# THE IRREGULARITY OF GRAPHS UNDER GRAPH OPERATIONS 

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#### Abstract

The irregularity of a simple undirected graph $G$ was defined by Albertson [5] as $\operatorname{irr}(G)=\sum_{u v \in E(G)}\left|d_{G}(u)-d_{G}(v)\right|$, where $d_{G}(u)$ denotes the degree of a vertex $u \in V(G)$. In this paper we consider the irregularity of graphs under several graph operations including join, Cartesian product, direct product, strong product, corona product, lexicographic product, disjunction and symmetric difference. We give exact expressions or (sharp) upper bounds on the irregularity of graphs under the above mentioned operations.


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## 1. Introduction

Let $G$ be a simple undirected graph with $|V(G)|=n$ vertices and $|E(G)|=m$ edges. The degree of a vertex $v$ in $G$ is the number of edges incident with $v$ and it is denoted by $d_{G}(v)$. A graph $G$ is regular if all its vertices have the same degree, otherwise it is irregular. However, in many applications and problems it is of big importance to know how irregular a given graph is. Several graph topological indices have been proposed for that purpose. Among the most investigated ones are: the irregularity of a graph introduced by Albertson [5], the variance of vertex degrees [7], and Collatz-Sinogowitz index [12].

The imbalance of an edge $e=u v \in E$, defined as $\operatorname{imb}(e)=\left|d_{G}(u)-d_{G}(v)\right|$, appeares implicitly in the context of Ramsey problems with repeat degrees [6], and later in the work of Chen, Erdős, Rousseau, and Schlep [11], where 2-colorings
of edges of a complete graph were considered. In [5], Albertson defined the irregularity of $G$ as

$$
\begin{equation*}
\operatorname{irr}(G)=\sum_{e \in E(G)} \operatorname{imb}(e) \tag{1}
\end{equation*}
$$

It is shown in [5] that for a graph $G, \operatorname{irr}(G)<4 n^{3} / 27$ and that this bound can be approached arbitrary closely. Albertson also presented upper bounds on irregularity for bipartite graphs, triangle-free graphs and a sharp upper bound for trees. Some claims about bipartite graphs given in [5] have been formally proved in [21]. Related to Albertson is the work of Hansen and Mélot [20], who characterized the graphs with $n$ vertices and $m$ edges with maximal irregularity. The irregularity measure irr also is related to the first Zagreb index $M_{1}(G)$ and the second Zagreb index $M_{2}(G)$, one of the oldest and most investigated topological graph indices, defined as follows:

$$
M_{1}(G)=\sum_{v \in V(G)} d_{G}^{2}(v) \quad \text { and } \quad M_{2}(G)=\sum_{u v \in E(G)} d_{G}(u) d_{G}(v)
$$

Alternatively the first Zagreb index can be expressed as

$$
\begin{equation*}
M_{1}(G)=\sum_{u v \in E(G)}\left(d_{G}(u)+d_{G}(v)\right) . \tag{2}
\end{equation*}
$$

Fath-Tabar [16] established new bounds on the first and the second Zagreb indices that depend on the irregularity of graphs as defined in (1). In line with the standard terminology of chemical graph theory, and the obvious connection with the first and the second Zagreb indices, Fath-Tabar named the sum in (1) the third Zagreb index and denoted it by $M_{3}(G)$. However, in the rest of the paper, we will use its older name and call it the irregularity of a graph. Two other most frequently used graph topological indices, that measure how irregular a graph is, are the variance of degrees and the Collatz-Sinogowitz index [12]. Let $G$ be a graph with $n$ vertices and $m$ edges, and $\lambda_{1}$ be the index or largest eigenvalue of the adjacency matrix $A=\left(a_{i j}\right)$ (with $a_{i j}=1$ if vertices $i$ and $j$ are joined by an edge and 0 otherwise). Let $n_{i}$ denotes the number of vertices of degree $i$ for $i=1,2, \ldots, n-1$. Then, the variance of degrees and the Collatz-Sinogowitz index are respectively defined as
(3) $\operatorname{Var}(G)=\frac{1}{n} \sum_{i=1}^{n-1} n_{i}\left(i-\frac{2 m}{n}\right)^{2} \quad$ and $\quad \operatorname{CS}(G)=\lambda_{1}-\frac{2 m}{n}$.

Results of comparing irr, CS and Var are presented in [7, 13, 18]. There have been other attempts to determine how irregular graph is $[2,3,4,8,9,10,22]$, but heretofore this has not been captured by a single parameter as it was done by the irregularity measure by Albertson. The graph operation, especially graph
products, plays significant role not only in pure and applied mathematics, but also in computer science. For example, the Cartesian product provide an important model for linking computers. In order to synchronize the work of the whole system it is necessary to search for Hamiltonian paths and cycles in the network. Thus, some results on Hamiltonian paths and cycles in Cartesian product of graphs can be applied in computer network design [27]. Many of the problems can be easily handled if the related graphs are regular or close to regular.

The aim of this paper is to investigate the irregularity measure by Albertson under several graph operations including join, Cartesian product, direct product, strong product, corona product, lexicographic product, disjunction and symmetric difference. Detailed exposition on some graph operations one can find in [19].

In the sequel we will introduce additional necessary notation and results that will be used in the rest of the paper. For details of the mathematical theory and chemical applications of the Zagreb indices see surveys [14, 17, 24, 25] and papers [15, 28, 29].

