

*Proof.* Let  $U$  be the underlying multidigraph of  $G([d, n, q, r], [s, m, p, t])$ . A vertex  $i$  is adjacent to vertices  $pqi + pr + t + p\alpha + \beta$ , for every  $0 \leq \alpha \leq d-1$  and  $0 \leq \beta \leq s-1$ . So the inclusion of  $U$  into  $G_r(p(d-1)+s, n, pq, pr+t)$  is trivial.

Now, we partition the arcs in  $U$ . Let  $uv, xy$  be two arcs of  $U$ . We say that  $uv$  and  $xy$  are in the same class of equivalence if, and only if  $\exists \alpha$  such that  $uv$  (resp.  $xy$ ) is induced by hyperarc  $E_{qu+r+\alpha}$  (resp. by hyperarc  $E_{qx+r+\alpha}$ ). Actually, the same choice of residue  $\alpha$ , applied respectively from  $u$  and from  $x$ , gives both of the arcs in  $U$ . This class is labeled by residue  $\alpha$ . This is a partition, since one, and only one choice is made for every arc. Remark that for all  $\alpha$ , all  $uv$  such that  $v \in E_{qu+r+\alpha}^+$  are in the same class of equivalence.

Let  $\alpha_0$  be an integer such that  $0 \leq \alpha_0 \leq d-1$ . Let  $H_{\alpha_0}$  be the subdihypergraph induced by the class labeled by  $\alpha_0$ . Remark that  $H_{\alpha_0}$  and  $G([1, n, q, r+\alpha_0], [s, m, p, t])$  are isomorphic. So it is easy to see that in  $H_{\alpha_0}$ , a vertex  $i$  is linked to every vertex  $j$  such that  $j \equiv p(qi+r+\alpha_0)+t+\beta \pmod{n}$ , for some  $\beta$  with  $0 \leq \beta \leq s-1$ . Therefore  $U(H_{\alpha_0}) = G(s, n, pq, p(r+\alpha_0)+t)$ . And since  $(H_{\alpha})_{0 \leq \alpha \leq d-1}$  partitions  $G([d, n, q, r], [s, m, p, t])$ , therefore  $(U(H_{\alpha}))_{0 \leq \alpha \leq d-1}$  partitions  $U$ .  $\square$

Particularly when the studied dihypergraph is a de Bruijn dihypergraph (resp. a Kautz dihypergraph) we conclude that:

**Corollary 4** ([7]). *The underlying multidigraph of  $GB_2(d, n, s, m)$  (resp. of  $GK(d, n, s, m)$ ) is  $GB(ds, n)$  (resp. is  $GK(ds, n)$ ).*

*Proof.* Indeed, for the de Bruijn hypergraphs we have  $r=t=0, q=d, p=s$  and we can remark that  $\bigcup_{\alpha=0}^{d-1} G(s, n, ds, s\alpha) = G(ds, n, ds, 0) = GB(ds, n)$ .  $\square$

More generally,  $U(G([d, n, q, r], [s, m, p, t])) = G_r(p(d-1)+s, n, pq, pr+t)$  when  $1 \leq p \leq s$ , or  $-s \leq p \leq -1$ . Another interesting property is the stability by the line dihypergraph operation. J.-C. Bermond (private communication) proved the following result:

**Proposition 34.** *If  $d|q, s|p, n$  is prime with  $pq, p$  is prime with  $d$  and  $q$  is prime with  $s$  then  $L(G([d, n, q, 0], [s, n, p, 0])) = G([d, nds, q, 0], [s, nds, p, 0])$*



*Proof.* In  $L(G([d, n, q, 0], [s, n, p, 0]))$  vertex  $i, E_j, i'$  is joined to the arc  $E_j, i', E_{j'}$  where:  $j \equiv qi + \alpha \pmod{n}$  for some  $0 \leq \alpha \leq d-1$ ,  $i' \equiv pj + \beta \pmod{n}$  for some  $0 \leq \beta \leq s-1$ , and  $j' \equiv qi' + \alpha' \pmod{n}$  for some  $0 \leq \alpha' \leq d-1$ .

Consider the one-to-one mapping of the vertices of  $L(G([d, n, q, 0], [s, n, p, 0]))$  in the set of integers modulo  $dsn$ : to the vertex  $i, E_j, i'$ , where  $j \equiv qi + \alpha \pmod{n}$  and  $i' \equiv pj + \beta \equiv pqi + p\alpha + \beta \pmod{n}$ , we associate the integer  $x = pqi + p\alpha + \beta$  modulo  $dsn$ .

Now consider the one-to-one mapping of the hyperarcs of  $L(G([d, n, q, 0], [s, n, p, 0]))$  in the set of integers modulo  $dsn$ : to the arc  $E_j, i', E_{j'}$  where  $i' \equiv pj + \beta \pmod{n}$  and  $j' \equiv qi' + \alpha' \pmod{n}$ , we associate the integer  $y = pqj + q\beta + \alpha'$  modulo  $dsn$ .

One can check that these mappings are one-to-one mappings due to the hypothesis.

The adjacency relation are kept as vertex  $x = pqi + p\alpha + \beta$  representing the vertex  $i, E_j, i'$  is joined in  $G([d, nds, q, 0], [s, nds, p, 0])$  to the hyperarcs  $y = qx + \alpha' = pq^2i + pq\alpha + q\beta + \alpha' = pqj + q\beta + \alpha'$  that are the images of the hyperarcs  $E_j, i', E_{j'}$  to which  $x$  is adjacent.  $\square$

We recall that de Bruijn and Kautz dihypergraphs are stable by line dihypergraph operation too:

**Theorem 35** ([6]). *The line dihypergraph of  $GB_2(d, n, s, m)$  (resp. of  $GK(d, n, s, m)$ ) is  $GB_2(d, dsn, s, dsm)$  (resp. is  $GK(d, dsn, s, dsm)$ ).*

Observe that even though they are not Consecutive- $(d, s)$  dihypergraphs, the de Bruijn dihypergraphs  $GB_1(d, n, s, m)$  have similar properties:

**Theorem 36** ([7]). *The underlying multidigraph of  $GB_1(d, n, s, m)$  is  $GB(ds, n)$ .*

**Theorem 37** ([6]). *The line dihypergraph of  $B_1(d, D, s)$  is isomorphic to  $B_1(d, D+1, s)$ .*

Remark that  $B_1(d, D, s)$  is  $d$ -regular and  $s$ -uniform [7].

### 5.3.3 Eulerian and Hamiltonian Properties

First scheme for the de Bruijn dihypergraphs is apart. So we deal with it first.

**Theorem 38.** *Let  $H = GB(d, n, s, m)$  be a de Bruijn dihypergraph.  $H$  is Hamiltonian if and only if one of the following cases is verified:*

1.  $ds \geq 3$
2.  $ds = 2$  and  $n$  is an even number.
3.  $ds \in \{1, 2\}$ , and  $n = 1$ .

*Proof.* Regardless of the scheme that is used for defining  $H$ ,  $U(H) = GB(ds, n)$ , by Corollary 4 and Theorem 36. By Theorem 31, we know that a de Bruijn digraph  $GB(d, n)$  is Hamiltonian if and only if  $d|n$  or  $d \geq 3$ . Therefore, by Lemma 4, we always know whether  $H$  is Hamiltonian.  $\square$

In the case when the studied de Bruijn dihypergraphs are alphabetically-defined ( $B_1(d, D, s)$ ) we are able to prove they are also Eulerian:

**Theorem 39.**  *$B_1(d, D, s)$  is Eulerian and Hamiltonian.*

*Proof.* Since  $B_1(d, D, s)$  and  $GB_1(d, (ds)^D, s, d^2(ds)^{D-1})$  are isomorphic, therefore we already know, by Theorem 38, every  $B_1(d, D, s)$  is Hamiltonian. But there is another way for proving it: using Theorem 37, we show by induction that  $L^{D-1}(B_1(d, 1, s)) = B_1(d, D, s)$ .  $B_1(d, 1, s)$  is  $d$ -regular, and  $s$ -uniform, and weakly-connected. Therefore, by Theorem 23,  $\forall D \geq 2$   $B_1(d, D, s)$  is Eulerian and Hamiltonian.

Finally, let us prove that  $B_1(d, 1, s)$  is Eulerian:

Let  $A, B$  be the two alphabets that are used for representing  $B_1(d, 1, s)$ . We recall that  $|A| = d$ , and  $|B| = s$ . In this special case:  $\mathcal{V}(B_1(d, 1, s)) = B \times A$  and  $\mathcal{E}(B_1(d, 1, s)) = A \times A$ . Remark that hyperarcs  $(a_i, a_j), (a_j, a_k)$  can always be linked, for example by vertex  $(b_0, a_j) \in (a_i, a_j)^+ \cap (a_j, a_k)^-$ . So we omit the vertex between two such hyperarcs.

For every  $0 \leq i \leq d-1$  we construct a dipath :

$$P_0 = (a_0, a_0), (a_0, a_2), (a_2, a_0), \dots, (a_0, a_j), (a_j, a_0), \dots, (a_0, a_{d-1}), (a_{d-1}, a_0); 2 \leq j \leq d-1$$

$$P_{d-1} = (a_{d-2}, a_{d-1}), (a_{d-1}, a_{d-1}), (a_{d-1}, a_{d-2}), \dots, (a_{d-j}, a_{d-j-1}), \dots, (a_2, a_1), (a_1, a_0); 1 \leq j \leq d-1$$

Otherwise  $P_i = (a_{i-1}, a_i), (a_i, a_i), (a_i, a_{i+2}), (a_{i+2}, a_i), \dots, (a_i, a_j), (a_j, a_i), \dots, (a_i, a_{d-1}), (a_{d-1}, a_i)$ , where  $i+2 \leq j \leq d-1$ .

Remark that the concatenation  $P_0 P_1 \dots P_{d-1}$  is an Eulerian circuit in  $B_1(d, 1, s)$ . So  $B_1(d, 1, s)$  is Eulerian.  $\square$

Because of Theorem 31, giving a necessary and sufficient condition for a de Bruijn dihypergraph to be Hamiltonian is the easy part. We now prove that Theorem 38 implies a necessary and sufficient condition for  $GB_2(d, n, s, m)$  to be Eulerian:

**Theorem 40.** *Let  $H = GB_2(d, n, s, m)$  be a de Bruijn dihypergraph.  $H$  is Eulerian if, and only if, one of the following cases is verified:*

1.  $ds \geq 3$
2.  $ds = 2$  and  $m$  is even.
3.  $ds \in \{1, 2\}$ , and  $m = 1$

*Proof.*  $H^* = GB_2(s, m, d, n)$ . So Theorem 38 gives a necessary and sufficient condition for  $H^*$  to be Hamiltonian. By Proposition 12, this is also a necessary and sufficient condition for  $H$  to be Eulerian.  $\square$

**Corollary 5.**  $B_2(d, D, s)$  is Eulerian and Hamiltonian.

*Proof.* Since  $B_2(d, D, s)$  and  $GB_2(d, (ds)^D, s, d^2(ds)^{D-1})$  are isomorphic, therefore it is a direct application of Theorems 38 and 40.  $\square$

The method that is used for deciding whether  $GB_2(d, n, s, m)$  is Eulerian or Hamiltonian can be applied to Kautz dihypergraphs in the same way. By Theorem 31, we have necessary and sufficient conditions for a generalized Kautz digraph to be Hamiltonian. Consequently:

**Theorem 41.** *Let  $H = GK(d, n, s, m)$  be a Kautz dihypergraph.*

1. *If  $ds \geq 3$  then  $H$  is Eulerian and Hamiltonian.*
2. *If  $ds = 2$  then  $H$  is Eulerian (resp. Hamiltonian) if, and only if  $m$  (resp.  $n$ ) is even or a power of 3.*
3. *If  $d = s = 1$ , then  $H$  is Eulerian (resp. Hamiltonian) if, and only if,  $m \in \{1, 2\}$  (resp.  $n \in \{1, 2\}$ ).*

Those methods can be generalized to the Consecutive- $(d, s)$  dihypergraphs too. But they are not sufficient for completing the characterization of their Eulerian and Hamiltonian properties. By the dual operation, a condition for a Consecutive- $(d, s)$  dihypergraph (not) to be Hamiltonian is always associated to a condition (not) to be Eulerian. So we detail some conditions for a Consecutive- $(d, s)$  dihypergraph (not) to be Hamiltonian, and we present the associated conditions (not) to be Eulerian as corollaries.

