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# Exploring the directed *h*-degree in directed weighted networks

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ABSTRACT

Most networks in information science appear as weighted networks, while many of them (e.g. author citation networks, web link networks and knowledge flow networks) are directed networks. Based on the definition of the *h*-degree, the directed *h*-degree is introduced for measuring both weighted networks and directed networks. After analyzing the properties and derived measures of the directed *h*-degree an actual application of LIS journals citation network is worked out.



## 1. Introduction

A network is, in its simplest form, a set of nodes connected by links. Being an essential and desirable method to abstract essential features from connected entities in the real-world, network science has been applied in technological, social, biological and informational systems (Borner, Sanyal, & Vespignani, 2007; Newman, 2010; Watts, 2004). Most networks studied in information science are weighted networks, i.e. the links have values, strengths or weights. The weights of links usually appear as natural numbers, for instance, the number of citations in author citation networks (Ding, 2011a; Ding, Yan, Frazho, & Caverlee, 2009) or journal citation networks (Leydesdorff, 2003), the number of collaborations in collaboration networks (Ding, 2011b), the number of hyperlinks in website link networks (Lang, Gouveia, & Leta, 2010) and the frequency of co-occurrence in co-word networks (Jacobs, 2002). Recently, describing essential features of nodes in a weighted network, we introduced the notion of the *h*-degree (Zhao, Rousseau, & Ye, 2011). We recall that the *h*-degree of a node in a weighted network is *h* if *h* is the largest number such that this node has *h* links and the weight of each link is greater than or equal to *h*. The *h*-degree and its related indicators have interesting features for exploring various networks (Rousseau, 2012; Schubert, 2012; Zhao et al., 2011).

Links in a network may be directed or not (Newman, 2010), leading to directed or undirected networks. In information science, a well-known example of a directed network is the paper citation network (Li & Willett, 2009; Price, 1965; Shibata, Kajikawa, & Matsushima, 2007). Besides, many other networks are also directed, such as author or journal citation networks, website link networks and information diffusion networks. In these networks, the heterogeneity of links is not only reflected by the disparity of the strength, but also registered as the difference of the directions. Moreover, link directions characterize

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**Table 1**
Some cases of networks in information science.

| Types of network | Examples of research (Author/Year/Journal) |
|---|---|
| Paper citation network | Price (1965). Science. |
| Author citation network | Ding (2011a). JASIST.[a] |
| Journal citation network | Leydesdorff (2003). Journal of Documentation. |
| Institution citation network | Yan and Sugimoto (2011). JASIST. |
| Subject citation network | Leydesdorff and Rafols (2009). JASIST. |
| Patent citation network | Chen and Hicks (2004). Scientometrics. |
| Author review network | Zuccala and van den Besselaar (2009). Scientometrics. |
| Paper co-citation network | Egghe and Rousseau (2002). Scientometrics. |
| Author co-citation network | White (2003). JASIST. |
| Bibliographic coupling network | Egghe and Rousseau (2002). Scientometrics. |
| Website link network | Thelwall (2001). Journal of Information Science. |
| Website co-link network | Lang et al. (2010). Scientometrics. |
| Author collaboration network | Kretschmer (2002). Library Trends. |
| Institution collaboration network | Nagpaul (2002). Scientometrics. |
| Patent collaboration network | Inoue, Souma, and Tamada (2010). Journal of Informetrics. |
| Editorial boards network | Malin and Caley (2007). Journal of the American Medical Informatics Association. |
| Co-word network | Jacobs (2002). Journal of Documentation. |
| Human intelligence network | Bao et al. (2003). JCSSTI.[b] |
| P2P network | Asvanund, Clay, Krishnan, and Smith (2004). Information Systems Research. |
| Knowledge flow network | Behrend and Erwee (2009). Journal of Knowledge Management. |

[a] JASIST: Journal of the American Society for Information Science and Technology.
[b] JCSSTI: Journal of the China Society for Scientific and Technical Information.

two kinds of reverse relationships, e.g. cited or citing, and information acquisition or information diffusion. Thus, it might be interesting to extend the notion of $h$-degree to directed networks.

In this work, we introduce the directed $h$-degree and related measures, aiming at quantitatively describing directed weighted networks. After reviewing the conceptual background, we define the directed $h$-degree, and discuss its theoretical features and relevant measures. Then, based on the citation network of international Library Science & Information Science (LIS) journals, the characteristics of the directed $h$-degree are explored empirically.

## 2. Literature review

### 2.1. Networks in information science

Newman (2003, 2010) divides real-world networks into four categories: technological networks, social networks, biological networks and information networks. Information networks, which are closely related to the information science, are characterized by the fact that nodes and links store information.

Price (1965) first proposed the citation network as the classic information network. It has also been recognized as one of the earliest reports of scale-free networks and power-law degree distribution (Newman, 2003, 2010; Shi, 2011; Watts, 2004). However, in the last century, the information sciences have not developed systematic tools for exploring networks in depth. With the widespread impact of network science over the last decade (Barabasi, 2012; Borgatti, Mehra, Brass, & Labianca, 2009), network analysis has attracted a great deal of attention in information science (Borner et al., 2007; Marion et al., 2003; Otte & Rousseau, 2002). Various types of information networks are built in numerous studies. Some of them are listed in Table 1.

It is worth noting that some networks in Table 1 are not only studied in the information sciences, but are also related to other fields. Citation networks as well as scientific collaboration networks can also be considered as social relation networks between researchers. The website link network often refers to information networks and technological networks (computer networks). The human intelligence network, which was first put forward by Bao, Xie, and Shen (2003), is a typical combination of information networks and social networks. Hence, a more explicit classification is needed for theoretical research.