A vertex is isolated if its degree is zero. An independent set is a set of vertices in a graph, no two of which are adjacent. The vertices from an independent set are independent vertices. For two graphs $G_{1}$ and $G_{2}$, with disjoint vertex sets $V\left(G_{1}\right)$ and $V\left(G_{2}\right)$ and disjoint edge sets $E\left(G_{1}\right)$ and $E\left(G_{2}\right)$, the disjoint union of $G_{1}$ and $G_{2}$ is the graph $G=G_{1} \cup G_{2}$, with the vertex set $V\left(G_{1}\right) \cup V\left(G_{2}\right)$ and the edge set $E\left(G_{1}\right) \cup E\left(G_{2}\right)$. Obviously, $\operatorname{irr}(G \cup H)=\operatorname{irr}(G)+\operatorname{irr}(H)$.

To obtain some of the bounds in the next section, we will use a recently introduced irregularity measure of a graph, so-called the total irregularity of a graph [1], defined as

$$
\begin{equation*}
\operatorname{irr}_{t}(G)=\frac{1}{2} \sum_{u, v \in V(G)}\left|d_{G}(u)-d_{G}(v)\right| \tag{4}
\end{equation*}
$$

Theorem 1 [1]. For a simple undirected graph $G$ with $n$ vertices, it holds that

$$
\operatorname{irr}_{t}(G) \leq \begin{cases}\frac{1}{12}\left(2 n^{3}-3 n^{2}-2 n\right) & n \text { even } \\ \frac{1}{12}\left(2 n^{3}-3 n^{2}-2 n+3\right) & n \text { odd }\end{cases}
$$

Moreover, the bounds are sharp.

## 2. Results

### 2.1. Join

The join $G+H$ of simple undirected graphs $G$ and $H$ is the graph with the vertex set $V(G+H)=V(G) \cup V(H)$ and the edge set $E(G+H)=E(G) \cup E(H) \cup$ $\{u v: u \in V(G), v \in V(H)\}$.

Theorem 2. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$ such that $n_{1} \geq n_{2}$. Then

$$
\operatorname{irr}(G+H) \leq \operatorname{irr}(G)+\operatorname{irr}(H)+n_{2}\left(n_{1}-1\right)\left(n_{1}-2\right) .
$$

Moreover, the bound is sharp.
Proof. By the definition, $|V(G+H)|=|V(G)|+|V(H)|=n_{1}+n_{2}$ and $|E(G+H)|$ $=|E(G)|+|E(H)|+n_{1} n_{2}$. The irregularity of $G+H$ is

$$
\begin{aligned}
\operatorname{irr}(G+H) & =\sum_{u v \in E(G+H)}\left|d_{G+H}(u)-d_{G+H}(v)\right| \\
& =\sum_{x y \in E(G)}\left|d_{G+H}(x)-d_{G+H}(y)\right| \\
& +\sum_{z t \in E(H)}\left|d_{G+H}(z)-d_{G+H}(t)\right| \\
& +\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G+H}(u)-d_{G+H}(v)\right| .
\end{aligned}
$$

For a vertex $u \in V(G)$, it holds that $d_{G+H}(u)=d_{G}(u)+n_{2}$, and for a vertex $v \in V(H)$, it holds that $d_{G+H}(v)=d_{H}(v)+n_{1}$. Thus, further we have

$$
\begin{aligned}
\operatorname{irr}(G+H) & =\sum_{x y \in E(G)}\left|d_{G}(x)-d_{G}(y)\right|+\sum_{z t \in E(H)}\left|d_{H}(z)-d_{H}(t)\right| \\
& +\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G}(u)-d_{H}(v)+n_{2}-n_{1}\right| \\
& =\operatorname{irr}(G)+\operatorname{irr}(H)+\sum_{u \in V(G)} \sum_{v \in V(H)}\left|n_{1}-n_{2}+d_{H}(v)-d_{G}(u)\right|
\end{aligned}
$$

Under the constrains $n_{1} \geq n_{2}, d_{G}(u) \leq n_{1}-1$, and $d_{H}(v) \leq n_{2}-1$, the double $\operatorname{sum} \sum_{u \in V(G)} \sum_{v \in V(H)}\left|n_{1}-n_{2}+d_{H}(v)-d_{G}(u)\right|$ is maximal when $H$ is a graph with maximal sum of vertex degrees, i.e., $H$ is the complete graph $K_{n_{2}}$, and $G$ is a graph with minimal sum of vertex degrees, i.e., $G$ is a tree on $n_{1}$ vertices $T_{n_{1}}$. Thus,

$$
\begin{aligned}
\sum_{v \in V(H)}^{u \in V(G)}\left|n_{1}-n_{2}+d_{H}(v)-d_{G}(u)\right| & \leq \sum_{v \in V\left(T_{n_{1}}\right)}\left|n_{1}-n_{2}+d_{K_{n_{2}}}(v)-d_{T_{n_{1}}}(u)\right| \\
& =\sum_{u \in V\left(K_{n_{2}}\right)} \sum_{u \in\left(T_{n_{1}}\right)} \sum_{v \in V\left(K_{n_{2}}\right)}\left|n_{1}-1-d_{T_{n_{1}}}(u)\right| \\
& =n_{2} \sum_{u \in V\left(T_{n_{1}}\right)}\left(n_{1}-1-d_{T_{n_{1}}}(u)\right) \\
& =n_{2} n_{1}\left(n_{1}-1\right)-2 n_{2}\left(n_{1}-1\right) \\
& =n_{2}\left(n_{1}-1\right)\left(n_{1}-2\right),
\end{aligned}
$$

and

$$
\begin{equation*}
\operatorname{irr}(G+H) \leq \operatorname{irr}(G)+\operatorname{irr}(H)+n_{2}\left(n_{1}-1\right)\left(n_{1}-2\right) \tag{5}
\end{equation*}
$$

When $n_{1} \leq 2, \operatorname{irr}(G)=\operatorname{irr}(H)=\operatorname{irr}(G+H)=0$, and the claim of the theorem is fulfilled. From the derivation, it follows that (5) is equality when $H$ is complete graph on $n_{2}$ vertices and $G$ is any tree on $n_{1}$ vertices.