**Proposition 42.** *Let  $H = G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. If the consecutive digraph  $G(s, n, pq, p(r + \alpha) + t)$  is Hamiltonian for some  $0 \leq \alpha \leq d-1$ , then  $H$  is Hamiltonian.*

$ds$	$n$	$m$	$GB_2(d, n, s, m)$	$GK(d, n, s, m)$
1			Eulerian $\iff m = 1$	Eulerian $\iff m \in \{1, 2\}$
1			Hamiltonian $\iff n = 1$	Hamiltonian $\iff n \in \{1, 2\}$
2	even		Hamiltonian	Hamiltonian
2		even	Eulerian	Eulerian
2	odd		Hamiltonian $\iff n = 1$	Hamiltonian $\iff n$ is a power of 3
2		odd	Eulerian $\iff m = 1$	Eulerian $\iff m$ is a power of 3
$\geq 3$			Eulerian and Hamiltonian	Eulerian and Hamiltonian

Table 1: Cases when Kautz and de Bruijn dihypergraphs are Eulerian or Hamiltonian

*Proof.* By Proposition 33,  $G(s, n, pq, p(r + \alpha) + t)$  is a subdigraph of  $U(H)$ . Therefore, if  $G(s, n, pq, p(r + \alpha) + t)$  is Hamiltonian, then  $U(H)$  is Hamiltonian, and so  $H$  is Hamiltonian by Lemma 4.  $\square$

**Corollary 6.** *Let  $H = G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. If the consecutive digraph  $G(d, m, pq, q(t + \beta) + r)$  is Hamiltonian for some  $0 \leq \beta \leq s - 1$ , then  $H$  is Eulerian.*

In the same way, we have a sufficient condition for a Consecutive- $(d, s)$  dihypergraph not to be Hamiltonian (resp. Eulerian).

**Proposition 43.** *Let  $H = G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. If the Consecutive digraph  $G(p(d - 1) + s, n, pq, pr + t)$  is not Hamiltonian, then  $H$  is not Hamiltonian.*

*Proof.* By Proposition 33,  $U(H)$  is a subdigraph of  $G_r$ , where  $G_r$  is a version of  $G(p(d - 1) + s, n, pq, pr + t)$  with possibly repeated arcs. Clearly, repeating some arcs does not change the Hamiltonicity. Therefore, if  $G(p(d - 1) + s, n, pq, pr + t)$  is not Hamiltonian, then  $G_r$  is not Hamiltonian either. As a consequence,  $U(H)$  is not Hamiltonian, and so  $H$  is not Hamiltonian, by Lemma 4.  $\square$

**Corollary 7.** *Let  $H = G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. If the Consecutive digraph  $G(q(s - 1) + d, m, pq, qt + r)$  is not Hamiltonian, then  $H$  is not Eulerian.*

Particularly when  $U(H) = G_r(p(d - 1) + s, n, pq, pr + t)$  (resp. when  $U(H^*) = G_r(q(s - 1) + d, m, pq, qt + r)$ ), Proposition 43 (resp. Corollary 7) becomes a necessary and sufficient condition for  $H$  to be Hamiltonian (resp. Eulerian).

**Corollary 8.** *Let  $H = G([d, n, q, r], [s, m, p, t])$  be a Consecutive- $(d, s)$  dihypergraph.*

1. *When  $1 \leq |p| \leq s$ ,  $H$  is Hamiltonian if and only if the Consecutive digraph  $G(p(d - 1) + s, n, pq, pr + t)$  is Hamiltonian.*
2. *Similarly, when  $1 \leq |q| \leq d$ ,  $H$  is Eulerian if and only if the Consecutive digraph  $G(q(s - 1) + d, m, pq, qt + r)$  is Hamiltonian.*

## 5.4 Existence of Complete Berge Circuits

In this section, we show the existence of Complete Berge Circuits in some consecutive dihypergraphs. However, we start by recalling some definitions and results we need.

$d$	Eulerian Properties	$s$	Hamiltonian Properties
1	$G(1, m, pq, 1)$ is Hamiltonian and $\gcd(m, pq - 1, q(\beta + t) + r) = 1$ , for some $0 \leq \beta \leq s - 1$	1	$G(1, n, pq, 1)$ is Hamiltonian and $\gcd(n, pq - 1, p(\alpha + r) + t) = 1$ , for some $0 \leq \alpha \leq d - 1$
2	1) $\gcd(m, pq) = 2$ 2) $\gcd(m, pq) = 1$ and $G(1, m, pq, q(t + \beta) + r)$ is Hamiltonian or $G(1, m, pq, q(t + \beta) + r + 1)$ is Hamiltonian for some $0 \leq \beta \leq s - 1$	2	1) $\gcd(n, pq) = 2$ 2) $\gcd(n, pq) = 1$ and $G(1, n, pq, p(r + \alpha) + t)$ is Hamiltonian or $G(1, n, pq, p(r + \alpha) + t + 1)$ is Hamiltonian for some $0 \leq \alpha \leq d - 1$
3	1) $2 \leq \gcd(m, pq) \leq 3$ 2) $\gcd(m, pq) = 1$ , with $1 \leq  pq  \leq 3$	3	1) $2 \leq \gcd(n, pq) \leq 3$ 2) $\gcd(n, pq) = 1$ , with $1 \leq  pq  \leq 3$
$\geq 4$	$d \geq \gcd(m, pq)$	$\geq 4$	$s \geq \gcd(n, pq)$

Table 2: Sufficient conditions for a Consecutive- $(d, s)$  dihypergraph  $G([d, n, q, r], [s, m, p, t])$  to be Eulerian or Hamiltonian.

#### 5.4.1 Arithmetical Results

By  $\mathbb{Z}_n$  we mean the residues modulo  $n$ . We recall some results and definitions that are useful for this subsection:

**Definition 17.** *The Euler function, denoted by  $\varphi$ , associates to a positive integer  $n$ , the number  $\varphi(n)$  of positive integers, that are lower than  $n$  and coprime to  $n$ . This is also the number  $\varphi(n)$  of elements  $i \in \mathbb{Z}_n$  such that  $x \rightarrow x + i$  is a circular permutation in  $\mathbb{Z}_n$ . In other words,  $\varphi(n)$  is the number of generator elements in  $\mathbb{Z}_n$ .*

The Euler function can be defined inductively with the following rules:

1.  $\varphi(1) = 1$ ;
2. If  $p$  is a prime number and  $m \geq 1$ , then  $\varphi(p^m) = (p - 1)p^{m-1}$ ;
3. If  $a$  is coprime to  $b$ , then  $\varphi(ab) = \varphi(a)\varphi(b)$ .

Let  $a, b$  be two positive integers. If  $a$  is coprime to  $b$ , then  $a$  is invertible in  $\mathbb{Z}_b$ , and the powers of  $a$  are a multiplicative group in  $\mathbb{Z}_b$ . The order of  $a$  in  $\mathbb{Z}_b$  is the minimum  $i \geq 1$  such that  $a^i \equiv 1 \pmod{b}$ .

**Theorem 44 (Euler).** *If  $a$  is coprime to  $b$  then  $a^{\varphi(b)} \equiv 1 \pmod{b}$ .*

So we know the order of  $a$  divides  $\varphi(b)$ .

#### 5.4.2 The Hamiltonian Properties of the Bipartite Representation Digraphs

We now try to decide whether there is a complete Berge dicycle in  $GB_2(d, n, s, m)$ , i.e there is a Hamiltonian dicycle in its bipartite representation digraph.

A necessary condition for a dihypergraph  $H$  to have a complete Berge dicycle is that  $n(H) = m(H)$ . Otherwise, there are more hyperarcs than vertices, or more vertices than hyperarcs and, as a consequence,  $R(H)$  cannot be Hamiltonian.

We now study the particular case when  $d = s$ . Actually, we are always able to decide whether there is a complete Berge circuit in  $GB_2(d, n, d, n)$ :

**Theorem 45.** *There is a complete Berge dicycle in  $GB_2(d, n, d, n)$  if and only if one of the following conditions is verified:*

1.  $d \geq 3$
2.  $d = 2$  and  $n$  is an even number
3.  $d = 2$  and  $n$  is a power of 3
4.  $d = n = 1$

Recall that for  $d \geq 2$ , those are exactly the cases when  $GK(d, n)$  is Hamiltonian, as presented in Theorem 31. However, the proof we present does not use this fact. The entire demonstration of Theorem 45 is decomposed in Lemmas 11, 12, 13, 14, 15, 16, 17, and 18.

**Lemma 11.** *If  $d = 1$ , then there is a complete Berge circuit in  $GB_2(1, n, s, n)$  if and only if the de Bruijn digraph  $GB(s, n)$  is Hamiltonian.*

*Proof.* If  $d = 1$ , then every vertex  $i$  is only incident to hyperarc  $E_i$ . So we may not distinguish the vertices from the hyperarcs, and we get a digraph, the relations of incidence of which are the relations of incidence between hyperarcs and vertices in the original dihypergraph. Therefore, Lemma 11 follows.  $\square$

The case when  $d = 1$  is entirely solved by Lemma 11.

For the next proofs, we see a Hamiltonian dicycle in the digraph  $GB(d, n)$  or  $GK(d, n)$  as a circular permutation  $\sigma$  in  $Z_n$ . If  $j$  is the vertex that follows  $i$  in the Hamiltonian dicycle, then  $\sigma(i) = j$ ; if  $k$  is the vertex that follows  $j$  in the cycle, then  $\sigma^2(i) = k$ , and so on.

Most of the remaining proofs use the notion of *dual counterpart*.

**Definition 18.** *Let  $H = (\mathcal{V}, \mathcal{E})$  be a dihypergraph, and  $P = v_0, E_0, v_1, \dots, E_{p-2}, v_{p-1}$  be a dipath in  $H$ . The dual counterpart of  $P$ , denoted by  $P^*$ , is the representation of  $P$  in the dual dihypergraph  $H^*$ . In other words,  $P^* = V_0, e_0, V_1, \dots, e_{p-2}, V_{p-1}$ .*

Observe that the dual counterpart of a dipath is not necessarily a dipath itself, unless  $P$  is a circuit.