### 2.2. Directed weighted networks

Based on the heterogeneity of links, weights and directions, networks can be divided into four types:

- Undirected unweighted networks
- Undirected weighted networks
- Directed unweighted networks
- Directed weighted networks

Typical information networks in Table 1 can be attributed to the latter three types as shown in Fig. 1, where most networks in information science are weighted networks. Among the 20 kinds of networks in Table 1, only paper citation networks

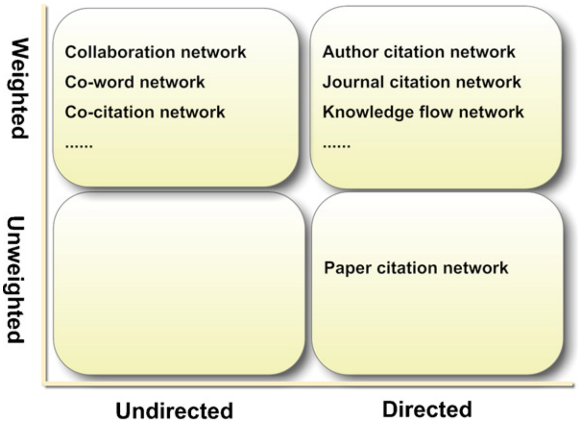


**Fig. 1.** Types of information networks that are divided by the heterogeneity of links.

and patent citation networks generally appear as unweighted networks. In fact, if one considers that paper $p_A$ might cite different parts or contents of another paper $p_B$, and the citations between $p_A$ and $p_B$ should be explicitly counted twice or more, in this context, paper citation networks also occur as weighted networks.

In some systems such as social systems, the weight, e.g. the strength of friendship or emotional interaction, is difficult to quantify accurately. Thus, many traditional tools in network analysis, especially the metrics in social network analysis (Albert & Barabasi, 2002; Newman, 2003, 2010; Scott, 2000), such as the original node degree, the betweenness centrality and closeness centrality, are designed for unweighted networks initially. However, in information science, the numbers of citations, the numbers of collaborations, the amounts of hyperlinks, the frequencies of words' co-occurrence and many other types of weights are well-defined. Consequently, for information networks, especially the weighted ones which frequently occur in information science, developing more appropriate measures becomes a vital and interesting task.

### 2.3. *h*-Degree

An up-to-date finding in measuring information networks is that the *h*-index (Hirsch, 2005), which has become one of the basic indicators in bibliometrics (Egghe, 2010), also reveals interesting features in networks. Schubert, Korn and Telcs (Korn, Schubert, & Telcs, 2009; Schubert, Korn, & Telcs, 2009) first analyzed networks by *h*-type measures, and proposed the lobby index of nodes based on the neighbors of nodes and the *h*-index of complete networks according to the degree of nodes. A recent work shows that, at least in small scale-free networks, the *h*-index of complete network has an empirical nonlinear relation with two traditional quantities, coreness and degree centrality of nodes (Ye, Zhao, & Rousseau, 2011).

Following these interesting ideas, recently, we introduced the *h*-degree, a basic metric for characterizing the nodes in weighted networks (Zhao et al., 2011). Compared with the node degree (so-called node strength in weighted networks), in some circumstances the *h*-degree can give different structural information. An example is shown in Fig. 2.

The *h*-degree can be used in weighted networks for which all link strength are natural numbers. Even if the link strength is not a natural number, it also can be converted to the form of a positive number by a numeric transformation. In a recent work, Schubert (2012) put forward a relevant measure within the framework of *h*-degree, called partnership ability index, which shows considerable potential for characterizing the collaboration ability in informetric as well as sociological studies (Rousseau, 2012).

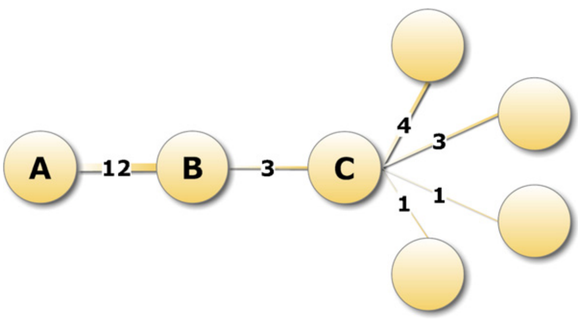


**Fig. 2.** Characterizing the nodes by degree and *h*-degree. *Remark*: In this artificial example, the node degrees of A, B and C are 12, 15 and 12, respectively; while the *h*-degrees of A, B and C are 1, 2 and 3, respectively.

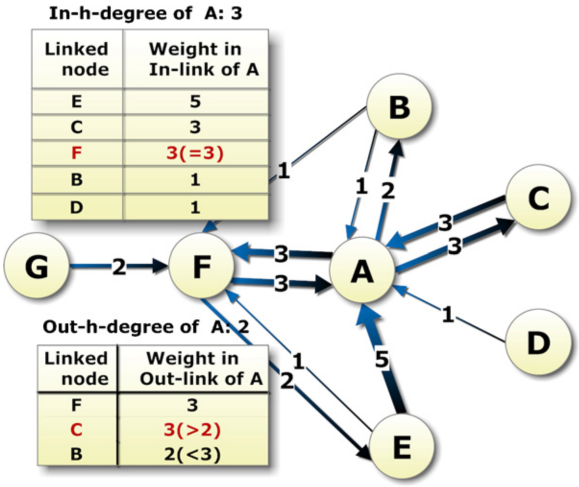


**Fig. 3.** An example for calculating the directed *h*-degree. *Remark*: Descending by strength, the weights of A's In-links are (5, 3, 3, 1, 1), thus the In-degree of A is 5 + 3 + 3 + 1 + 1 = 13 and the In-*h*-degree is 3 (3 In-links' strengths are greater than or equal to 3). Further, the weights of A's Out-links are (3, 3, 2), hence its Out-degree is 3 + 3 + 2 = 8 and its Out-*h*-degree is 2 (2 Out-links' strengths are greater than or equal to 2).

*h*-Degree and related measures have some potential features in network analysis. For example, they are more appropriate for weighted networks than traditional indicators which are suitable for unweighted networks. Moreover, they balance the number of links and the strength of links naturally. They inherit the merits of the *h*-index, in particular, their meanings are clear and they are easy to calculate.