Example 3. Let denote by $H_{i}$ a graph with $\left|V\left(H_{i}\right)\right|=i$ isolated vertices. Then, the bipartite graph $K_{i, j}$ is a join of $H_{i}$ and $H_{j}$. Analogously, the complete $k$-partite graph $G=K_{n_{1}, \ldots, n_{k}}$ is join of $H_{n_{1}}, \ldots$, and $H_{n_{k}}$. We have that $\operatorname{irr}\left(K_{n_{i}, n_{j}}\right)=$ $n_{i} n_{j}\left|n_{j}-n_{i}\right|$. For the irregularity of $K_{n_{1}, \ldots, n_{k}}$ we obtain

$$
\begin{aligned}
\operatorname{irr}\left(K_{n_{1}, \ldots, n_{k}}\right) & =\sum_{u v \in E\left(K_{n_{1}, \ldots, n_{k}}\right)}\left|d_{G}(u)-d_{G}(v)\right| \\
& =\sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \sum_{u v \in E\left(K_{n_{i}, n_{j}}\right)}\left|d_{G}(u)-d_{G}(v)\right| \\
& =\sum_{i=1}^{k-1} \sum_{j=i+1}^{k} n_{i} n_{j}\left|n_{j}-n_{i}\right|=\sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \operatorname{irr}\left(K_{n_{i}, n_{j}}\right) .
\end{aligned}
$$

### 2.2. Cartesian product

The Cartesian product $G \square H$ of two simple undirected graphs $G$ and $H$ is the graph with the vertex set $V(G \square H)=V(G) \times V(H)$ and the edge set $E(G \square H)=$ $\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right):\left[\left(u_{i} u_{j} \in E(G)\right) \wedge\left(v_{k}=v_{l}\right)\right] \vee\left[\left(v_{k} v_{l} \in E(H)\right) \wedge\left(u_{i}=u_{j}\right)\right]\right\}$.
Theorem 4. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$. Then

$$
\operatorname{irr}(G \square H)=n_{2} \operatorname{irr}(G)+n_{1} \operatorname{irr}(H)
$$

Proof. From the definiton of the Cartesian product, it follows $|V(G \square H)|=$ $|V(G)||V(H)|,|E(G \square H)|=n_{2}|E(G)|+n_{1}|E(H)|$, and $d_{G \square H}\left(u_{i}, v_{k}\right)=d_{G}\left(u_{i}\right)+$ $d_{H}\left(v_{k}\right)$. Hence,

$$
\begin{aligned}
\operatorname{irr}(G \square H) & =\sum_{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right) \in E(G \square H)}\left|d_{G \square H}\left(u_{i}, v_{k}\right)-d_{G \square H}\left(u_{j}, v_{l}\right)\right| \\
& =\sum_{u_{i} u_{j} \in E(G)} \sum_{v \in V(H)}\left|d_{G \square H}\left(u_{i}, v\right)-d_{G \square H}\left(u_{j}, v\right)\right| \\
& +\sum_{v_{k} v_{l} \in E(H)} \sum_{u \in V(G)}\left|d_{G \square H}\left(u, v_{k}\right)-d_{G \square H}\left(u, v_{l}\right)\right| \\
& =\sum_{u_{i} u_{j} \in E(G)} \sum_{v \in V(H)}\left|\left(d_{G}\left(u_{i}\right)+d_{H}(v)\right)-\left(d_{G}\left(u_{j}\right)+d_{H}(v)\right)\right| \\
& +\sum_{v_{k} v_{l} \in E(H)} \sum_{u \in V(G)}\left|\left(d_{G}(u)+d_{H}\left(v_{k}\right)\right)-\left(d_{G}(u)+d_{H}\left(v_{l}\right)\right)\right| \\
& =n_{2} \operatorname{irr}(G)+n_{1} \operatorname{irr}(H) .
\end{aligned}
$$

### 2.3. Direct product

The direct product $G \times H$ (also known as tensor product, Kronecker product [26], categorical product [23] and conjunctive product) of simple undirected graphs $G$


Figure 1. (a) Path graph on $l$ vertices $P_{l}$, and cycle graph on $k$ vertices $C_{k}$,
(b) direct product graph $P_{l} \times C_{k}$, and
(c) strong product graph $P_{l} \boxtimes C_{k}$.
and $H$ is the graph with the vertex set $V(G \times H)=V(G) \times V(H)$, and the edge set $E(G \times H)=\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right):\left(u_{i}, u_{j}\right) \in E(G) \wedge\left(v_{k}, v_{l}\right) \in E(H)\right\}$.