When  $n$  is an odd number, Theorem 45 can be proven with a concatenation of circuits:

**Lemma 12.** *If  $GK(d, n)$  is Hamiltonian, and  $n$  is odd, then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .*

*Proof.* We use Definition 14 for the proof. Let  $0, \sigma(0), \sigma^2(0), \dots, \sigma^{n-1}(0)$  be a Hamiltonian dicycle in  $GK(d, n)$ . Observe that  $P_1 = 0, E_{\sigma(0)}, \sigma^2(0), \dots, \sigma^{2j}(0), E_{\sigma^{2j+1}(0)}, \dots, \sigma^{n-1}(0)$ , for  $0 \leq j \leq \frac{n-1}{2}$ , is a dipath in  $GB_2(d, n, d, n)$ . Let  $P_2 = P_1^* = E_0, \sigma(0), E_{\sigma^2(0)}, \dots, E_{\sigma^{n-1}(0)}$  be its *dual counterpart*. Since  $n$  is odd, then  $P_1$  and  $P_2$  can be linked together, and  $C = P_1 P_2 = 0, E_{\sigma(0)}, \sigma^2(0), \dots, \sigma^{n-1}(0), E_0, \sigma(0), E_{\sigma^2(0)}, \dots, E_{\sigma^{n-1}(0)}$  is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .  $\square$

In the same way, if  $GB(d, n)$  is Hamiltonian, and  $n$  is odd, then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ . However, by Theorem 31, if  $GB(d, n)$  is Hamiltonian then  $GK(d, n)$  is also Hamiltonian, but the converse is not true. That is why we use  $GK(d, n)$ , hence Definition 14, for the proof.

Actually Lemma 12 is a consequence of Proposition 17 (Kronecker product). Indeed, let  $n$  be an odd number. One may consider the bipartite representation digraph  $R(GB_2(d, n, d, n))$  as the Kronecker product  $GK(d, n) \otimes C_2$ , where  $C_2$  is a canonical dicycle of size 2. Let  $C_n$  be a Hamiltonian dicycle in  $GK(d, n)$ . Its length is obviously  $n$ . Since  $\gcd(n, 2) = 1$ , therefore, by Corollary 17,  $C_n \otimes C_2$  is a dicycle of length  $2n$ . Therefore,  $C_n \otimes C_2$  is a Hamiltonian dicycle of  $R(GB_2(d, n, d, n))$ .

The concatenation does not work when  $n$  is an even number. However, there is a way to adapt the proof of Lemma 12 when  $d$  divides  $n$ .

**Lemma 13.** *If  $d|n$ , then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .*

*Proof.* Since  $d|n$ , therefore  $GB(d, n)$  is Hamiltonian by Theorem 31. If  $n$  is odd, we can use Lemma 12. Therefore we assume that  $n$  is even. Let  $0, \sigma(0), \sigma^2(0), \dots, \sigma^{n-1}(0)$  be a Hamiltonian dicycle in  $GB(d, n)$ .

Let  $P_1 = 0, E_{\sigma(0)}, \sigma^2(0), \dots, E_{\sigma^{n-1}(0)}$  be the dipath in  $GB_2(d, n, d, n)$  built with half of indices for the vertices, and the other half for the hyperarcs. Let  $P_2 = E_0, \sigma(0), E_{\sigma^2(0)}, \dots, \sigma^{n-1}(0)$  be its dual counterpart. Since  $d|n$  we have the following property: *two vertices that are incident to the same hyperarc are incident to the same hyperarcs.*

There cannot be two vertices that have between 1 and  $d-1$  hyperarcs in common. Remark that 0 and  $\sigma^{n-1}(0)$  are incident to the same hyperarc  $E_0$ . So  $\sigma^{n-1}(0)$  is also incident to hyperarc  $E_{\sigma(0)}$ , and  $E_{\sigma^{n-1}(0)}$  is also incident to vertex  $\sigma(0)$ . Therefore  $0, E_0, \sigma(0), E_{\sigma^2(0)}, \dots, \sigma^{n-1}(0), E_{\sigma(0)}, \sigma^2(0), \dots, E_{\sigma^{n-1}(0)}, 0$  is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .  $\square$

One can also prove that if  $d^2$  divides  $n$ , then there is a complete Berge circuit in  $GB_2(d, n, d, n)$ .

Let us write  $n = d^2m$ . The bipartite representation digraph  $D = R(GB_2(d, m, d, m))$  is  $d$ -regular. Therefore, by Theorem 22, for all  $i \geq 1$ ,  $L^i(D)$  is Hamiltonian. Particularly when  $i = 2$ . By Theorem 1,  $L^2(D)$  and  $R(L(GB_2(d, m, d, m)))$  are isomorphic. Moreover, by Theorem 35,  $L(GB_2(d, m, d, m)) = GB_2(d, n, d, n)$ . Therefore, there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ , by Proposition 24.

More generally, if  $ds|n$  then  $R(GB_2(d, n, s, n))$  is isomorphic to the line digraph of  $D = L(R(GB_2(d, \frac{n}{ds}, s, \frac{n}{ds})))$ , by Theorems 1 and 35. One can easily check that  $D$  is an Eulerian digraph. Consequently,  $R(GB_2(d, n, s, n))$  is Hamiltonian.

Furthermore, when  $d|n$ , one can observe that  $GB_2(d, n, d, n) = GB_{(d,d)}(d, n, d, n)$ , the definition of which can be found at the end of Section 5.2, and Lemma 13 becomes itself a particular case of:

**Lemma 14.** *If  $\gcd(d, n) \geq 2$  then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .*

*Proof.* We note  $\lambda = \gcd(n, d)$ . If there is a complete Berge dicycle in the subdihypergraph  $GB_{(\lambda, \lambda)}(d, n, d, n)$ , then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ . By hypothesis,  $\exists q \geq 1$  such that  $n = q\lambda$ . Then remark the following relation between the bipartite representation digraphs:

$$L(R(GB_{(\lambda, \lambda)}(d, q, d, q))) \text{ and } R(GB_{(\lambda, \lambda)}(d, n, d, n)) \text{ are isomorphic.} \quad (1)$$

Indeed, we know that  $L(GB_{\lambda}(d, q)) = GB_{\lambda}(d, n)$  by Proposition 32. Considering the incidence relations between hyperarcs and vertices (resp. between vertices and hyperarcs), previous remark follows.

Clearly,  $R(GB_{(\lambda, \lambda)}(d, q, d, q))$  is  $\lambda$ -regular. Moreover,  $GB_{\lambda}(d, q)$  is Eulerian, and so strongly connected, because its line digraph  $GB_{\lambda}(d, n)$  is Hamiltonian, by Theorem 31. Let  $x, y$  be two vertices in  $GB_{\lambda}(d, q)$ . Since the loop  $00$  is an arc in  $GB_{\lambda}(d, q)$ , therefore one can always find a dipath of even length between  $x$  and  $y$ . Indeed, there is a dipath from  $x$  to 0, there is a dipath from 0 to  $y$ , and we can insert a loop between both of those dipaths if needed. Consequently  $GB_{(\lambda, \lambda)}(d, q, d, q)$  is connected. So its bipartite representation digraph is also connected. Therefore,  $R(GB_{(\lambda, \lambda)}(d, q, d, q))$  is Eulerian. So its line digraph is Hamiltonian, by Theorem 22.  $\square$

Like in Lemmas 12 and 13, Lemma 14 can also be proven with a concatenation of dicycles. Since  $GB_\lambda(d, n)$  is Hamiltonian, by Theorem 31, we can choose  $0, \sigma(0), \sigma^2(0), \dots, \sigma^{n-1}(0)$ , a Hamiltonian dicycle of  $GB_\lambda(d, n)$ . The property: *two vertices are incident to the same hyperarcs, or have no hyperarc in common*, used for Lemma 13, is still true for  $GB_{(\lambda, \lambda)}(d, n, d, n)$ . Therefore we can adapt the proof of Lemma 13 and we show that  $0, E_0, \sigma(0), E_{\sigma^2(0)}, \dots, \sigma^{n-1}(0), E_{\sigma(0)}, \sigma^2(0), \dots, E_{\sigma^{n-1}(0)}, 0$  is a complete Berge dicycle of  $GB_{(\lambda, \lambda)}(d, n, d, n)$  when  $n$  is even.

When  $d$  is coprime to  $n$ , we use methods that are very different from the previous ones. When  $d \geq 4$ , and  $n$  is coprime to  $d$ , we can prove Theorem 45 with the Hamiltonian properties of Consecutive- $d$  digraphs:

**Lemma 15.** *If  $d \geq 4$ , and  $n$  is coprime to  $d$ , then there is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .*

*Proof.* We need  $d \geq 4$  because the Hamiltonian properties of the Consecutive-3 digraphs have yet to be completely solved. We arbitrarily choose to associate hyperarc  $E_{di}$  to vertex  $i$  for all  $i$ . Since  $\gcd(n, d) = 1$ , therefore  $d$  is invertible in  $Z_n$ , and  $i \rightarrow di$  is a bijection between vertices and hyperarcs. If, for all  $i$ , we associate vertex  $i$  to the hyperarc  $E_{di}$ , we get a digraph  $G$ , whose vertices are the residues modulo  $n$ ; there is an arc in  $G$  from  $i$  to  $j$  if, and only if, hyperarc  $E_{di}$  is incident to vertex  $j$  in  $GB_2(d, n, d, n)$ , i.e.  $j \equiv d^2i + \alpha \pmod{n}$ , for some  $\alpha$  with  $0 \leq \alpha \leq d - 1$ .

$G$  is the Consecutive- $d$  digraph  $G(d, n, d^2, 0)$ . By Theorem 30, we know that  $G$  is Hamiltonian. Let  $0, \sigma(0), \sigma^2(0), \dots, \sigma^{n-1}(0)$  be a Hamiltonian dicycle in  $G$ . Then, by construction,  $0, E_0, \sigma(0), E_{d\sigma(0)}, \dots, \sigma^{n-1}(0), E_{d\sigma^{n-1}(0)}, 0$  is a complete Berge dicycle in  $GB_2(d, n, d, n)$ .  $\square$

The only remaining cases are  $d = 2$  and  $d = 3$ . Both of them use an explicit construction for a complete Berge dicycle in  $GB_2(d, n, d, n)$ , for some particular values of  $n$ . First we deal with the case when  $d = 3$ . Here is a useful definition for the following results:

**Definition 19.** *Let  $C_1, C_2$  be two circuits, that are subdigraphs of the same digraph  $D$ . A pair of interchange is a couple of vertices  $(x, y)$ , such that  $x$  is in  $C_1$  whereas  $y$  is in  $C_2$ . Those vertices must verify the following property: the predecessor of  $x$  in  $C_1$  is incident to  $y$  in  $D$ , and the predecessor of  $y$  in  $C_2$  is incident to  $x$  in  $D$  too.*

Those pairs of interchange are a precious tool for merging disjoint circuits together, using a method that is sometimes called the *link-method interchange*. That method is at the basis of many proofs concerning the Hamiltonian Properties of Consecutive- $d$  digraphs (see [17], [14], [10], [11], and [15]). Many examples are given in the rest of the paper.

**Lemma 16.** *For every positive integer  $n$ , there is a complete Berge circuit in  $GB_2(3, n, 3, n)$ .*

*Proof.* If  $n$  is odd, that is a direct consequence of Lemma 12 and Theorem 31. Furthermore, when  $n$  is a multiple of 3, that is a consequence of Lemma 13. So we assume that  $n$  is even, and that  $n$  is coprime to 3.