As demonstrated in Fig. 1, some information networks are undirected weighted networks, e.g. collaboration networks and co-word networks, which can be analyzed quantitatively by the *h*-degree. However, many other information networks, such as citation networks and link networks, occur as directed networks. For these directed weighted networks, the original *h*-degree needs to be extended.

## 3. Theoretical aspects

### 3.1. Definition of directed h-degree

From the viewpoints of nodes links in directed networks can be expressed as "in" or "out". For a pair of two linked nodes, when the node is the end of the relationship, this link is the In-link of the node. Conversely, if the node is the starting point of the relationship, this link is the Out-link of the node. Hence the degree of a node can be divided into In-degree and Out-degree (Newman, 2010). Inspired by this partition, we define the directed *h*-degree based on the directions of links, which naturally leads to the In-*h*-degree ($h_I$) and Out-*h*-degree ($h_O$), as follows.

**Definition 1.** In a directed weighted network, the In-*h*-degree ($h_I$) of Node n is equal to $h_{I(n)}$ if $h_{I(n)}$ is the largest natural number such that n has at least $h_{I(n)}$ In-links each with strength at least equal to $h_{I(n)}$.

**Definition 2.** In a directed weighted network, the Out-*h*-degree ($h_O$) of Node n is equal to $h_{O(n)}$ if $h_{O(n)}$ is the largest natural number such that n has at least $h_{O(n)}$ Out-links each with strength at least equal to $h_{O(n)}$.

According to the definitions, the In-*h*-degree and Out-*h*-degree characterize the In-link and Out-link of a node, respectively. A high In-*h*-degree (or Out-*h*-degree) represents that the node not only links many other nodes, but also maintains relatively high strength In-links (or Out-links) with these linked nodes. Such directed *h*-degree can be calculated quickly by ranking In-links and Out-links in a descending order, as shown in Fig. 3.

### 3.2. Properties of the directed h-degree

The study of network science over the last decade shows that the degree of nodes in most real-world networks does not present regular, random or uniform distributions, but emerges as a power-law distribution (Barabasi, 2009; Barabasi & Albert, 1999; Rousseau, 1997). One characteristic of power-law distribution in networks is that most node degrees are low, but only a few nodes have high degrees. This leads to the fact that nodes with high degrees play important roles in organizing networks, and they significantly influence the structure and function of the whole network. Therefore, the measurement of important nodes in networks is a priority in network studies (Boccaletti, Latora, Moreno, Chavez, & Hwang, 2006; Everett, Sinclair, & Dankelmann, 2004; Freeman, 1978).

*h*-Degree can be an indicator for exploring the important nodes on the basis of power-law, by the extraction of nodes' links with high strength. The algorithm of *h*-degree emphasizes that a key node should have two merits at the same time: First, it links a lot of nodes, and organizes a large number of nodes in a network. Second, the links between this node and the other nodes should be strong enough, and then it has the ability to sustain a large part of the network. In a weighted network, the node with the highest *h*-degree usually appears as a hub or authority. The directed *h*-degree naturally inherits this feature. Furthermore, it may reflect two different kinds of importance of a node. For example, in journal citation networks, that one journal shows a high value both in In-*h*-degree and Out-*h*-degree means it not only has an appreciable impact on many other journals, but also integrates a lot of scientific information or knowledge from other journals.

There are some special cases of directed *h*-degree. When the number of In-links (or Out-links) of a node is 0, the In-*h*-degree (or Out-*h*-degree) will be 0. If a node has many In-links (or Out-links) but all their strength is 1, the In-*h*-degree (or Out-*h*-degree) will just be 1. When the number of In-links (or Out-links) of a node is 1, regardless of their links' strength, the In-*h*-degree (or Out-*h*-degree) will always be equal to 1.

In a network with N nodes, $N_{I(n)}$ denotes the numbers of node *n*'s neighbor nodes which maintain In-links with node *n*, $N_{O(n)}$ is the numbers of node *n*'s neighbor nodes which maintain Out-links with node *n*, $d_{I(n)}$ and $d_{O(n)}$ denote the In-degree and Out-degree of node *n* respectively. Then it is easy to check the following inequalities:

$$0 \le h_{I(n)} \le N_{I(n)} < N \tag{1}$$

$$0 \le h_{O(n)} \le N_{O(n)} < N \tag{2}$$

$$d_{I(n)} \ge h_{I(n)}^2 \tag{3}$$

$$d_{O(n)} \ge h_{O(n)}^2 \tag{4}$$

Inequalities (1)–(4) indicate that the In-*h*-degree (or Out-*h*-degree) of a node is limited by the total number of network nodes, the number of adjacent nodes and the square root of In-links' (or Out-links') strength.

### 3.3. Extended measures based on directed *h*-degree

Nodes and links are the most basic units in networks. The directed *h*-degree refers to nodes and relevant links and leads to an underlying measure in directed weighted networks. According to this measure, we introduce a group of measures similar to the framework of the *h*-degree (Zhao et al., 2011), which focuses on abstracting network structures from the micro level (single nodes) to the macro level (the whole network).

As a key notion in a network analysis, centrality characterizes the position of nodes in a network based on structural information. The best known centrality is degree centrality ($C_{d(n)}$), based on node degree ($d_{(n)}$), which is defined as $C_{d(n)} = d_{(n)}/(N-1)$ (Freeman, 1978). Inheriting this definition and the *h*-centrality to the context of directed *h*-degree, we propose the following definitions.