Theorem 5. Let $G$ and $H$ be simple undirected graphs. Then

$$
\operatorname{irr}(G \times H) \leq \operatorname{irr}(G) M_{1}(H)+\operatorname{irr}(H) M_{1}(G)
$$

Moreover, the bound is sharp for infinitely many graphs.
Proof. From the definition of the direct product, it follows $|V(G \times H)|=|V(G)|$ $|V(H)|,|E(G \times H)|=2|E(G)||E(H)|$, and $d_{G \times H}\left(u_{i}, v_{k}\right)=d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right)$. The irregularity of the direct product $G \times H$ is

$$
\begin{aligned}
\operatorname{irr}(G \times H) & =\sum_{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right) \in E(G \times H)}\left|d_{G \times H}\left(u_{i}, v_{k}\right)-d_{G \times H}\left(u_{j}, v_{l}\right)\right| \\
& =2 \sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right)-d_{G}\left(u_{j}\right) d_{H}\left(v_{l}\right)\right| \\
& =\sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)} \mid\left(d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right)\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right) \\
& +\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left(d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right) \mid .
\end{aligned}
$$

Applying the triangle inequality in the above expression and by equation (2), we obtain

$$
\begin{aligned}
\operatorname{irr}(G \times H) & \leq \sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)}\left[\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right|\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\right. \\
& \left.+\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right|\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\right] \\
& =\operatorname{irr}(G) M_{1}(H)+\operatorname{irr}(H) M_{1}(G) .
\end{aligned}
$$

To prove that the presented bound is the best possible, consider the direct product $P_{l} \times C_{k}, l \geq 1, k \geq 3$ (an illustration is given in Figure 1(b)). Straightforward calculations gives that $M_{1}\left(P_{l}\right)=4 l-6, M_{1}\left(C_{k}\right)=4 k, \operatorname{irr}\left(P_{l}\right)=2, \operatorname{irr}\left(C_{k}\right)=0$. The graph $P_{l} \times C_{k}$ is comprised of $2 k$ vertices of degree 2 , and $k(l-2)$ vertices of degree 4. Each vertex of degree 2 is adjacent with exactly two vertices with degree 4. Hence, $\operatorname{irr}\left(P_{l} \times C_{k}\right)=8 k$. On the other hand, the bound obtain here is $\operatorname{irr}\left(P_{l} \times C_{k}\right) \leq \operatorname{irr}\left(P_{l}\right) M_{1}\left(C_{k}\right)+\operatorname{irr}\left(C_{k}\right) M_{1}\left(P_{l}\right)=8 k$.

### 2.4. Strong product

The strong product $G \boxtimes H$ of two simple undirected graphs $G$ and $H$ is the graph with the vertex set $V(G \boxtimes H=V(G) \times V(H)$ and the edge set $E(G \boxtimes H)=$ $\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right):\left[\left(u_{i} u_{j} \in E(G)\right) \wedge\left(v_{k}=v_{l}\right)\right] \vee\left[\left(v_{k} v_{l} \in E(H)\right) \wedge\left(u_{i}=u_{j}\right)\right] \vee\right.$ $\left.\left[\left(u_{i} u_{j} \in E(G)\right) \wedge\left(v_{k} v_{l} \in E(H)\right)\right]\right\}$.
Theorem 6. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$, $|E(G)|=m_{1},|V(H)|=n_{2}$ and $|E(H)|=m_{2}$. Then

$$
\operatorname{irr}(G \boxtimes H) \leq\left(n_{2}+4 m_{2}+M_{1}(H)\right) \operatorname{irr}(G)+\left(n_{1}+4 m_{1}+M_{1}(G)\right) \operatorname{irr}(H)
$$

Moreover, the bound is sharp for infinitely many graphs.
Proof. For the strong product $V(G \boxtimes H)$, it holds that $|V(G \boxtimes H)|=|V(G)|$ $|V(H)|,|E(G \boxtimes H)|=|V(H)||E(G)|+|V(G)||E(H)|+2|E(G)||E(H)|$, and $d_{G \boxtimes H}\left(u_{i}, v_{k}\right)=d_{G}\left(u_{i}\right)+d_{H}\left(v_{k}\right)+d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right)$. The irregularity of $G \boxtimes H$ is

$$
\begin{align*}
\operatorname{irr}(G \boxtimes H) & =\sum_{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right) \in E(G \boxtimes H)}\left|d_{G \boxtimes H}\left(u_{i}, v_{k}\right)-d_{G \boxtimes H}\left(u_{j}, v_{l}\right)\right| \\
& =\sum_{v_{k}=v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|d_{G \boxtimes H}\left(u_{i}, v_{k}\right)-d_{G \boxtimes H}\left(u_{j}, v_{l}\right)\right|  \tag{6}\\
& +\sum_{u_{i}=u_{j} \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G \boxtimes H}\left(u_{i}, v_{k}\right)-d_{G \boxtimes H}\left(u_{j}, v_{l}\right)\right| \\
& +2 \sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G \boxtimes H}\left(u_{i}, v_{k}\right)-d_{G \boxtimes H}\left(u_{j}, v_{l}\right)\right| .
\end{align*}
$$

By an algebraic transformation and applying the triangle inequality, we obtain

$$
\begin{align*}
\left|d_{G \boxtimes H}\left(u_{i}, v_{k}\right)-d_{G \boxtimes H}\left(u_{j}, v_{l}\right)\right| & =\mid d_{G}\left(u_{i}\right)+d_{H}\left(v_{k}\right)+d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right) \\
& -d_{G}\left(u_{j}\right)-d_{H}\left(v_{l}\right)-d_{G}\left(u_{j}\right) d_{H}\left(v_{l}\right) \mid \\
& \leq\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right|+\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{l}\right)-d_{H}\left(v_{k}\right)\right|  \tag{7}\\
& +\frac{1}{2}\left(d_{H}\left(v_{l}\right)+d_{H}\left(v_{k}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =f_{1}(i, j, k, l) .
\end{align*}
$$