Let  $R$  be the bipartite representation digraph of  $GB_2(3, n, 3, n)$ . To every vertex  $i$  we associate the hyperarc  $E_{3i+1}$ . Similarly, to every hyperarc  $E_j$  we associate the vertex  $3j+1$ . Since  $\gcd(n, 3) = 1$ , we partition the digraph  $R$  into pairwise vertex-disjoint circuits, denoted  $C_1, C_2, \dots, C_k$ . If  $k = 1$ , then  $C_1$  is a Hamiltonian circuit.

Let us assume that  $k \geq 2$ . Let  $C_x, C_y$  be two disjoint circuits such that a vertex  $i$  is in  $C_x$  whereas the vertex  $i+1$  is in  $C_y$ . We want to prove the pair  $(i, i+1)$  is a *pair of interchange*. Let  $E_j, E_{j'}$  be the predecessor of  $i$  in  $C_x$  and the predecessor of  $i+1$  in  $C_y$ , respectively. By construction:  $3j+1 = i$ , and  $3j'+1 = i+1$ . Consequently:

$$3j+2 = i+1 \text{ and } 3j' = i$$

So we can merge  $C_x$  and  $C_y$  into a new circuit  $C_{x \cup y}$ , such that  $E_j$  is the predecessor of  $i$  and  $E_j$  is the predecessor of  $i+1$  in  $C_{x \cup y}$ . However, observe that if vertices  $i, i+1, i+2$  are in three distinct circuits  $C_x, C_y, C_z$ , then we can merge  $C_x$  and  $C_y$  with the pair  $(i, i+1)$ , we can merge  $C_y$  and  $C_z$  with the pair  $(i+1, i+2)$ , but we cannot merge  $C_{x \cup y}$  and  $C_z$  with  $(i+1, i+2)$ , nor  $C_x$  and  $C_{y \cup z}$  with  $(i, i+1)$ . Consequently, we restrain ourselves to the pairs of interchange  $g(i) = (2i, 2i+1)$ , with  $0 \leq i \leq n/2 - 1$ . In so doing, all the possible exchanges are pairwise independent (that is they are disjoint). Remark that we can also define those pairs of interchange by the pairs  $g(i) = (2i \pmod n, 2i+1 \pmod n)$ , with  $i \in \mathbb{Z}_n$ . In that case  $g(i) = g(i + \frac{n}{2})$ .

In the same way, we can only use for the hyperarcs the pairs of interchange  $(E_j, E_{j+1})$  or the pairs of interchange  $(E_{j+1}, E_{j+2})$ . This time we restrain ourselves to the pairs of interchange  $f(j) = (E_{2j+1 \pmod n}, E_{2j+2 \pmod n})$ , with  $j \in \mathbb{Z}_n$ . Those pairs are pairwise independent.

Let  $UC_1, UC_2, \dots, UC_k$  be the undirected versions of the circuits  $C_1, C_2, \dots, C_k$ , and  $L$  be the union of those cycles (therefore  $L$  is an undirected graph). For all  $i, j$  we associate in  $L$  an edge  $(2i \pmod n, 2i+1 \pmod n)$  to the pair  $g(i)$ , and an edge  $(E_{2j+1 \pmod n}, E_{2j+2 \pmod n})$  to the pair  $f(j)$ . We get a graph  $G$ . Remark that if  $G$  is connected, then we can merge all the circuits  $C_x$ , with  $1 \leq x \leq k$ , into one circuit  $C$ . Indeed, when  $UC_x$  and  $UC_y$  are linked by a pair  $g(i)$  or a pair  $f(j)$  in  $G$ , that means that  $C_x$  and  $C_y$  can be merged into one circuit  $C_{x \cup y}$ . Moreover, all the possible interchange pairs are pairwise independent. Observe that if all the pairs  $g(i)$ , with  $i \in \mathbb{Z}_n$ , can be linked with some edges in  $G$ , then  $G$  is connected.

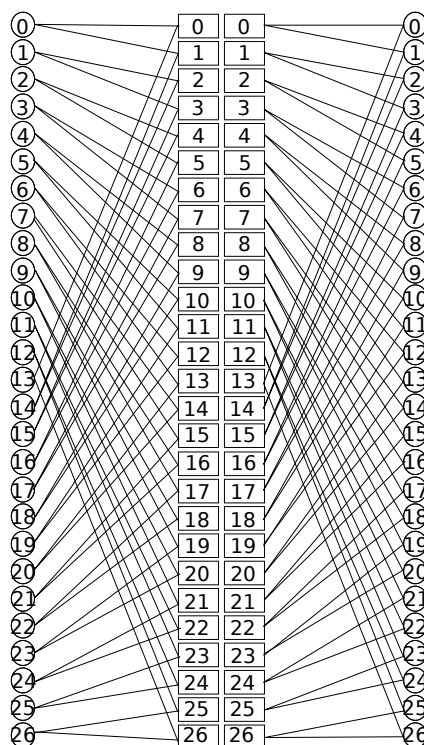
Let  $i$  be a residue modulo  $n$ . The vertex  $2i \pmod n$  is adjacent to the hyperarc  $E_{6i+1 \pmod n}$  in  $G$ , and the vertex  $2i+1 \pmod n$  is adjacent to the hyperarc  $E_{6i+4 \pmod n}$  in  $G$ . Moreover, since  $n$  is even, and  $6i+3$  is odd, therefore  $6i+3 \pmod n$  is odd. So  $(E_{6i+3 \pmod n}, E_{6i+4 \pmod n})$  is an interchange pair  $f(j)$  for some  $j$ . Actually  $6i+3 = 6i+2+1 \equiv 6i+2*3*3^{-1}+1 \equiv 6i+6*3^{-1}+1 \equiv 3*(2*(i+3^{-1}))+1 \pmod n$ . As a consequence,  $g(i)$  and  $g(i+3^{-1})$  are connected in  $G$ . Since  $3^{-1}$  is a generator element in  $\mathbb{Z}_n$ , therefore all the  $g(i)$  can be linked together.  $\square$

Finally, we deal with the case when  $d = 2$ . Like in the case when  $d = 3$  we start with an explicit construction:

**Lemma 17.** *If  $n$  is a power of 3, then there is a complete Berge circuit  $C$  in  $GB_2(2, n, 2, n)$ . For all  $i$ , the next vertex after  $i$  in  $C$  is  $4i+1 \pmod n$ .*

*Proof.* It can be seen as a particular case of Lemma 12. Indeed, we know by [15] that  $i \rightarrow -2i-1$  is a Hamiltonian circuit in  $GK(2, n)$ . Using Definition 14, it gives us a complete Berge dicycle in  $GB_2(2, n, 2, n)$ . Remark that if  $C$  is a complete Berge dicycle in  $GB_2(d, n, d, n)$  the order in which we visit the vertices in  $C$  does not depend on the chosen definition for the de Bruijn dihypergraphs. Since  $-2(-2i-1)-1 = 4i+2-1 = 4i+1$ , therefore  $i \rightarrow 4i+1$  is a complete Berge dicycle in  $GB_2(2, n, 2, n)$ .  $\square$



Figure 9: The de Bruijn dihypergraph  $GB_2(2, 27, 2, 27)$ .

This circuit can be found with the following algorithm:

1. Start from vertex 0,
2. From vertex  $i$ , go to the hyperarc  $E_{2i}$ ,
3. From hyperarc  $E_j$ , go to vertex  $2j + 1$ ,
4. Stop when  $2j + 1 = 0$ .

We still have to prove there is no complete Berge dicycle in the remaining cases:

**Lemma 18.** *If  $n$  is an odd number, then there is a complete Berge dicycle in  $GB_2(2, n, 2, n)$  if, and only if,  $n$  is a power of 3.*

*Proof.* Let us suppose there is a complete Berge dicycle  $C$  in  $GB_2(2, n, 2, n)$ . Let  $i$  be a vertex such that from  $i$ , we had chosen hyperarc  $E_{2i \pmod n}$ . Since  $\gcd(2, n) = 1$ , therefore 2 is inversible in  $\mathbb{Z}_n$ . Then, for  $j = i - 2^{-1} \pmod n$ , since  $2j + 1 = 2i \pmod n$  we must also choose hyperarc  $E_{2j \pmod n}$ , and so on. Consequently, since  $2^{-1}$  is a generator of  $\mathbb{Z}_n$ , we must do the same choice for every vertex. Reciprocally, we must do the same choice for every hyperarc.

Let us call  $\sigma$  the application of  $\mathbb{Z}_n$  that associates any vertex  $i$  to its successor  $\sigma(i)$ , in a given complete Berge dicycle. There are only four possibilities for  $\sigma$  :

1.  $e : i \rightarrow 4i \pmod n$

2.  $f : i \rightarrow 4i + 1 \pmod n$
3.  $g : i \rightarrow 4i + 2 \pmod n$
4.  $h : i \rightarrow 4i + 3 \pmod n$

Since  $4 * 0 = 0$ , solution 1 does not generate a complete Berge dicycle. Besides, if  $\gcd(n, 3) = 1$  then none of the other solutions work. Indeed, the equation  $\sigma(i) = i \iff 4i + k = i \pmod n \iff 3i = -k \pmod n$ , for some  $k$  with  $1 \leq k \leq 3$ , will always have a solution.

Let us write  $n = c3^p$ ,  $p \geq 1$  and  $\gcd(3, c) = 1$ .  
By induction, we prove that :

1.  $f^i(0) = \frac{4^i - 1}{3} \pmod n$
2.  $g^i(0) = 2f^i(0) = \frac{2(4^i - 1)}{3} \pmod n$
3.  $h^i(0) = 3f^i(0) = 4^i - 1 \pmod n$ .

Let  $\varphi$  be the Euler function. We know that  $\varphi(n) = \varphi(c)\varphi(3^p) = 2\varphi(c)3^{p-1}$ . Since  $\gcd(n, 2) = 1$ , then, by the Euler's Theorem (Theorem 44),  $2^{\varphi(n)} = 1 \pmod n$ . Therefore,  $4^{\varphi(c)3^{p-1}} = 1 \pmod n$  and, since  $\varphi(c)3^{p-1} < n$ ,  $h$  never generates a complete Berge dicycle either.

Moreover, since 2 is inversible in  $\mathbb{Z}_n$ , then we also know that  $f$  generates a complete Berge dicycle if, and only if, this is also the case for solution  $g$ . Actually, when we choose  $f$ , we choose  $g$  in the dual, and reciprocally. Let us concentrate now on  $f$ .

$$f^i(0) = f^j(0) \text{ is equivalent to } \frac{4^i - 1}{3} = \frac{4^j - 1}{3} \pmod n, \text{ which implies that } 4^i = 4^j \pmod{3n}.$$

Again because of the Euler's Theorem, we know that  $4^{\varphi(c)3^p} = 1 \pmod{3n}$ . And the only solution for having  $\varphi(c) = c$  is  $c = 1$ ; otherwise  $\varphi(c) < c$ . Therefore, if  $n$  is not a power of 3,  $f$  and  $g$  do not generate a complete Berge dicycle.