**Definition 3.** In a directed weighted network with *N* nodes ($N > 1$), the In-*h*-centrality ($C_{hI(n)}$) of node n is defined as:

$$C_{hI(n)} = \frac{h_{I(n)}}{N-1} \tag{5}$$

**Definition 4.** In a directed weighted network with *N* nodes ($N > 1$), the Out-*h*-centrality ($C_{hO(n)}$) of node n is defined as:

$$C_{hO(n)} = \frac{h_{O(n)}}{N-1} \tag{6}$$

It is worth noting that In-*h*-centrality (or Out-*h*-centrality) is a normalization of the In-*h*-degree (or Out-*h*-degree). In a network this normalized form does not change the rank of In-*h*-degree (or Out-*h*-degree). Thus they might be used in comparing the nodes coming from different networks or a dynamic network (when *N*, the number of nodes, links or their weights are changing over time). Some properties of these centralities are given as follows.

**Proposition 1.** *In a directed weighted network with N nodes ($N > 1$), for a non-isolated node n, the following inequalities always hold*:

$$0 \le C_{hI(n)} \le \frac{N_{I(n)}}{N-1} \le 1 \tag{7}$$

$$0 \le C_{hO(n)} \le \frac{N_{O(n)}}{N-1} < 1 \tag{8}$$

**Proof.** By inequalities (1) and (2), we have $0 \le h_{I(n)}/(N-1) \le N_{I(n)}/(N-1) \le 1$ and $0 \le h_{O(n)}/(N-1) \le N_{O(n)}/(N-1) \le 1$. Because $h_{I(n)}/(N-1) = C_{hI(n)}$ and $h_{O(n)}/(N-1) = C_{hO(n)}$, inequality (7) and (8) follow immediately.□

**Proposition 2.** *In a directed weighted network with N nodes ($N > 1$), for a non-isolated node n, the following inequalities always hold*:

$$C_{hI(n)} \le \frac{\sqrt{C_{I(n)}}}{N-1} \tag{9}$$

$$C_{hO(n)} \leq \frac{\sqrt{C_{O(n)}}}{N-1} \quad (10)$$

*where the $C_{I(n)}$ and $C_{O(n)}$ denote the in-degree centrality and out-degree centrality, respectively.*

**Proof.** By inequalities (3) and (4), we have $(h_{I(n)}/[N-1])^2 \leq d_{I(n)}/(N-1)^2$ and $(h_{O(n)}/[N-1])^2 \leq d_{O(n)}/(N-1)^2$. Thus these inequalities hold immediately from the Definitions 3 and 4.□

Propositions 1 and 2 suggest the range of value for In-*h*-centrality and Out-*h*-centrality. In a network of a large size, the numeric difference between degree and *h*-degree might be enormous.

The most significant differences of the directed *h*-degree and the original one is that the former represents the directions of links. This leads to a way to compare the heterogeneity of nodes by the links' difference of directions. The metric, called *h*-difference ($h_{dif}$), is defined as follows.

**Definition 5.** In a directed weighted network with *N* nodes ($N > 1$), the *h*-difference ($h_{dif(n)}$) of node n is defined as:

$$h_{dif(n)} = h_{I(n)} - h_{O(n)} \quad (11)$$

*h*-Difference expresses the discrepancy of links' directions based on the directed *h*-degree. We observe that the *h*-difference can take positive as well as negative values. It might have potential to extract some important and implicit structural information in networks. For example, in many information networks *h*-difference characterizes the difference between information input and output of a node. This measure also has a relation with in-*h*-centrality and out-*h*-centrality, as follows.

**Proposition 3.** *In a directed weighted network with N nodes ($N > 1$), for a non-isolated node n, the following equation always holds*:

$$h_{dif(n)} = (N-1)(C_{hI(n)} - C_{hO(n)}) \quad (12)$$

**Proof.** By Definition 5 we know that $h_{dif(n)} = (N-1)(h_{I(n)}/[N-1] - h_{O(n)}/[N-1])$. According to Definition 3, it leads to Eq. (12).□

We used the *h*-centralization for characterizing whole networks (Zhao et al., 2011). Adopting a similar approach, the In-*h*-centralization ($N_{hI}$) and Out-*h*-centralization of networks ($N_{hO}$) are proposed as follows.

**Definition 6.** In a directed weighted network with *N* nodes ($N > 1$), the In-*h*-centralization ($N_{hI(G)}$) of this network is defined as:

$$N_{hI(G)} = \frac{\sum_{n=1}^{N}[MAX_{I(G)} - h_{I(n)}]}{(N-1)^2} \quad (13)$$

**Definition 7.** In a directed weighted network *G* with *N* nodes ($N > 1$), the Out-*h*-centralization ($NC_{hO(G)}$) of this network is defined as:

$$N_{hO(G)} = \frac{\sum_{n=1}^{N}[MAX_{O(G)} - h_{O(n)}]}{(N-1)^2} \quad (14)$$

where $MAX_{I(G)}$ and $MAX_{O(G)}$ respectively denote the maximum values of $h_{I(n)}$ and $h_{O(n)}$ in the network *G*.

As measures for how central its most high *h*-degree node is by comparing with all the other nodes, In-*h*-centralization and Out-*h*-centralization provide insight into the distribution of (In- and Out-) weight in a complete, directed network. A high In-*h*-centralization (or Out-*h*-centralization) implies that this network contains one or a few very central nodes with high In-*h*-degree (or Out-*h*-degree). This also means if these central nodes become ineffective, the whole network will be damaged noticeably. Conversely, networks of low In-*h*-centralization (or Out-*h*-centralization) ought to rely less on the high In-*h*-degree (or Out-*h*-degree) nodes. In-*h*-centralization and Out-*h*-centralization focus on different or inverse relations in a network, thus we suggest the *h*-difference for the whole network, as follows.

**Definition 8.** In a directed weighted network *G* with *N* nodes ($N > 1$), the *h*-difference ($Nh_{dif(G)}$) of this whole network is defined as:

$$Nh_{dif(G)} = N_{hI(G)} - N_{hO(G)} \quad (15)$$

The *h*-difference of networks can also be computed by Proposition 4.