Substituting (7) in (6), we obtain

$$
\begin{align*}
\operatorname{irr}(G \boxtimes H) & \leq \sum_{\substack{v_{k}=v_{l} \in V(H) \\
u_{i} u_{j} \in E(G)}} f_{1}(i, j, k, l)+\sum_{\substack{u_{i}=u_{j} \in V(G) \\
v_{k} v_{l} \in E(H)}} f_{1}(i, j, k, l)  \tag{8}\\
& +2 \sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}} f_{1}(i, j, k, l) .
\end{align*}
$$

We have

$$
\begin{aligned}
\sum_{\substack{v_{k}=v_{v} \in V(H) \\
u_{i} u_{j} \in E(G)}} f_{1}(i, j, k, l) & =\sum_{v \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& +\sum_{v \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|d_{H}(v)-d_{H}(v)\right| \\
& +\frac{1}{2} \sum_{v \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}(v)-d_{H}(v)\right| \\
& +\frac{1}{2} \sum_{v \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left(d_{H}(v)+d_{H}(v)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =\left(n_{2}+2 m_{2}\right) \operatorname{irr}(G) .
\end{aligned}
$$

Similarly,

$$
\begin{aligned}
\sum_{\substack{u_{i}=u_{j} \in V(G) \\
v_{k} v_{l} \in E(H)}} f_{1}(i, j, k, l) & =\sum_{u \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G}(u)-d_{G}(u)\right| \\
& +\sum_{u \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{u \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left(d_{G}(u)+d_{G}(u)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{u \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}(u)-d_{G}(u)\right| \\
& =\left(n_{1}+2 m_{1}\right) \operatorname{irr}(H) .
\end{aligned}
$$

Finally,

$$
\begin{aligned}
\sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}} f_{1}(i, j, k, l) & =\sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& +\sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i} u_{i} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =\left(m_{2}+\frac{1}{2} M_{1}(H)\right) \operatorname{irr}(G)+\left(m_{1}+\frac{1}{2} M_{1}(G)\right) \operatorname{irr}(H)
\end{aligned}
$$

From (8), (9), (10) and (11), we have

$$
\operatorname{irr}(G \boxtimes H) \leq\left(n_{2}+4 m_{2}+M_{1}(H)\right) \operatorname{irr}(G)+\left(n_{1}+4 m_{1}+M_{1}(G)\right) \operatorname{irr}(H) .
$$

To prove that the presented bound is the best possible, consider the strong product $P_{l} \boxtimes C_{k}, l \geq 1, k \geq 3$ illustrated in Figure $1(\mathrm{c})$. Simple calculations gives that $M_{1}\left(P_{l}\right)=4 l-6, M_{1}\left(C_{k}\right)=4 k, \operatorname{irr}\left(P_{l}\right)=2, \operatorname{irr}\left(C_{k}\right)=0$. The graph $P_{l} \boxtimes C_{k}$ is comprised of $2 k$ vertices of degree 5 , and $k(l-2)$ vertices of degree 8. Each vertex of degree 5 is adjacent with exactly three vertices with degree 8. Hence, $\operatorname{irr}\left(P_{l} \boxtimes C_{k}\right)=18 k$. On the other hand, the bound obtain here is $\operatorname{irr}\left(P_{l} \boxtimes C_{k}\right) \leq\left(k+4 k+M_{1}\left(C_{k}\right)\right) \operatorname{irr}\left(P_{l}\right)+\left(l+4(l-1)+M_{1}\left(P_{l}\right)\right) \operatorname{irr}\left(C_{k}\right)=18 k$.

### 2.5. Corona product

The corona product $G \odot H$ of simple undirected graphs $G$ and $H$ with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$, is defined as the graph who is obtained by taking the disjoint union of $G$ and $n_{1}$ copies of $H$ and for each $i, 1 \leq i \leq n_{1}$, inserting edges between the $i$ th vertex of $G$ and each vertex of the $i$ th copy of $H$. Thus, the corona graph $G \odot H$ is the graph with the vertex set $V(G \odot H)=V(G) \bigcup_{i=1, \ldots, n_{1}} V\left(H_{i}\right)$ and the edge set $E(G \odot H)=E(G) \bigcup_{i=1, \ldots, n_{1}} E\left(H_{i}\right) \cup\left\{u_{i} v_{j}: u_{i} \in V(G), v_{j} \in V\left(H_{i}\right)\right\}$, where $H_{i}$ is the $i$ th copy of the graph $H$.

Theorem 7. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$. Then

$$
\operatorname{irr}(G \odot H) \leq \operatorname{irr}(G)+n_{1} \operatorname{irr}(H)+n_{1}\left(n_{2}^{2}+n_{1} n_{2}-4 n_{2}+2\right) .
$$

Moreover, the bound is sharp.