By Lemma 17,  $i \rightarrow 4i + 1$  gives a complete Berge dicycle when  $n$  is a power of 3. Therefore there is a complete Berge dicycle in  $GB_2(2, n, 2, n)$  if and only if  $n$  is a power of 3. □

**Remark 11.** *This proof could be shortened using the characterization of the Hamiltonian Consecutive-1 digraphs. Indeed, we show there are only four possibilities for having a complete Berge circuit in  $GB_2(2, n, 2, n)$ . They correspond, respectively, to the relations of incidence in  $G(1, n, 4, 0)$ ,  $G(1, n, 4, 1)$ ,  $G(1, n, 4, 2)$  and  $G(1, n, 4, 3)$ . Then, by Theorem 30, we know whether one of those digraphs is Hamiltonian, depending on the value of  $n$ . The Hamiltonicity of, at least, one of these digraphs, is a necessary and sufficient condition for  $GB_2(2, n, 2, n)$  to have a complete Berge circuit.*

$n \setminus d$	1	2	3	$\geq 4$
even	Lemma 11	Lemma 13 or 14	Lemmas 13, 16	Lemmas 14, 15
odd	Lemma 11	Lemmas 17, 18	Lemma 12	Lemmas 14, 15

### 5.4.3 Generalization

The methods applied in the previous section can be extended to a larger family of digraphs, as it is detailed in the Appendix. Some similar results can be found for the Consecutive- $(d, s)$  dihypergraphs  $G([d, n, q, r], [s, n, p, t])$  too:

**Lemma 19.** *Let  $H = G([1, n, q, r], [s, n, p, t])$  be a Consecutive- $(1, s)$  dihypergraph. There is a complete Berge circuit in  $H$  if and only if  $q$  is coprime to  $n$  and  $G(s, n, pq, pr + t)$  is Hamiltonian.*

*Proof.* Each vertex in  $H$  is incident to only one hyperarc. Therefore a necessary condition for having a complete Berge circuit in  $H$  is that for all  $i \neq i'$ ,  $qi + r \not\equiv qi' + r \pmod{n}$ . That is equivalent to  $\gcd(n, q) = 1$ .

Conversely, if  $n$  is coprime to  $q$ , then we define a digraph  $G$  such that  $\mathcal{V}(G) = \mathbb{Z}_n$ , and there is an arc from vertex  $i$  to vertex  $i'$  if and only if  $E_{qi+r}$  is incident to  $i'$ . Observe that there is a complete Berge circuit in  $H$  if and only if  $G$  is Hamiltonian. Moreover,  $G$  is isomorphic to  $G(s, n, pq, pr + t)$ .  $\square$

Furthermore, we can partially solve the case when  $\gcd(n, q) \geq 2$ . In that case, we always know whether there is a complete Berge circuit in  $G([d, n, q, r], [d, n, q, r])$ . We show this characterization with the following two lemmas, the first of which deals with a more general case.

**Lemma 20.** *Let  $H = G([d, n, q, r], [s, n, p, t])$  be a consecutive- $(d, s)$  dihypergraph. We denote  $\lambda = \gcd(n, q)$ . If  $\lambda \geq \max(2, d + 1)$ , then there is no complete Berge circuit in  $H$ .*

*Proof.* Let  $n' = \frac{n}{\lambda}$ . Observe that for all  $k$ , with  $0 \leq k \leq \lambda - 1$ , vertices  $i$  and  $i + kn'$  are incident to the same hyperarcs. Since  $n'd < n$ , therefore there are empty in-sets.  $\square$

When there are empty in-sets, there is no Eulerian circuit, hence there is no complete Berge circuit either. Observe that it is the same result when  $\mu = \gcd(n, p) \geq \max(2, s + 1)$ .

If  $d$  is greater than  $\lambda$ , then we can adapt the proof of Lemma 14.

**Lemma 21.** *Let  $H = G([d, n, q, r], [d, n, q, r])$  be a consecutive- $(d, d)$  dihypergraph. We denote  $\lambda = \gcd(n, q)$ . If  $2 \leq \lambda \leq d$ , then there is a complete Berge circuit in  $H$ .*

*Proof.* Let  $n' = \frac{n}{\lambda}$ . Since  $L(G(\lambda, n', q, r)) = G(\lambda, n, q, r)$  ([14]), therefore  $L(R(G([\lambda, n', q, r], [\lambda, n', q, r])))$  is isomorphic to  $R(G([\lambda, n, q, r], [\lambda, n, q, r]))$ . Observe that  $G(\lambda, n', q, r)$  is Eulerian and so connected [14].

First, let us assume that  $n'$  is coprime to  $q$ . Let  $R_u$  be the undirected version of  $R(G([\lambda, n', q, r], [\lambda, n', q, r]))$ . Since  $qi + r = q(i - q^{-1}) + r + 1$ , therefore there is a path of length 2 between vertices  $i$  and  $i - q^{-1}$  in  $R_u$ . Consequently, all the vertices are linked together in  $R_u$ , because  $q^{-1}$  is a generator element of  $\mathbb{Z}_n$ . So  $R(G([\lambda, n', q, r], [\lambda, n', q, r]))$  is weakly connected.

Else, let  $\lambda' = \gcd(n', q)$ . Clearly,  $\lambda'$  is lower than  $\lambda$ . Therefore, the dihypergraph  $G([\lambda, n', q, r], [\lambda, n', q, r])$  satisfies the conditions of Lemma 21, and we show by induction that its bipartite representation digraph is always a weakly connected digraph.

$R(G([\lambda, n', q, r], [\lambda, n', q, r]))$  is a connected regular digraph, i.e. it is an Eulerian digraph. Therefore, its line digraph  $R(G([\lambda, n, q, r], [\lambda, n, q, r]))$ , hence  $R(G([d, n, q, r], [d, n, q, r]))$ , is Hamiltonian.  $\square$

**Remark 12.** *The last two lemmas show that if  $2 \leq \lambda \leq d$ , then there is a complete Berge circuit in  $G([d, n, q, r], [d, n, q, r])$  if and only if  $G(d, n, q, r)$  is Hamiltonian.*

Other extensions of the results about  $GB_2(d, n, d, n)$  are proposed. For example, when  $n$  is odd, we easily generalize Lemma 12:

**Lemma 22.** *Let  $H = G([d, n, q, r], [d, n, q, r])$  be a Consecutive- $(d, d)$  dihypergraph. If  $n$  is odd and the Consecutive- $d$  digraph  $G(d, n, q, r)$  is Hamiltonian, then there is a complete Berge circuit in  $H$ .*

*Proof.* Let  $C_n$  be a Hamiltonian circuit in  $G(d, n, q, r)$ , and  $C_2$  be a canonical circuit of length 2. By Corollary 17,  $C_n \otimes C_2$  is a circuit of length  $2n$ . Moreover, observe that  $R(H)$  is isomorphic to  $G(d, n, q, r) \otimes C_2$ . Therefore  $C_n \otimes C_2$  is a Hamiltonian circuit in  $R(H)$ .  $\square$

If  $n$  is coprime to  $q$ , and so if  $n$  is coprime to  $p$  by the dual dihypergraph operation, we can generalize Lemma 15:

**Lemma 23.** *Let  $H = G([d, n, q, r], [s, n, p, t])$  be a consecutive- $(d, s)$  dihypergraph. If  $q$  is coprime to  $n$ , and  $G(s, n, pq, r)$  is Hamiltonian then there is a complete Berge circuit in  $H$ .*

*Proof.* To every vertex  $i$  we associate the hyperarc  $E_{qi}$ . That is a bijection between vertices and hyperarcs because  $\gcd(n, q) = 1$ . In so doing, we get a digraph  $G$ , whose set of vertices is labeled by  $\mathbb{Z}_n$ , such that there is an arc from vertex  $i$  to vertex  $j$  if and only if  $E_{qi}$  is incident to  $j$ . Actually,  $G$  is isomorphic to the Consecutive- $s$  digraph  $G(s, n, pq, r)$ . Moreover,  $G(s, n, pq, r)$  is Hamiltonian. Let  $0, \sigma(0), \dots, \sigma^{n-1}(0), 0$  be a Hamiltonian circuit in  $G(s, n, pq, r)$ . Then  $0, E_0, \sigma(0), E_{q\sigma(0)}, \dots, \sigma^i(0), E_{q\sigma^i(0)}, \dots, \sigma^{n-1}(0), E_{q\sigma^{n-1}(0)}, 0$  is a complete Berge circuit in  $H$ .  $\square$

We can also extend Lemma 16 to the Consecutive dihypergraphs when  $n$  is even:

**Lemma 24.** *Let  $H = G([d, n, q, r], [s, n, p, t])$  be a Consecutive- $(d, s)$  dihypergraph. If  $n$  is even,  $n$  is coprime to  $p$ ,  $\gcd(n, \frac{q-1}{2}) = 1$ ,  $r$  is even and  $d, s \geq 3$ , then there is a complete Berge circuit in  $R(H)$ .*

*Proof.* To every vertex  $i$ , we associate the hyperarc  $E_{qi+r+1}$ . Similarly, to every hyperarc  $E_j$ , we associate the vertex  $pj + t + 1$ . Since  $\gcd(n, p) = \gcd(n, q) = 1$ , therefore we get pairwise vertex-disjoint circuits in  $R(H)$ , denoted  $C_1, C_2, \dots, C_k$ . If  $k = 1$ , then  $C_1$  is a Hamiltonian circuit in  $R(H)$ .

Let us assume that  $k \geq 2$ . We use the pairs of interchange  $g(i) = (2i \pmod{n}, 2i + 1 \pmod{n})$ , and  $f(j) = (E_{2j+1 \pmod{n}}, E_{2j+2 \pmod{n}})$ , with  $i, j \in \mathbb{Z}_n$ . Those pairs are disjoint.

Let  $UC_1, UC_2, \dots, UC_k$  be the undirected versions of the circuits  $C_1, C_2, \dots, C_k$ , and  $L$  be the union of those cycles. For all  $i, j$  we associate in  $L$  an edge  $(2i \pmod{n}, 2i + 1 \pmod{n})$  to the pair  $g(i)$ , and an edge  $(E_{2j+1 \pmod{n}}, E_{2j+2 \pmod{n}})$  to the pair  $f(j)$ . We get a graph  $G$ . Remark that if  $G$  is connected, then we can merge all the circuits  $C_x$ , with  $1 \leq x \leq k$ , into one circuit  $C$ . Moreover, if all the pairs  $g(i)$ , with  $i \in \mathbb{Z}_n$ , can be linked with some edges in  $G$ , then  $G$  is connected.

Let  $i$  be a residue modulo  $n$ . Vertex  $2i$  is adjacent to hyperarc  $E_{2qi+r+1}$ , and vertex  $2i + 1$  is adjacent to hyperarc  $E_{2qi+r+q+1}$ . Since  $q$  is coprime to  $n$ , and  $n$  is even, therefore  $q$  is odd. So  $(E_{2qi+r+q}, E_{2qi+r+q+1})$  is a pair of interchange. Furthermore  $2qi + q = 2qi + (q - 1) + 1 = 2qi + 2q' + 1 = 2q(i + q^{-1}q') + 1$ , where  $q' = (q - 1)/2$ . Since  $\gcd(n, q') = 1$  therefore  $q^{-1}q'$  is a generator element in  $\mathbb{Z}_n$ , and so all the pairs  $g(i)$  are linked together.  $\square$

Furthermore, when  $n$  is coprime to  $q$  and  $d = 2$  (resp. when  $n$  is coprime to  $p$  and  $s = 2$ ), we always know whether there is a complete Berge circuit in  $G([2, n, q, r], [s, n, p, t])$  (resp. in  $G([d, n, q, r], [2, n, p, t])$ ).