**Proposition 4.** *In a directed weighted network G with N nodes ($N > 1$), the mathematic relationship between h-difference ($Nh_{dif(G)}$) of the whole network and the h-difference ($h_{dif(n)}$) of nodes is*:

$$Nh_{dif(G)} = \frac{N \cdot [MAX_{I(G)} - MAX_{O(G)}] - \sum_{n=1}^{N} h_{dif(n)}}{N^2 - 2N + 1} \quad (16)$$

**Table 2**
The parameter set of directed *h*-degree of main LIS journals whose In-*h*-degree is greater than 5.

| LIS journals | $h_I$ | $h_O$ | $C_{hI}$ | $C_{hO}$ | $h_S$ |
|---|---|---|---|---|---|
| J AM SOC INF SCI TEC | 19 | 20 | 0.422 | 0.444 | −1 |
| J DOC | 16 | 14 | 0.356 | 0.311 | 2 |
| J ACAD LIBR | 15 | 13 | 0.333 | 0.289 | 2 |
| LIBR INFORM SCI RES | 14 | 14 | 0.311 | 0.311 | 0 |
| MIS QUART | 14 | 8 | 0.311 | 0.178 | 6 |
| COLL RES LIBR | 13 | 10 | 0.289 | 0.222 | 3 |
| INFORM MANAGE-AMSTER | 12 | 8 | 0.267 | 0.178 | 4 |
| INFORM PROCESS MANAG | 12 | 10 | 0.267 | 0.222 | 2 |
| INFORM SYST RES | 12 | 7 | 0.267 | 0.156 | 5 |
| J INFORM SCI | 12 | 14 | 0.267 | 0.311 | −2 |
| LIBR TRENDS | 12 | 10 | 0.267 | 0.222 | 2 |
| ASLIB PROC | 11 | 11 | 0.244 | 0.244 | 0 |
| J MANAGE INFORM SYST | 11 | 7 | 0.244 | 0.156 | 4 |
| ONLINE INFORM REV | 10 | 13 | 0.222 | 0.289 | −3 |
| INFORM SOC | 9 | 8 | 0.200 | 0.178 | 1 |
| INFORM TECHNOL LIBR | 9 | 7 | 0.200 | 0.156 | 2 |
| J INFORM TECHNOL | 9 | 9 | 0.200 | 0.200 | 0 |
| LIBR QUART | 9 | 9 | 0.200 | 0.200 | 0 |
| LIBRI | 9 | 10 | 0.200 | 0.222 | −1 |
| SCIENTOMETRICS | 9 | 13 | 0.200 | 0.289 | −4 |
| ELECTRON LIBR | 8 | 12 | 0.178 | 0.267 | −4 |
| INFORM SYST J | 8 | 8 | 0.178 | 0.178 | 0 |
| INT J INFORM MANAGE | 8 | 10 | 0.178 | 0.222 | −2 |
| J LIBR INF SCI | 8 | 9 | 0.178 | 0.200 | −1 |
| GOV INFORM Q | 7 | 12 | 0.156 | 0.267 | −5 |
| LIBR COLLECT ACQUIS | 7 | 8 | 0.156 | 0.178 | −1 |
| LIBR RESOUR TECH SER | 7 | 8 | 0.156 | 0.178 | −1 |
| PROGRAM-ELECTRON LIB | 7 | 9 | 0.156 | 0.200 | −2 |
| REF USER SERV Q | 7 | 8 | 0.156 | 0.178 | −1 |
| CAN J INFORM LIB SCI | 6 | 9 | 0.133 | 0.200 | −3 |
| ONLINE | 6 | 2 | 0.133 | 0.044 | 4 |

*Note*: Journals ranked in a descending order by In-*h*-degree. The full journal titles are shown in Appendix A. $h_I$: In-*h*-degree; $h_O$: Out-*h*-degree; $C_{hI}$: In-*h*-centrality; $C_{hO}$: Out-*h*-centrality; $h_S$: *h*-difference of nods.

**Proof.** By Definitions 6–8 we have

$$Nh_{dif(G)} = \left\{ \frac{\sum_{n=1}^{N}[MAX_{I(G)} - h_{I(n)}]}{(N-1)^2} \right\} - \left\{ \frac{\sum_{n=1}^{N}[MAX_{O(G)} - h_{O(n)}]}{(N-1)^2} \right\}$$
$$= \frac{N \cdot [MAX_{I(G)} - MAX_{O(G)}] - \sum_{n=1}^{N}[h_{I(n)} - h_{O(n)}]}{N^2 - 2N + 1} \tag{17}$$

As $h_{dif(n)} = h_{I(n)} - h_{O(n)}$, Eq. (16) follows immediately.□

Similar to the *h*-difference of nodes, the *h*-difference of network aims to compare the distribution of weight in different or inverse directions. If the value of *h*-difference is much larger than 1, it suggests that there might be an interesting difference between the node(s) with high In-*h*-degree and the node(s) which has high Out-*h*-degree.

In applications, the directed *h*-centrality, *h*-centralization and *h*-difference have been normalized by the size of network nodes, and thus they are available for comparing analogous networks with different scales or dynamic networks in different periods. In the next section, we give a case study of directed *h*-degree and its extended measures.

## 4. Empirical study

### 4.1. Dataset

To explore the empirical nature of the above-mentioned metrics in a directed weighted network, we collected the publications and citations of international journals in Information Science & Library Science (LIS) published from 2001 to 2010 in the *Web of Science* (*WoS*). By extracting the citations between each journal, a typical directed weighted network, the journal citation network, was constructed. The process is as follows.

First, based on the journals included in Journal Citation Reports (JCR) Social Sciences Edition 2001, we excluded discontinued journals and the journals with incomplete data during 2001–2010. Since the journal "*Library Journal*" had published 51 051 book reviews during this period, the function "Citation Report" in the WoS is not available for this journal. Thus we remove this journal. Then the remaining 46 journals are regarded as the available samples (see Appendix A).