Proof. By the definition of $G \odot H,|V(G \odot H)|=|V(G)|+n_{1}|V(H)|=n_{1}+n_{1} n_{2}$, and $|E(G \odot H)|=|E(G)|+n_{1}|E(H)|+n_{1} n_{2}$. The irregularity of $G \odot H$ is

$$
\begin{aligned}
\operatorname{irr}(G \odot H) & =\sum_{u v \in E(G \odot H)}\left|d_{G \odot H}(u)-d_{G \odot H}(v)\right| \\
& =\sum_{x y \in E(G)}\left|d_{G \odot H}(x)-d_{G \odot H}(y)\right| \\
& +\sum_{i=1}^{n_{1}} \sum_{z t \in E\left(H_{i}\right)}\left|d_{G \odot H}(z)-d_{G \odot H}(t)\right| \\
& +\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G \odot H}(u)-d_{G \odot H}(v)\right| .
\end{aligned}
$$

For a vertex $u \in V(G)$, it holds that $d_{G \odot H}(u)=d_{G}(u)+n_{2}$ and for a vertex $v \in V\left(H_{i}\right), 1 \leq i \leq n_{2}$, we have $d_{G \odot H}(v)=d_{H}(v)+1$. Thus,

$$
\begin{aligned}
\operatorname{irr}(G \odot H) & =\sum_{x y \in E(G)}\left|d_{G}(x)+n_{2}-d_{G}(y)-n_{2}\right| \\
& +\sum_{i=1}^{n_{1}} \sum_{z t \in E(H)}\left|d_{H}(z)+1-d_{H}(t)-1\right| \\
& +\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G}(u)+n_{2}-d_{H}(v)-1\right| \\
& =\sum_{x y \in E(G)}\left|d_{G}(x)-d_{G}(y)\right|+n_{1} \sum_{z t \in E(H)}\left|d_{H}(z)-d_{H}(t)\right| \\
& +\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G}(u)-d_{H}(v)+n_{2}-1\right| \\
& =\operatorname{irr}(G)+n_{1} \operatorname{irr}(H)+\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G}(u)-d_{H}(v)+n_{2}-1\right| .
\end{aligned}
$$

Since $n_{1} \geq n_{2}$, the double sum in (12) is maximal when $\sum_{u \in V(G)} d_{G}(u)$ is maximal, i.e., $G$ is the complete graph $K_{n_{1}}$, and $\sum_{v \in V(H)} d_{H}(v)$ is minimal, i.e., $H$ is a tree on $n_{2}$ vertices $T_{n_{2}}$. Thus,

$$
\begin{align*}
\sum_{\substack{u \in V(G) \\
v \in V(H)}} f_{1}(i, j, k, l) & =\sum_{u \in V(G)} \sum_{v \in V(H)}\left|d_{G}(u)-d_{H}(v)+n_{2}-1\right| \\
& \leq \sum_{u \in V\left(K_{n_{1}}\right)} \sum_{v \in V\left(T_{n_{2}}\right)}\left|d_{K_{n_{1}}}(u)-d_{T_{n_{2}}}(v)+n_{2}-1\right| \\
& =\sum_{u \in V\left(K_{n_{1}}\right)} \sum_{v \in V\left(T_{n_{2}}\right)}\left|n_{1}-1-d_{T_{n_{2}}}(v)+n_{2}-1\right|  \tag{13}\\
& =n_{1} \sum_{v \in V\left(T_{n_{2}}\right)}\left(n_{1}+n_{2}-2-d_{T_{n_{2}}}(v)\right) \\
& =n_{1} n_{2}\left(n_{1}+n_{2}-2\right)-2 n_{1}\left(n_{2}-1\right) \\
& =n_{1}\left(n_{2}^{2}+n_{1} n_{2}-4 n_{2}+2\right) .
\end{align*}
$$

Substituting (13) into (12), we obtain

$$
\begin{equation*}
\operatorname{irr}(G \odot H) \leq \operatorname{irr}(G)+n_{1} \operatorname{irr}(H)+n_{1}\left(n_{2}^{2}+n_{1} n_{2}-4 n_{2}+2\right) \tag{14}
\end{equation*}
$$

From the derivation of the bound (14), it follows that the sharp bound is obtained when $G$ is compete graph on $n_{1}$ vertices and $H$ is any tree on $n_{2}$ vertices.

### 2.6. Lexicographic product

The lexicographic product $G \circ H$ (also known as the graph composition) of simple undirected graphs $G$ and $H$ is the graph with the vertex set $V(G \circ H)=V(G) \times$ $V(H)$ and the edge set $E(G \circ H)=\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right):\left[u_{i} u_{j} \in E(G)\right] \vee\left[\left(v_{k} v_{l} \in\right.\right.\right.$ $\left.\left.E(H)) \wedge\left(u_{i}=u_{j}\right)\right]\right\}$.
Theorem 8. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$, $|E(G)|=m_{1},|V(H)|=n_{2}$ and $|E(H)|=m_{2}$. Then

$$
\operatorname{irr}(G \circ H) \leq n_{2}^{3} \operatorname{irr}(G)+n_{1} \operatorname{irr}(H)+\frac{1}{6} m_{1}\left(2 n_{2}^{3}-3 n_{2}^{2}-2 n_{2}+3\right) .
$$

Proof. By the definition of $G \circ H$, it follows that $|V(G \circ H)|=n_{1} n_{2},|E(G \circ H)|$ $=n_{1} m_{2}+n_{2}^{2} m_{1}$ and $d_{G \circ H}\left(u_{i}, v_{j}\right)=n_{2} d_{G}\left(u_{i}\right)+d_{H}\left(v_{j}\right)$ for all $1 \leq i \leq n_{1}, 1 \leq j \leq$ $n_{2}$. Applying those relations, we obtain

$$
\begin{aligned}
\operatorname{irr}(G \circ H) & =\sum_{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right) \in E(G \circ H)}\left|d_{G \circ H}\left(u_{i}, v_{k}\right)-d_{G \circ H}\left(u_{j}, v_{l}\right)\right| \\
& =\sum_{u_{i} \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|\left(n_{2} d_{G}\left(u_{i}\right)+d_{H}\left(v_{k}\right)\right)-\left(n_{2} d_{G}\left(u_{i}\right)+d_{H}\left(v_{l}\right)\right)\right| \\
& +\sum_{v_{k}, v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|n_{2} d_{G}\left(u_{i}\right)+d_{H}\left(v_{k}\right)-n_{2} d_{G}\left(u_{j}\right)-d_{H}\left(v_{l}\right)\right| \\
& =\sum_{u_{i} \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\sum_{v_{k}, v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|n_{2}\left(d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right)+\left(d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right)\right| \\
& =n_{1} \operatorname{irr}(H) \\
& +\sum_{v_{k}, v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|n_{2}\left(d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right)+d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| .
\end{aligned}
$$