**Lemma 25.** *Let  $H = G([2, n, q, r], [s, n, p, t])$  be a Consecutive dihypergraph. If  $n$  is coprime to  $q$ , then there is a complete Berge circuit in  $H$  if and only if either  $G(s, n, pq, pr + t)$  or  $G(s, n, pq, pr + t + p)$  is a Hamiltonian Consecutive- $s$  digraph.*

*Proof.* Let  $i$  be a vertex such that we associate to  $i$  the hyperarc  $E_{qi+r}$ . Then we must associate the hyperarc  $E_{qj+r}$  to the vertex  $j = i - q^{-1}$ , because  $qj + r + 1 = qi + r$ . Consequently, since  $q^{-1}$  is a generator element of  $\mathbb{Z}_n$ , therefore we must do the same choice of residue modulo 2 for all the vertices in  $H$ . If we associate to a vertex  $i$  the hyperarc  $E_{qi+r}$  we get the Consecutive- $s$  digraph  $G(s, n, pq, pr + t)$ . If we associate to a vertex  $i$  the hyperarc  $E_{qi+r+1}$  we get the Consecutive- $s$  digraph  $G(s, n, pq, pr + t + p)$ .  $\square$

Thank to these new lemmas, we nearly always know whether there is a complete Berge circuit in  $G([d, n, q, r], [d, n, q, r])$ . The only remaining case is when  $d = 3$ .

$n \setminus d$	1	2	3	$\geq 4$
even	Lemma 19	Lemmas 20, 21	Lemma 24 (partially)	Lemmas 20, 21, 23
odd	Lemma 19	Lemma 25	Lemma 22 (partially)	Lemmas 20, 21, 23

Table 3: Necessary and sufficient conditions for  $G([d, n, q, r], [d, n, q, r])$  to have a complete Berge circuit

#### 5.4.4 The particular case of the Kautz Dihypergraphs

The Kautz dihypergraph  $GK(d, n, d, n)$  is close to the dihypergraph  $GB_2(d, n, d, n)$ , but the existence of complete Berge circuits in it is much harder to prove because of its asymmetry. Indeed, the relations of incidence from its vertices to the hyperarcs are not the same as the relations of incidence from its hyperarcs to the vertices.

Nonetheless, we are able to show the existence of complete Berge dicycles in  $GK(d, n, d, n)$  for some particular values of  $(d, n)$ . Remark that  $R(GK(d, n, d, n))$  is isomorphic to the bipartite digraph  $BD(d, n)$  (see [22]).

**Theorem 46.** *Let  $H = GK(d, n, d, n)$  be a Kautz dihypergraph. There is a complete Berge dicycle in  $H$  if one of the following conditions is verified:*

1.  $d \geq 4$
2.  $d = 3$  and  $n$  is even
3.  $d = 2$ , and  $n$  is even or  $n$  is a power of 5
4.  $d = 1$  and  $n \in \{1, 2\}$

Conditions 2 and 4 are corollaries of Lemmas 24 and 19, respectively. When  $d$  is coprime to  $n$ , Condition 1 is a direct consequence of Lemma 23. We show the other cases with the following Lemmas:

**Lemma 26.** *Let  $H = GK(2, n, 2, n)$  be a Kautz dihypergraph. If  $n$  is odd, then there is a complete Berge circuit in  $H$  if and only if  $n$  is a power of 5.*

*Proof.*  $H$  is isomorphic to  $G([2, n, 2, 0], [2, n, n-2, n-2])$ . By Lemma 25, there is a complete Berge circuit in  $H$  iff either  $G(2, n, n-4, n-2)$  or  $G(2, n, n-4, n-4)$  is Hamiltonian. By Theorem 30, one of those digraphs is Hamiltonian iff either  $G(1, n, n-4, n-1)$ ,  $G(1, n, n-4, n-2)$ ,  $G(1, n, n-4, n-3)$  or  $G(1, n, n-4, n-4)$  is Hamiltonian. Again by Theorem 30, a necessary and sufficient condition for one of those digraphs to be Hamiltonian is that  $n$  is a power of 5.  $\square$

Remark that neither  $GK(2, n)$ , nor  $GB(2, n)$  is Hamiltonian when  $n$  is a power of 5.

It remains the case when  $\gcd(d, n) \geq 2$ .

**Lemma 27.** *If  $\lambda = \gcd(d, n) \geq 2$ , then there is a complete Berge circuit in  $GK(d, n, d, n)$ .*

*Proof.* Let us denote  $q = \frac{n}{\lambda}$ . First observe that  $L(R(GK_{(\lambda, \lambda)}(d, q, d, q)))$  and  $R(GK_{(\lambda, \lambda)}(d, n, d, n))$  are isomorphic. Indeed,  $L(R(GK_{(\lambda, \lambda)}(d, q, d, q)))$  is a bipartite digraph  $(\mathcal{V}_1, \mathcal{V}_2, \mathcal{E})$ . Vertices in  $\mathcal{V}_1$  are labeled by the arcs in  $GB_\lambda(d, q)$ , and vertices in  $\mathcal{V}_2$  are labeled by the arcs in  $GK_\lambda(d, q)$ . To an arc  $xy$  in  $GB_\lambda(d, q)$ , we associate the label  $f(x, y)$ , where  $f(x, y) = dx + \alpha \pmod{n}$  if  $y = dx + \alpha \pmod{q}$ . Similarly, to an arc  $zt$  in  $GK_\lambda(d, q)$ , we associate the label  $f(q-1-z, t)$ . This label exists, because  $d(q-1-z) + \beta = t \pmod{q}$  for some  $\beta$  with  $0 \leq \beta \leq d-1$ , and so  $(q-1-z)t$  is an arc in  $GB_\lambda(d, q)$ . Observe that those mappings are one to one. Furthermore:

$$\{d(n-1-f(x, y)) + \alpha : 0 \leq \alpha \leq \lambda-1\} = \{d(n-1-y) + \alpha : 0 \leq \alpha \leq \lambda-1\} = \{f(q-1-y, z) : yz \in \mathcal{E}(GK_\lambda(d, q))\}$$

$$\{d(f(q-1-z, t)) + \beta : 0 \leq \beta \leq \lambda-1\} = \{dt + \beta : 0 \leq \beta \leq \lambda-1\} = \{f(t, x) : tx \in \mathcal{E}(GB_\lambda(d, q))\}$$

The relations of incidence between  $\mathcal{V}_1$  and  $\mathcal{V}_2$  are the relations of incidence in  $GK_\lambda(d, n)$ . In the same way, the relations of incidence between  $\mathcal{V}_2$  and  $\mathcal{V}_1$  are the relations of incidence in the digraph  $GB_\lambda(d, n)$ . By Definition 16, this bipartite digraph is isomorphic to  $R(GK_{(\lambda, \lambda)}(d, n, d, n))$ .

Let us show that  $R(GK_{(\lambda, \lambda)}(d, q, d, q))$  is connected. Actually, the proof is similar to the one presented in Lemma 21. First, let us assume that  $\gcd(q, d) = 1$ . Let  $R_u$  be the undirected version of  $R(GK_{(\lambda, \lambda)}(d, q, d, q))$ . For all  $i, i, di, i - d^{-1}$  is a path of  $R_u$  between vertices  $i$  and  $i - d^{-1}$ . Since  $d^{-1}$  is a generator element in  $\mathbb{Z}_n$ , therefore all the vertices are linked together. Else, let us denote  $\lambda' = \gcd(q, d)$ . Obviously,  $\lambda' \leq \lambda$ . By induction, if there is a complete Berge circuit in  $GK_{(\lambda', \lambda')}(d, q, d, q)$ , therefore its bipartite representation digraph is connected. Hence  $R(GK_{(\lambda, \lambda)}(d, q, d, q))$  is connected too.

Moreover,  $R(GK_{(\lambda, \lambda)}(d, q, d, q))$  is regular. Therefore it is an Eulerian digraph. So its line digraph  $R(GK_{(\lambda, \lambda)}(d, n, d, n))$ , hence  $R(GK(d, n, d, n))$ , is Hamiltonian.  $\square$

We conjecture the following characterization of the complete Berge circuits in  $GK(d, n, d, n)$ :

**Conjecture 47.** *Let  $H = GK(d, n, d, n)$  be a Kautz dihypergraph. If  $d \geq 3$  then there is a complete Berge circuit in  $H$ .*

## 6 Conclusion

We define an Eulerian circuit in a dihypergraph as a circuit  $C$  such that every hyperarc appears exactly once in  $C$ , and a Hamiltonian circuit as a dicycle  $C'$  such that every vertex appears exactly once in  $C'$ . We show that the Eulerian dihypergraphs are the dual dihypergraphs of the Hamiltonian dihypergraphs. Consequently, both of the problems are NP-complete. Nonetheless, we are able to provide some necessary conditions for a dihypergraph to be Eulerian, hence necessary conditions for its dual to be Hamiltonian. We prove those conditions are sufficient for some particular subclasses of dihypergraphs, that are detailed in this paper. Furthermore, we also show that the study of Eulerian dihypergraphs could be restrained to the study of Eulerian BF-graphs, without any loss of generality.

Partial extensions of some known results about the Eulerian digraphs are found for the regular, uniform dihypergraphs. Particularly, the iterated line dihypergraphs of a uniform, regular dihypergraph are always Eulerian and Hamiltonian. We also propose two stronger definitions of an Eulerian dihypergraph, namely the strongly Eulerian and universally Eulerian dihypergraphs. We show that those stronger notions imply the simple Eulerianity. Moreover, stronger results about the Eulerian digraphs can be extended to strongly Eulerian and universally Eulerian dihypergraphs. Especially, the line dihypergraph of a strongly (resp. universally) Eulerian dihypergraph is Hamiltonian.

Finally, we generalize the Kautz and the de Bruijn dihypergraphs by the Consecutive- $(d, s)$  dihypergraphs. We present some basic properties of this new family of dihypergraphs. We also completely solve the characterization of the Eulerian and Hamiltonian de Bruijn and Kautz dihypergraphs. In a lot of cases, we give some necessary and sufficient conditions for a Consecutive- $(d, s)$  dihypergraph to be Eulerian or Hamiltonian.

The existence of complete Berge circuits in  $G([d, n, q, r], [s, n, p, t])$ , is investigated too. Since they correspond to Hamiltonian circuits in the bipartite representation digraphs  $R(G([d, n, q, r], [s, n, p, t]))$ , we were able to use in this part the Hamiltonian properties of the Kronecker product, of the Consecutive digraphs, and the link-method interchange that is at the basis of many proofs of Hamiltonicity for the Consecutive digraphs. Although we were able to build a complete Berge dicycle in  $GB_2(d, n, d, n)$  from a Hamiltonian dicycle in  $GK(d, n)$  in many cases, we were unable to do the inverse operation.

Since BF-graphs are amongst the simplest dihypergraphs, we think the study of their Eulerian properties could be useful, in order to find new Eulerian dihypergraphs. Moreover, although the definition of a strongly

Eulerian dihypergraph is a bit artificial, we think that strongly and universally Eulerian dihypergraphs should be further studied.