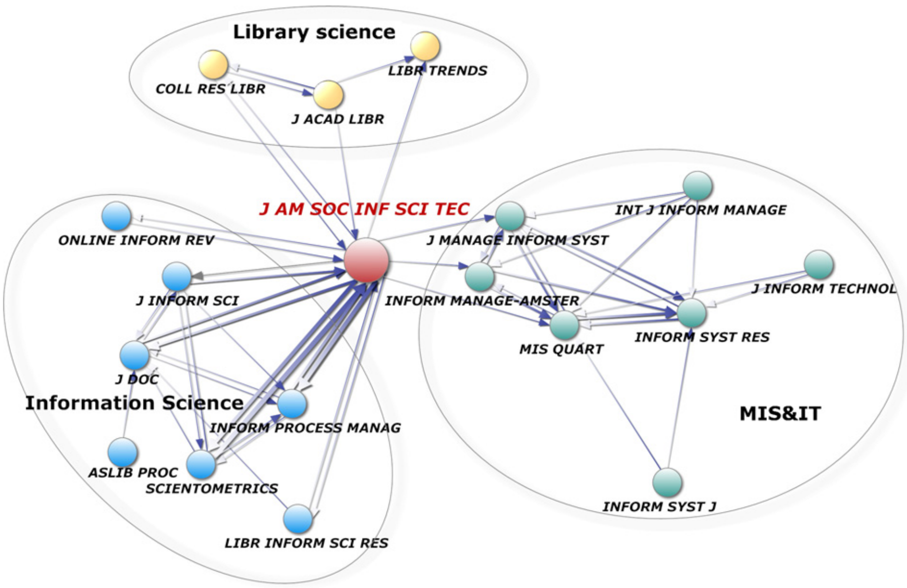


**Fig. 4.** The main structure of LIS journal citation network. *Remark*: The figure includes the links whose strength (citations) is at least 50 and the nodes linked by them. This result shows that the LIS journal citation network is roughly divided into three groups, library science-based, information science-based and information system-based. *J AM SOC INF SCI TEC* is the key node in the junction of the three groups. It connects most of the important journals in LIS, and maintains strong relationships with many other nodes (thus it has high *h*-degree). Consequently, the central position of this journal in LIS is remarkable.

Second, we retrieve the sets of papers published by each journal during the period 2001–2010 in the *WoS* and abstract citation records of each journal. According to this data, the citation matrix of 46 journals is constructed.

Next, we convert this matrix to a journal citation network, and calculate directed *h*-degree, directed *h*-centrality and *h*-difference of each node in the network. On this basis, the directed *h*-centralization and *h*-difference of the whole network are computed.

### 4.2. Results and discussion

We start by discussing the metrics of the whole network. In this LIS journal citation network, the In-*h*-centralization ($N_{hI}$) is equal to 0.251 and the Out-*h*-centralization ($N_{hO}$) is 0.270. As a result, the *h*-difference ($Nh_{dif} = -0.019$) is less than 0. It indicates that in the sample network, the centralization of In-links' weight is slightly less than that of Out-links' weight generally. It is partly because that the maximum values of In-*h*-degree ($MAX_I = 19$) and Out-*h*-degree ($MAX_O = 20$) reveal a small difference. More details of nodes' measures are presented in Table 2.

From the perspective of network analysis the directed *h*-degree tends to give a relatively accurate result which reflects the actual status of key node. In the past several decades, the impact factor (IF) has been the most known and widely used indicator in the global journal evaluation. Despite *J AM SOC INF SCI TEC* is considered one of the leading journals in LIS and was ranked first by peer-review (Nisonger & Davis, 2005), it was only ranked the 13th, 12th, 7th, 11th and 10th by IF in the latest 5 versions of Journal Citation Reports (2007–2011). However, the directed *h*-degree yields a very different result. This journal is ranked the first in both In-*h*-degree, which represents the breadth and strength of academic impact, and Out-*h*-degree, which expresses the extent and intensity of the information integration. These results explicitly suggest that *J AM SOC INF SCI TEC* has been a central node in LIS in the last decade. Also, the network visualization in Fig. 4 tells a consistent story.

The Wilcoxon's signed rank test of the data in present work also shows a consistent result with the previous data of co-citation network (Zhao et al., 2011): the *h*-degree and degree of nodes are (statistically) significantly different as shown in Table 3.

In journal citation networks, In-*h*-degree reflects the academic impact of the node. Hence, it demonstrates certain significance for evaluation. The high In-*h*-degree indicates that the node has a wide and strong impact at least on local networks.

**Table 3**
Wilcoxon signed ranks test of node degree (so-called node strength in weighted networks) and *h*-degree in the LIS journal network.

| Item | In-*h*-degree vs. In-degree | Out-*h*-degree vs. Out-degree |
|---|---|---|
| *Z* | −5.582 | −5.683 |
| Statistical significance (2-sided test) | 0.000 | 0.000 |