By applying the triangle inequality in the last expression, we have

$$
\operatorname{irr}(G \circ H) \leq n_{1} \operatorname{irr}(H)+n_{2}^{3} \operatorname{irr}(G)+|E(G)| \sum_{v_{k}, v_{l} \in V(H)}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right|
$$

Finally, by Theorem 1, we obtain

$$
\operatorname{irr}(G \circ H) \leq n_{2}^{3} \operatorname{irr}(G)+n_{1} \operatorname{irr}(H)+\frac{1}{6} m_{1}\left(2 n_{2}^{3}-3 n_{2}^{2}-2 n_{2}+3\right) .
$$

### 2.7. Disjunction

The disjunction $G \vee H$ of simple undirected graphs $G$ and $H$ with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$ is the graph with the vertex set $V(G \vee H)=V(G) \times V(H)$ and the edge set $E(G \vee H)=\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right): u_{i} u_{j} \in E(G) \vee v_{k} v_{l} \in E(H)\right\}$.
Theorem 9. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$, $|E(G)|=m_{1},|V(H)|=n_{2}$ and $|E(H)|=m_{2}$. Then

$$
\begin{aligned}
\operatorname{irr}(G \vee H) & \leq\left(n_{2}^{3}-M_{1}(H)\right) \operatorname{irr}(G)+\left(2 n_{2} m_{2}+M_{1}(H)\right) \operatorname{irr}_{t}(G) \\
& +\left(n_{1}^{3}-M_{1}(G)\right) \operatorname{irr}(H)+\left(2 n_{1} m_{1}+M_{1}(G)\right) \operatorname{irr}_{t}(H) .
\end{aligned}
$$

Proof. By definition of $G \vee H$, it holds that $|V(G \vee H)|=n_{1} n_{2},|E(G \vee H)|=$ $n_{2}^{2} m_{1}+n_{1}^{2} m_{2}-2 m_{1} m_{2}$ and $d_{(G \vee H)}\left(u_{i}, v_{k}\right)=n_{2} d_{G}\left(u_{i}\right)+n_{1} d_{H}\left(v_{k}\right)-d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right)$ for all $1 \leq i \leq n_{1}, 1 \leq j \leq n_{2}$. Applying those relations, we obtain

$$
\begin{align*}
\operatorname{irr}(G \vee H) & =\sum_{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right) \in E(G \vee H)}\left|d_{G \vee H}\left(u_{i}, v_{k}\right)-d_{G \vee H}\left(u_{j}, v_{l}\right)\right| \\
& =\sum_{v_{k}, v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)}\left|d_{G \vee H}\left(u_{i}, v_{k}\right)-d_{G \vee H}\left(u_{j}, v_{l}\right)\right|  \tag{15}\\
& +\sum_{u_{i}, u_{j} \in V(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G \vee H}\left(u_{i}, v_{k}\right)-d_{G \vee H}\left(u_{j}, v_{l}\right)\right| \\
& -2 \sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)}\left|d_{G \vee H}\left(u_{i}, v_{k}\right)-d_{G \vee H}\left(u_{j}, v_{l}\right)\right| .
\end{align*}
$$

After an algebraic transformation and the triangle inequality, we have

$$
\begin{aligned}
\left|d_{G \vee H}\left(u_{i}, v_{k}\right)-d_{G \vee H}\left(u_{j}, v_{l}\right)\right| & =\mid n_{2} d_{G}\left(u_{i}\right)+n_{1} d_{H}\left(v_{k}\right)-d_{G}\left(u_{i}\right) d_{H}\left(v_{k}\right) \\
& -n_{2} d_{G}\left(u_{j}\right)-n_{1} d_{H}\left(v_{l}\right)+d_{G}\left(u_{j}\right) d_{H}\left(v_{l}\right) \mid \\
& \leq n_{2}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right|+n_{1}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =f_{2}(i, j, k, l) .
\end{aligned}
$$

Substituting (16) in (15), we obtain

$$
\begin{align*}
\operatorname{irr}(G \vee H) & \leq \sum_{v_{k}, v_{l} \in V(H)} \sum_{u_{i} u_{j} \in E(G)} f_{2}(i, j, k, l) \\
& +\sum_{u_{i}, u_{j} \in V(G)} \sum_{v_{k} v_{l} \in E(H)} f_{2}(i, j, k, l)  \tag{17}\\
& -2 \sum_{u_{i} u_{j} \in E(G)} \sum_{v_{k} v_{l} \in E(H)} f_{2}(i, j, k, l)
\end{align*}
$$