Observe that our definition of a circuit, presented in Section 2.2, is called "simple circuit" in the literature. Other definitions of circuits can be found in [21] and [27], namely: B-,F-,BF- and L-circuits. One may consider using them for defining new kinds of Eulerian circuits, hence new definitions of an Eulerian dihypergraph.

We mention in the paper the properties of the Consecutive dihypergraphs may be improved using some modified Consecutive- $d$  digraphs, as the ones presented in [20]. Let  $D(d, n, q, r), D(s, m, p, t)$  be two such modified Consecutive digraphs. Then we could define the modified Consecutive- $(d, s)$  dihypergraph  $D([d, n, q, r], [s, m, p, t])$ , such that the relations of incidence between the  $n$  vertices and the  $m$  hyperarcs (resp. between the  $m$  hyperarcs and the  $n$  vertices) are the relations of incidence of  $D(d, n, q, r)$  (resp. of  $D(s, m, p, t)$ ). They may have more interesting properties than the original Consecutive dihypergraphs.

Finally, we remark that it is easier to study the existence of complete Berge circuits in  $G([d, n, q, r], [s, n, p, t])$  when  $d = s, q = p$ , and  $r = t$ . Actually, that is because  $R(G([d, n, q, r], [d, n, q, r]))$  can be *factorized* using the Kronecker product; indeed:  $R(G([d, n, q, r], [d, n, q, r])) = G(d, n, q, r) \otimes C_2$ . More generally,  $R(G([d, n, q, r], [s, n, p, t]))$  can always be factorized, using a digraph product presented in [3]. Using this product, denoted  $\otimes_{\phi_n}$ ,  $R(G([d, n, q, r], [s, n, p, t]))$  is isomorphic to  $G(d, n, q, r) \otimes_{\phi_n} G(s, n, p, t)$ . A study of the Hamiltonian properties of this product may help finding new results about the complete Berge circuits in the Consecutive- $(d, s)$  dihypergraphs. A complete characterization of the Hamiltonian Consecutive digraphs may help too. Both of these ideas should be explored further.

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## 7 Appendix

### 7.1 On Strongly Eulerian Dihypergraphs

We are unable to give a full characterization of the strongly Eulerian dihypergraphs. However, we present some basic results about them.

**Proposition 48.** *Let  $D_1, D_2, \dots, D_c$  be Eulerian digraphs, such that there is no isolated vertex,  $\mathcal{V}(D_1) = \mathcal{V}(D_2) = \dots = \mathcal{V}(D_c) = \mathcal{V}$ , and  $\mathcal{E}(D_1), \mathcal{E}(D_2), \dots, \mathcal{E}(D_c)$  are pairwise disjoint sets. Let us assume that all these digraphs are  $d$ -regular. Then one can build a strongly Eulerian dihypergraph, whose underlying multidigraph is  $\bigcup_{i=1}^c D_i$ .*

*Proof.* Let  $H$  be a dihypergraph, such that  $\mathcal{V}(H) = \mathcal{V}$ . We define  $\mathcal{E}(H)$  as follows: let  $v$  be a vertex. For all  $i$ , with  $1 \leq i \leq c$ , we order the in-links of  $v$  in  $D_i$ , denoted  $u_1^i v, u_2^i v, \dots, u_d^i v$ . Then we define  $d$  B-arcs  $V_1, V_2, \dots, V_d$ , such that for all  $j$  with  $1 \leq j \leq d$ ,

$$V_j^- = \bigcup_{i=1}^c \{u_j^i\}$$

$$V_j^+ = \{v\}$$

By construction,  $m(H) = d \cdot n(H)$ , and  $H$  is a  $(c, 1)$ -uniform dihypergraph. Let  $\varphi_i$  be a function such that for all hyperarc  $V_j$ , we have  $\varphi_i(V_j) = (u_{i,j}, v)$ . Clearly,  $\varphi_1, \varphi_2, \dots, \varphi_c$  is a digraph-partition of  $H$ . Furthermore, for all  $i$  we have  $D_{\varphi_i}[H] = D_i$ . Therefore  $H$  is strongly Eulerian.  $\square$

Observe that  $H$  may be a F-graph too, using the same kind of construction. We may also define a strongly Eulerian dihypergraph, using only one  $d$ -regular digraph.

**Proposition 49.** *Let  $D$  be a simple, connected,  $d$ -regular digraph. For all vertex  $v$  we define a bijection between the out-neighbours of  $v$  and  $\{0, 1, \dots, d-1\}$ . Let  $\sigma_1, \sigma_2, \dots, \sigma_c$  be permutations of  $\{0, 1, \dots, d-1\}$ , such that for all  $i$  for every  $j \neq j'$ ,  $\sigma_j(i) \neq \sigma_{j'}(i)$ . Then one can define a strongly Eulerian dihypergraph from  $D$  and these permutations, denoted  $H = H_D[\sigma_1, \dots, \sigma_c]$ .*

*Proof.* Let  $H$  be a dihypergraph such that  $\mathcal{V}(H) = \mathcal{V}(D)$ . We define  $\mathcal{E}(H)$  as follows: let  $v$  be a non-isolated vertex. We define  $d$  hyperarcs  $V_1, V_2, \dots, V_d$  that are associated to  $v$ , such that:

$$V_j^- = \{v\}$$

$$V_j^+ = \bigcup_{i=1}^c \{\sigma_i(u_j)\}$$

where  $u_j$  is the  $j$ th out-neighbour of  $v$  in  $D$ . By construction,  $H$  is a  $(1, c)$ -uniform dihypergraph. Let  $\varphi_i$  be a function such that for all hyperarc  $V_j$  we have  $\varphi_i(V_j) = (v, \sigma_i(u_j))$ . Clearly,  $\varphi_1, \varphi_2, \dots, \varphi_c$  is a digraph-partition of  $H$ . Furthermore, for every  $i$ ,  $D_{\varphi_i}[H]$  is isomorphic to  $D$ . Therefore  $H$  is strongly Eulerian.  $\square$

Propositions 48 and 49 can be combined for creating more complicated strongly Eulerian dihypergraphs.

Finally, we present a non-trivial example of strongly Eulerian dihypergraphs, using the Consecutive- $(d, s)$  dihypergraphs.

**Proposition 50.** *The dihypergraph  $H = G([d, n, q, r], [s, n, p, t])$  is strongly Eulerian if it satisfies the following conditions:*

1.  $pq - 1 \neq 2$  is prime,
2.  $n$  is a power of  $pq - 1$
3.  $0 < p(d - 1 + r) + (t + s - 1) < pq - 1$

*Proof.* First observe that  $\gcd(n, p) = \gcd(n, q) = 1$ . Therefore  $H$  can be partitioned into the digraphs  $G(1, n, pq, p(\alpha + r) + \beta + t)$ , with  $0 \leq \alpha \leq d - 1$  and  $0 \leq \beta \leq s - 1$ . By Theorem 30, a necessary and sufficient condition for  $G(1, n, pq, p(\alpha + r) + \beta + t)$  to be Hamiltonian (hence a circuit) is that:

1.  $n$  is coprime to  $pq$ ,
2. every prime number  $k$ , such that  $k$  divides  $n$ , divides  $pq - 1$ ,
3.  $\gcd(n, pq - 1, p(\alpha + r) + \beta + t) = 1$ .

Conditions 1 and 2 are automatically verified. Moreover,  $p(\alpha + r) + \beta + t \leq p(d - 1 + r) + s - 1 + t < pq - 1$ . Since  $pq - 1$  is prime, therefore  $pq - 1$  is coprime to  $p(\alpha + r) + \beta + t$ , and so Condition 3 is also verified. Consequently, all the  $G(1, n, pq, p(\alpha + r) + \beta + t)$  are circuits, that is they are Eulerian.  $\square$

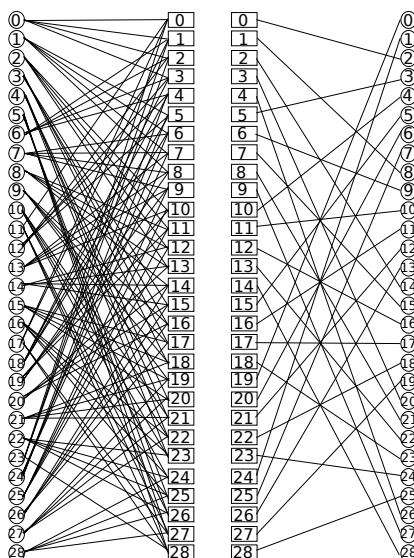


Figure 10: The Consecutive- $(d, s)$  dihypergraph  $G([4, 29, 5, 0], [1, 29, 6, 2])$  is strongly Eulerian.

## 7.2 The Hamiltonian Property of Large Generalized Cycles

The digraph  $BGC(p, d, n)$  is presented in [22] as the Kronecker product of the de Bruijn digraph  $GB(d, n)$  with a canonical circuit of length  $p$ , that is  $BGC(p, d, n) = C_p \otimes GB(d, n)$ . Using some methods presented in Section 5.4.2, we give necessary and sufficient conditions for  $BGC(p, d, n)$  to be Hamiltonian in nearly all the cases.

If  $p = 1$ , then  $BGC(1, d, n)$  is isomorphic to the generalized de Bruijn digraph  $GB(d, n)$ . Moreover, if  $p = 2$ , then  $BGC(2, d, n)$  is isomorphic to the bipartite representation digraph  $R(GB_2(d, n, d, n))$ . We recall the Hamiltonian properties of the generalized de Bruijn digraph in Theorem 31 and we deal with the existence of complete Berge circuit in  $GB_2(d, n, d, n)$  in Section 5.4. Consequently, we consider that  $p$  is greater than 2.

**Theorem 51.** For  $p \geq 3$  the digraph  $BGC(p, d, n)$  is Hamiltonian if and only if one of the following conditions is verified:

1.  $d \geq 3$ ,
2.  $d = 2$  and  $n$  is even,
3.  $d = 2$ , and for every prime number  $q$  such that  $q$  divides  $n$ ,  $q$  divides  $2^p - 1$ ,
4.  $d = n = 1$ .

If  $d = 1$ , then we trivially verify that  $BGC(p, 1, n)$  is Hamiltonian if and only if  $GB(1, n)$  is Hamiltonian. So the only solution is the degenerate case when  $n = 1$ .