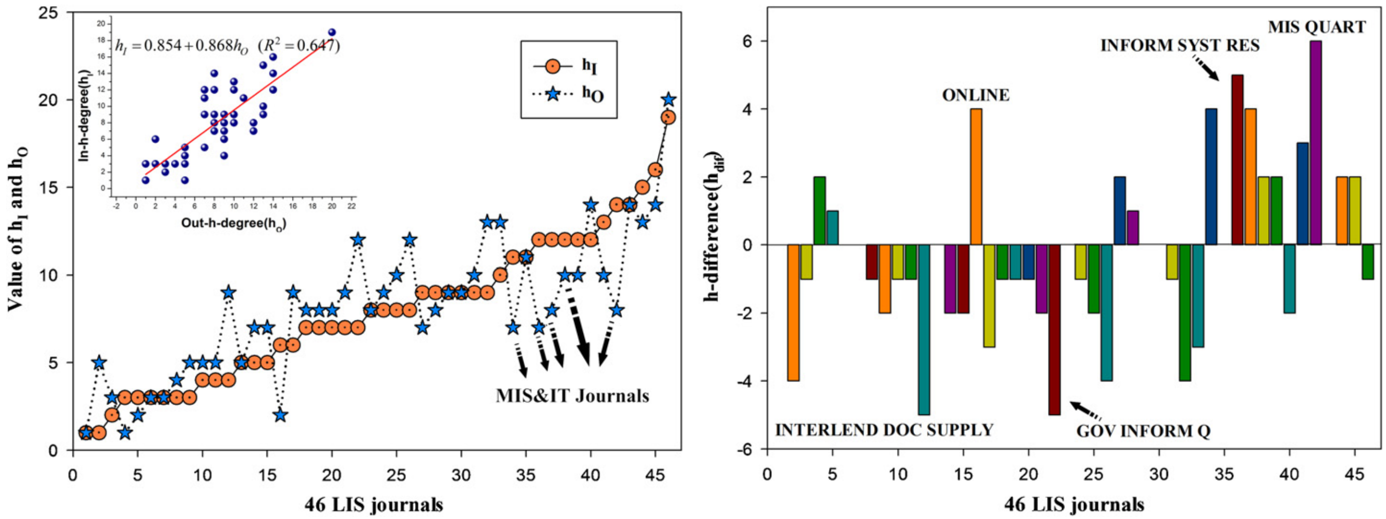


**Fig. 5.** *h*-Difference ($h_{dif}$) of nodes in LIS journal citation network. *Remark*: In these two figures, journals are ranked from left to right in an ascending order by In-*h*-degree. There are 14 nodes (30.4%) whose $h_{dif}$ are larger than 0, 9 nodes (19.6%) whose $h_{dif}$ are equal to 0 and 23 nodes (50.0%) whose $h_{dif}$ are less than 0.

Different from In-*h*-degree, Out-*h*-degree mainly characterizes the status that the node absorbs information from other nodes. Our previous analysis of paper co-citation networks shows that the *h*-degree of nodes in that network ranges only from 1 to 10. Thus we consider that *h*-degree may inherit a limitation of *h*-index: the discrimination is rather weak. However, in this article, the In-*h*-degree of sample nodes is from 1 to 19, while the Out-*h*-degree is from 1 to 20. This suggests that when the *h*-degree is used for the networks whose link strengths are relatively high, such as journal citation networks, discrimination may increase.

Another key feature of the directed *h*-degree, which is very different from the original *h*-degree, is that it provides a way to compare the asymmetry of links' strength in diverse directions. One can observe the difference of nodes by a view of the distinction of In-*h*-degree and Out-*h*-degree, i.e. the *h*-difference. As displayed in Fig. 5, the two kinds of directed *h*-degree in the LIS journal citation network show a simultaneous growth trend, but the significance of correlation between them is not very strong ($R^2 = 0.647$). It reveals that In-*h*-degree and Out-*h*-degree have a certain mutual independence, and the *h*-difference expresses the measurable meaning of a single node.

One reason leading to a high value of *h*-difference in the LIS journal citation network may be the scope and extent of a journal. For example, some interdisciplinary journals, such as the journal *ONLINE* and some journals referring to management information system (MIS) or information technology (IT) (e.g. *MIS QUART* and *INFORM SYST RES*), have high values in *h*-difference, i.e. In-*h*-degree is larger than Out-*h*-degree. It indicates that, comparing with the breadth and strength of their citations pointing to other journals in LIS, these journals are cited by other journals more frequently. The maximum *h*-difference occurs with *MIS QUART* ($h_{dif} = 6$), which is an important journal in management science and computer science as well. On the contrary, the scope and extent of research involved in *INTERLEND DOC SUPPLY* and *GOV INFORM Q* appear to be relatively narrow, thus their *h*-difference appears less than 0, i.e. the cited extent and strength are lower than citing extent and strength. In the journal citation network, they mainly absorb information or knowledge from other journals and research fields. However, for various networks, the meaning of *h*-difference ought to be different. For instance, in website link networks, *h*-difference may largely depend on the size and standing of websites. In personal email networks, it could reflect the difference of individual roles.

We conclude by discussing some features of the directed *h*-degree. First, as a supplement and popularization of *h*-degree, it spontaneously inherits the characteristics of *h*-degree as combining numbers and strengths of links, being appropriate for measuring weighted networks, meeting the feature of power-law in networks better, and being easy to compute. The *h*-degree and the directed *h*-degree can be applied, respectively to weighted networks with undirected links (such as the networks based on the relationship of 'Co-occurrence' (Leydesdorff & Vaughan, 2006; Vanrijsbergen, 1977)) and weighted networks with directed links (such as citation networks, website link networks and knowledge flow networks). Consequently, based on the frameworks of *h*-degree and directed *h*-degree, we provide a comprehensive tool which has potential in most information networks (see Table 1 and Fig. 1). The directed *h*-degree may also have potential applications in other directed weighted networks involving many disciplines from social sciences to natural sciences, such as social networks, technology networks and biological networks.

However, as there is no "perfect" single measure, the directed *h*-degree also has limitations. Hence, various *h*-type indices can be used as helpful modifications of the directed *h*-degree. In some applications, the strength of links in a weighted network may not be assigned by a natural number, thus this metric needs a numerical transformation. Centrality of nodes sometimes appears in several possible forms, e.g. the central node of the whole network, the central node in a sub-network and as a "bridge" node. A particular node can even play multiple roles at the same time. The directed *h*-degree is not appropriate for detecting the node which has only a few neighboring nodes and is a bridge node between two large node groups. Therefore, similar to other network measures, the directed *h*-degree is just one view for abstracting the structure of nodes and networks. Discovering more quantities which extract networks from diverse aspects is significant in further studies.

## 5. Conclusion

In this work, we introduced a measure set, based on the notion of directed *h*-degree, to abstract the structure information in directed weighted networks. These measures divide *h*-degree into In-*h*-degree and Out-*h*-degree by different directions of links, and provide a potential way to measure the characteristics of both nodes and the whole network in directed weighted networks. The case of the LIS journal citation network shows that directed *h*-degree reflects the real influence of key nodes such as *J AM SOC INF SCI TEC* in the sample network. Furthermore, a new metric beyond the original *h*-degree, named the *h*-difference, could present a potential perspective which reflects the difference of nodes by the different or inverse directions of their links.