Applying (1), (2) and (4), we have

$$
\begin{aligned}
\sum_{\substack{v_{k}, v_{v} \in V(H) \\
u_{i} u_{j} \in E(G)}} f_{2}(i, j, k, l) & =\sum_{\substack{v_{k}, v_{l} \in V(H) \\
u_{i} u_{j} \in E(G)}} n_{2}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& +\sum_{\substack{v_{k}, v_{l} \in V(H) \\
u_{i} u_{j} \in E(G)}} n_{1}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{v_{k}, v_{l} \in V(H) \\
u_{i} u_{j} \in E(G)}}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{v_{k}, v_{l} \in V(H) \\
u_{i} u_{j} \in E(G)}}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =n_{2}\left(n_{2}^{2}+2 m_{2}\right) \operatorname{irr}(G)+\left(M_{1}(G)+2 n_{1} m_{1}\right) \operatorname{irr}_{t}(H) .
\end{aligned}
$$

Similarly,

$$
\begin{aligned}
\sum_{\substack{u_{i}, u_{j} \in V(G) \\
v_{k} v_{l} \in E(H)}} f_{2}(i, j, k, l) & =\sum_{\substack{u_{i}, u_{j} \in V(G) \\
v_{k} v_{l} \in E(H)}} n_{2}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| r \\
& +\sum_{\substack{u_{i}, u_{j} \in V(G) \\
v_{k}, v_{l}}} n_{1}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i}, u_{j} \in V(G) \\
v_{k}}}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i}, u_{j} \in V(G) \\
v_{k} v_{l} \in E(H)}}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =n_{1}\left(n_{1}^{2}+2 m_{1}\right) \operatorname{irr}(H)+\left(M_{1}(H)+2 n_{2} m_{2}\right) \operatorname{irr}_{t}(G) .
\end{aligned}
$$

Finally,

$$
\begin{aligned}
\sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}} f_{2}(i, j, k, l) & =\sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} \in E(H)}} n_{2}\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& +\sum_{\substack{u_{i} u_{i} \in E(H) \\
v_{k} v_{l} \in E(H)}} n_{1}\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left(d_{G}\left(u_{i}\right)+d_{G}\left(u_{j}\right)\right)\left|d_{H}\left(v_{k}\right)-d_{H}\left(v_{l}\right)\right| \\
& +\frac{1}{2} \sum_{\substack{u_{i} u_{j} \in E(G) \\
v_{k} v_{l} \in E(H)}}\left(d_{H}\left(v_{k}\right)+d_{H}\left(v_{l}\right)\right)\left|d_{G}\left(u_{i}\right)-d_{G}\left(u_{j}\right)\right| \\
& =\left(n_{2} m_{2}+\frac{1}{2} M_{1}(H)\right) \operatorname{irr}(G)+\left(n_{1} m_{1}+\frac{1}{2} M_{1}(G)\right) \operatorname{irr}(H) .
\end{aligned}
$$

Combining (17), (18), (19) and (20), we finally obtain

$$
\begin{align*}
\operatorname{irr}(G \vee H) & \leq\left(n_{2}^{3}-M_{1}(H)\right) \operatorname{irr}(G)+\left(2 n_{2} m_{2}+M_{1}(H)\right) \operatorname{irr}_{t}(G) \\
& +\left(n_{1}^{3}-M_{1}(G)\right) \operatorname{irr}(H)+\left(2 n_{1} m_{1}+M_{1}(G)\right) \operatorname{irr}_{t}(H) . \tag{21}
\end{align*}
$$

### 2.8. Symmetric difference

The symmetric difference $G \oplus H$ of simple undirected graphs $G$ and $H$ with $|V(G)|=n_{1}$ and $|V(H)|=n_{2}$ is the graph with the vertex set $V(G \oplus H)=V(G) \times$ $V(H)$ and the edge set $E(G \oplus H)=\left\{\left(u_{i}, v_{k}\right)\left(u_{j}, v_{l}\right)\right.$ : either $u_{i} u_{j} \in E(G)$ or $v_{k} v_{l}$ $\in E(H)\}$. It holds that $|V(G \oplus H)|=n_{1} n_{2},|E(G \oplus H)|=n_{1}^{2} m_{2}+n_{2}^{2} m_{1}-$ $4 m_{1} m_{2}$ and $d_{(G \oplus H)}\left(u_{i}, v_{j}\right)=n_{2} d_{G}\left(u_{i}\right)+n_{1} d_{H}\left(v_{j}\right)-2 d_{G}\left(u_{i}\right) d_{H}\left(v_{j}\right)$ for all $1 \leq$ $i \leq n_{1}, 1 \leq j \leq n_{2}$. Much as in the previous case, we present only the bound on the irregularity of symmetric difference of two graphs.
Theorem 10. Let $G$ and $H$ be simple undirected graphs with $|V(G)|=n_{1}$, $|E(G)|=m_{1},|V(H)|=n_{2}$ and $|E(H)|=m_{2}$. Then

$$
\begin{aligned}
\operatorname{irr}(G \oplus H) & \leq\left(n_{2}^{3}-4 M_{1}(H)\right) \operatorname{irr}(G)+2\left(n_{2} m_{2}+M_{1}(H)\right) \operatorname{irr}_{t}(G) \\
& +\left(n_{1}^{3}-4 M_{1}(G)\right) \operatorname{irr}(H)+2\left(n_{1} m_{1}+M_{1}(G)\right) \operatorname{irr}_{t}(H) .
\end{aligned}
$$

## 3. Conclusion

In this paper we consider the irregularity of simple undirected graphs, as defined by Albertson [5], under several graph operations. We presented the exact expression for Cartesian product, and sharp upper bounds for join, corona product, direct product and strong product. It is an open problem if the presented upper bounds on the irregularity of lexicographic product, disjunction and symmetric difference are the best possible.

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