Let us assume that  $\gcd(n, d) \geq 2$ :

**Lemma 28.** If  $\lambda = \gcd(n, d) \geq 2$ , then  $BGC(p, d, n)$  is Hamiltonian.

*Proof.* Let  $n' = \frac{n}{\lambda}$ . We denote by  $BGC_\lambda(p, d, n)$  the digraph  $C_p \otimes GB_\lambda(d, n)$ . Observe that  $L(GB_\lambda(d, n')) = GB_\lambda(d, n) \implies L(BGC_\lambda(p, d, n')) = BGC_\lambda(p, d, n)$ . Moreover,  $GB_\lambda(d, n')$  is Eulerian, and so strongly connected. Since there is a loop in  $GB_\lambda(d, n')$ , namely  $00$ , therefore there is always a dipath of length  $l$ , such that  $l \equiv 0 \pmod{p}$ , between two of its vertices. Consequently,  $BGC_\lambda(p, d, n')$  is also strongly connected. Furthermore, it is a  $\lambda$ -regular digraph. Therefore  $BGC_\lambda(p, d, n')$  is Eulerian, and so its line digraph  $BGC_\lambda(p, d, n)$  is Hamiltonian. As a consequence,  $BGC(p, d, n)$  is Hamiltonian too.  $\square$

If  $d \geq 4$ , and  $n$  is coprime to  $d$ , then we can use the Hamiltonian Properties of the Consecutive- $d$  digraphs:

**Lemma 29.** If  $d \geq 4$  and  $n$  is coprime to  $d$ , then  $BGC(p, d, n)$  is Hamiltonian.

*Proof.* Vertices in  $BGC(p, d, n)$  are labeled by  $\mathbb{Z}_n \times \mathbb{Z}_p$ . For all  $i, \alpha$ , with  $i \in \mathbb{Z}_n$  and  $0 \leq \alpha \leq p-2$ , we associate the vertex  $(i, \alpha)$  to the vertex  $(di, \alpha + 1)$ . Since  $\gcd(d, n) = 1$  therefore it is a bijection. In so doing, we get a digraph  $G$ , whose set of nodes is  $\mathbb{Z}_n$ , such that there is an arc from a vertex  $i$  to a vertex  $j$  iff the vertex  $(d^{p-1}i, p-1)$  is incident to the vertex  $(j, 0)$  in  $BGC(p, d, n)$ . Actually,  $G$  is isomorphic to the Consecutive- $d$  digraph  $G(d, n, d^p, 0)$ . Since  $\gcd(n, d^p) = 1$  and  $d \geq 4$ , therefore it is a Hamiltonian digraph by Theorem 30. Let  $0, \sigma(0), \sigma^2(0), \dots, \sigma^{n-1}(0), 0$  be a Hamiltonian circuit in  $G$ . Then  $(0, 0), (0, 1), \dots, (0, p-1), (\sigma(0), 0), (d\sigma(0), 1), \dots, (d^{p-1}\sigma(0), p-1), (\sigma^2(0), 0), \dots, (\sigma^i(0), 0), (d\sigma^i(0), 1), \dots, (d^{p-1}\sigma^i(0), p-1), \dots, (\sigma^{n-1}(0), 0), (d\sigma^{n-1}(0), 1), \dots, (d^{p-1}\sigma^{n-1}(0), p-1), (0, 0)$  is a Hamiltonian circuit in  $BGC(p, d, n)$ .  $\square$

The only remaining cases are when  $d = 2$  and  $d = 3$ . If  $d = 2$  and  $n$  is even, then there is a Hamiltonian circuit on  $BGC(p, 2, n)$  by Lemma 28. Else:

**Lemma 30.** If  $n$  is odd, then  $BGC(p, 2, n)$  is Hamiltonian if and only if for all prime number  $q$  such that  $q|n$ ,  $q$  divides  $2^p - 1$ .

*Proof.* Let  $\alpha_0$  be a fixed residue modulo  $p$ . Let  $i$  be a residue modulo  $n$ , such that we associate the vertex  $(i, \alpha_0)$  to the vertex  $(2i, \alpha_0 + 1)$ . Then we also have to associate the vertex  $(j, \alpha_0)$  to the vertex  $(2j, \alpha_0 + 1)$ , with  $j = i - 2^{-1}$ . Furthermore, since  $2^{-1}$  is a generator element in  $\mathbb{Z}_n$ , therefore we have to do the same choice of residue modulo 2 for every vertex  $(i, \alpha_0)$ . At the end, there are only  $2^p$  possible Hamiltonian circuits, namely:  $C_0, C_1, \dots, C_{2^p-1}$ , such that after a vertex  $(i, 0)$ , the next vertex in  $C_r$  whose label is also in  $\mathbb{Z}_n \times \{0\}$  is  $(2^p i + r, 0)$ . Then observe that  $C_r$  is a Hamiltonian dicycle iff  $i \rightarrow 2^p i + r$  is a circular permutation. Clearly  $n$  is coprime to  $2^p$ . By Theorem 30, a necessary condition for  $i \rightarrow 2^p i + r$  to be a circular permutation, that is  $G(1, n, 2^p, r)$  is Hamiltonian, is that for all prime number  $q$  such that  $q$  divides  $n$ ,  $q$  also divides  $2^p - 1$ . This condition is also sufficient, because we can always choose  $r = 1$ , and in so doing  $\gcd(n, 2^p - 1, r) = 1$ .  $\square$

**Remark 13.** Especially when  $M_p = 2^p - 1$  is a Mersenne prime number,  $BGC(p, 2, n)$  is Hamiltonian iff  $n$  is a power of  $M_p$ , and there are always  $\varphi(M_p) = M_p - 1$  possible Hamiltonian circuits, where  $\varphi$  denotes the Euler's function.

If  $d = 3$ , we give a complete characterization of the Hamiltonian digraphs  $BGC(p, 3, n)$ , using two methods of link-interchanges.

**Lemma 31.** *If  $n$  is even, then  $BGC(p, 3, n)$  is Hamiltonian.*

*Proof.* When  $n$  is a multiple of 3, that is a direct consequence of Lemma 29. Consequently, we assume that  $n$  is coprime to 3. To a vertex  $(i, \alpha)$  we associate the vertex  $(3i + 1, \alpha + 1)$ . In so doing, since 3 is coprime to  $n$ , therefore we partition  $BGC(p, 3, n)$  into mutually vertex-disjoint circuits. Let us denote those dicycles by  $C_1, C_2, \dots, C_k$ . If  $k = 1$ , then  $C_1$  is a Hamiltonian circuit.

Else we use the pairs of interchange  $g(i) = [(2i, 0), (2i + 1, 0)]$  and  $f(j) = [(2j + 1, 1), (2j + 2, 1)]$ , with  $i, j \in \mathbb{Z}_n$ . Those pairs are mutually disjoint. Let  $UC_1, UC_2, \dots, UC_k$  be the undirected versions of the circuits  $C_1, C_2, \dots, C_k$ , and  $L$  be the union of those cycles. For all  $i, j$  we associate in  $L$  an edge  $[(2i \pmod n, 0), (2i + 1 \pmod n), 0]$  to the pair  $g(i)$ , and an edge  $[(2j + 1 \pmod n, 1), (2j + 2 \pmod n), 1]$  to the pair  $f(j)$ . We get a graph  $G$ . Remark that if  $G$  is connected, then we can merge all the circuits  $C_x$ , with  $1 \leq x \leq k$ , into one circuit  $C$ . Moreover, if all the pairs  $g(i)$ , with  $i \in \mathbb{Z}_n$ , can be linked with some edges in  $G$ , then  $G$  is connected.

Let  $i$  be a residue modulo  $n$ . Vertex  $(2i, 0)$  is incident to vertex  $(6i + 1, 1)$  and vertex  $(2i + 1, 0)$  is incident to vertex  $(6i + 4, 1)$ . Since  $n$  is even and  $6i + 3$  is odd, therefore  $6i + 3 \pmod n$  is odd. Consequently,  $[(6i + 3, 1), (6i + 4, 1)]$  is a pair of interchange  $f(j)$  for some  $j$ . Furthermore  $6i + 3 = 6(i + 3^{-1}) + 1$ , and so  $g(i)$  and  $g(i + 3^{-1})$  are linked together. Since  $3^{-1}$  is a generator element in  $\mathbb{Z}_n$ , therefore all the pairs  $g(i)$  are connected.  $\square$

It is interesting to notice that no extra-pairs of interchange  $[(i, \alpha), (i + 1, \alpha)]$  with  $\alpha \neq \{0, 1\}$  are needed. The demonstration of Lemma 31 is similar to the proof of Lemma 16.

We propose another set of interchanges when  $n$  is odd. Let  $P_n = \{(i, i + 1) : i < n \text{ and } i \text{ is odd}\}$ . Actually, we use  $P_n$  because of the properties that are proven with this set in [18].

**Lemma 32.** *If  $n$  is odd, then  $BGC(p, 3, n)$  is Hamiltonian.*

*Proof.* The proof is quite the same as for Lemma 31, except that we choose the set of interchange  $P = \{(i, \alpha), (i + 1, \alpha) : (i, i + 1) \in P_n\}$ . Clearly, all the pairs in  $P$  are disjoint. Let  $UC_1, UC_2, \dots, UC_k$  be the undirected versions of the circuits  $C_1, C_2, \dots, C_k$ , and  $L$  be the union of those cycles. For all pair  $[(i, \alpha), (i + 1, \alpha)] \in P$ , we add an edge  $[(i, \alpha), (i + 1, \alpha)]$  in  $L$ . We get a graph  $G$ , and we want to show that  $G$  is connected for completing the proof.

By [18],  $G$  is connected when  $p = 1$ . Consequently, for every  $i, j \in \mathbb{Z}_n$ , for all  $\alpha \in \mathbb{Z}_p$ , there exists  $\beta \in \mathbb{Z}_p$  such that there is a path in  $G$  from  $(i, \alpha)$  to  $(j, \beta)$ . Particularly, for every  $i \in \mathbb{Z}_n$ , for all  $\alpha \in \mathbb{Z}_p$ , there exists  $\beta \in \mathbb{Z}_p$  such that there is a path in  $G$  from  $(i, \alpha)$  to  $(-2^{-1}, \beta)$ . Furthermore,  $3 * (-2^{-1}) + 1 = (1 + 2) * (-2^{-1}) + 1 = -2^{-1} - 1 + 1 = -2^{-1}$ . Therefore, for all  $\alpha, \beta \in \mathbb{Z}_p$ , there is a path in  $G$  from  $(-2^{-1}, \alpha)$  to  $(-2^{-1}, \beta)$ . So  $G$  is connected.  $\square$

In the same way, the digraph  $KGC(p, d, n)$  is presented in [22]. Its set of vertices is labeled by  $\mathbb{Z}_n \times \mathbb{Z}_p$ . For all  $\alpha$ , with  $0 \leq \alpha \leq p - 2$ , a vertex  $(i, \alpha)$  is incident to the vertices  $(di + \beta, \alpha + 1)$ , with  $0 \leq \beta \leq d - 1$ . Furthermore, a vertex  $(i, p - 1)$  is incident to the vertices  $(-di - d + \beta, 0)$ , with  $0 \leq \beta \leq d - 1$ . Observe that  $KGC(2, d, n)$  is isomorphic to the bipartite digraph  $BD(d, n)$ , that is the representation digraph  $R(GK(d, n, d, n))$  (see Section 5.4.4). Moreover, the digraph  $C_p \otimes GK(d, n)$  is isomorphic to  $KGC(p, d, n)$  if  $p$  is odd, and is isomorphic to  $BGC(p, d, n)$  otherwise. Thus using the same methods, we propose an equivalent of Theorem 51:

**Theorem 52.** *The digraph  $KGC(p, d, n)$  is Hamiltonian if one of the following conditions is verified:*

1.  $d \geq 4$ ,

2.  $d = 3$ , and  $n$  is even, or  $p$  is odd, or 3 divides  $n$ ,
3.  $d = 2$  and  $n$  is even,
4.  $d = 2$ , and for every prime number  $q$  such that  $q$  divides  $n$ ,  $q$  divides  $2^p + 1$ ,
5.  $d = 1$ , and  $n \in \{1, 2\}$ .

Furthermore, if  $d = 1$  or  $d = 2$ , the last three conditions are necessary and sufficient conditions.

We also propose the following conjecture:

**Conjecture 53.** *If  $d \geq 3$  then  $KGC(p, d, n)$  is Hamiltonian.*

The conjecture is true for  $d$  greater than 3.



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