Deconstructing entities and their relations in information science by networks is expected to be a powerful method to understand the complex phenomenon of information more clearly and deeply. We believe that the network analysis method will provide a valuable opportunity to improve information science research from exploring the surface information to extracting the deep structure and relationship. As the basis of this methodology, the measurement of information networks is and will continue to be an interesting and challenging work in the information science and related fields.

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## Appendix A. Journals in Information Science & Library Science used in this study

| No. | Journal abbreviation | Journal title |
|---|---|---|
| 1 | *ASLIB PROC* | *ASLIB PROCEEDINGS* |
| 2 | *CAN J INFORM LIB SCI* | *CANADIAN JOURNAL OF INFORMATION AND LIBRARY SCIENCE-REVUE CANADIENNE DES SCIENCES DE L INFORMATION ET DE BIBLIOTHECONOMIE* |
| 3 | *COLL RES LIBR* | *COLLEGE & RESEARCH LIBRARIES* |
| 4 | *ECONTENT* | *ECONTENT* |
| 5 | *ELECTRON LIBR* | *ELECTRONIC LIBRARY* |
| 6 | *GOV INFORM Q* | *GOVERNMENT INFORMATION QUARTERLY* |
| 7 | *INFORM MANAGE-AMSTER* | *INFORMATION & MANAGEMENT* |
| 8 | *INFORM PROCESS MANAG* | *INFORMATION PROCESSING & MANAGEMENT* |
| 9 | *INFORM SOC* | *INFORMATION SOCIETY* |
| 10 | *INFORM SYST J* | *INFORMATION SYSTEMS JOURNAL* |
| 11 | *INFORM SYST RES* | *INFORMATION SYSTEMS RESEARCH* |
| 12 | *INFORM TECHNOL LIBR* | *INFORMATION TECHNOLOGY AND LIBRARIES* |
| 13 | *INT J GEOGR INF SCI* | *INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE* |
| 14 | *INT J INFORM MANAGE* | *INTERNATIONAL JOURNAL OF INFORMATION MANAGEMENT* |
| 15 | *INTERLEND DOC SUPPLY* | *INTERLENDING & DOCUMENT SUPPLY* |
| 16 | *J ACAD LIBR* | *JOURNAL OF ACADEMIC LIBRARIANSHIP* |
| 17 | *J AM MED INFORM ASSN* | *JOURNAL OF THE AMERICAN MEDICAL INFORMATICS ASSOCIATION* |
| 18 | *J AM SOC INF SCI TEC* | *JOURNAL OF THE AMERICAN SOCIETY FOR INFORMATION SCIENCE AND TECHNOLOGY* |
| 19 | *J DOC* | *JOURNAL OF DOCUMENTATION* |
| 20 | *J HEALTH COMMUN* | *JOURNAL OF HEALTH COMMUNICATION* |
| 21 | *J INFORM SCI* | *JOURNAL OF INFORMATION SCIENCE* |
| 22 | *J INFORM TECHNOL* | *JOURNAL OF INFORMATION TECHNOLOGY* |
| 23 | *J LIBR INF SCI* | *JOURNAL OF LIBRARIANSHIP AND INFORMATION SCIENCE* |
| 24 | *J MANAGE INFORM SYST* | *JOURNAL OF MANAGEMENT INFORMATION SYSTEMS* |
| 25 | *J SCHOLARLY PUBL* | *JOURNAL OF SCHOLARLY PUBLISHING* |
| 26 | *KNOWL ORGAN* | *KNOWLEDGE ORGANIZATION* |
| 27 | *LAW LIBR J* | *LAW LIBRARY JOURNAL* |
| 28 | *LIBR COLLECT ACQUIS* | *LIBRARY COLLECTIONS ACQUISITIONS & TECHNICAL SERVICES* |
| 29 | *LIBR INFORM SCI* | *LIBRARY AND INFORMATION SCIENCE* |
| 30 | *LIBR INFORM SCI RES* | *LIBRARY & INFORMATION SCIENCE RESEARCH* |
| 31 | *LIBR QUART* | *LIBRARY QUARTERLY* |
| 32 | *LIBR RESOUR TECH SER* | *LIBRARY RESOURCES & TECHNICAL SERVICES* |
| 33 | *LIBR TRENDS* | *LIBRARY TRENDS* |
| 34 | *LIBRI* | *LIBRI* |
| 35 | *MIS QUART* | *MIS QUARTERLY* |
| 36 | *ONLINE* | *ONLINE* |
| 37 | *ONLINE INFORM REV* | *ONLINE INFORMATION REVIEW* |
| 38 | *PROGRAM-ELECTRON LIB* | *PROGRAM-ELECTRONIC LIBRARY AND INFORMATION SYSTEMS* |
| 39 | *REF USER SERV Q* | *REFERENCE & USER SERVICES QUARTERLY* |
| 40 | *RESTAURATOR* | *RESTAURATOR-INTERNATIONAL JOURNAL FOR THE PRESERVATION OF LIBRARY AND ARCHIVAL MATERIAL* |
| 41 | *SCIENTIST* | *SCIENTIST* |
| 42 | *SCIENTOMETRICS* | *SCIENTOMETRICS* |
| 43 | *SOC SCI COMPUT REV* | *SOCIAL SCIENCE COMPUTER REVIEW* |
| 44 | *SOC SCI INFORM* | *SOCIAL SCIENCE INFORMATION SUR LES SCIENCES SOCIALES* |
| 45 | *TELECOMMUN POLICY* | *TELECOMMUNICATIONS POLICY* |
| 46 | *Z BIBL BIBL* | *ZEITSCHRIFT FUR BIBLIOTHEKSWESEN UND BIBLIOGRAPHIE* |

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