Authority Centrality and *Hub Centrality* as metrics of systemic importance of financial market infrastructures

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Authority Centrality and *Hub Centrality* as metrics of systemic importance of financial market infrastructures[1]

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Network analysis has been applied to identify systemically important financial institutions after the 2008 financial crisis. Such applications have stressed the importance of *centrality* within the too-connected-to-fail concept.

Yet, despite their well-known importance for financial stability, financial market infrastructures' *centrality* has not been equally covered by literature. Some particularities of strictly hierarchical (i.e. directed and acyclic) networks may explain the inconvenience arising from using basic metrics of *centrality*, and may explain why assessing *centrality* has been limited to financial institutions' case.

This paper addresses the assessment of systemic importance for Colombian financial infrastructures by means of the estimation of *authority centrality* and *hub centrality*. Their particular advantage consists of assessing importance as the mutually reinforcing *centrality* arising from nodes pointing to other nodes (i.e. *hubs*) and from nodes being pointed-to by other nodes (i.e. *authorities*), even in the case of directed and acyclic networks.

Results are valuable since they quantitatively support financial authorities' efforts to (i) identify systemically important financial infrastructures under the too-connected-to-fail concept; (ii) focus the intensity of oversight, supervision and regulation where the infrastructure-related systemic impact is the greatest; and (iii) enhance their policy and decision-making capabilities.

Keywords: financial market infrastructures, systemic risk, authority, hub, centrality, HITS algorithm, too-connected-to-fail.

JEL classification: D85, E42, G2.

[1] The opinions and statements are the sole responsibility of the authors and do not necessarily represent neither those of Banco de la República nor of its Board of Directors. Results are illustrative; they may not be used to infer credit quality or to make any type of assessment for any financial infrastructure. The authors are indebted to Clara Machado for the discussions that supported the model's design and the document's final version. Comments and suggestions from Joaquín Bernal, Freddy Cepeda and Fabio Ortega are acknowledged and appreciated. As usual, any remaining errors are the authors' own.

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Contents

Abbreviations

ACH	Automated Clearing House
BIS	Bank for International Settlements
BVC	Colombian Stock Exchange (Bolsa de Valores de Colombia)
BR	Central Bank of Colombia (Banco de la República)
CCDC	Colombian Currency Clearing House (Cámara de Compensación de Divisas de Colombia)
CCH	Colombia's Cheques Clearing House
CCP	Central Counterparty
CRCC	Central Counterparty of Colombia (Cámara de Riesgo Central de Contraparte de Colombia)
CSD	Central Securities Depository
CSS	Currencies Settlement System
CUD	Colombia's Large-Value Payment System (Cuentas de Depósito)
DAG	Directed Acyclic Graph
DCV	Central Securities Depository for sovereign securities (Depósito Central de Valores)
DECEVAL	Central Securities Depository for corporate and government (non-sovereign) securities (Depósito Centralizado de Valores de Colombia)
DERIVEX	Energy futures trading platform
DSR	Deceval/Registration Systems (Deceval/Sistema de Registro)
FMI	Financial Market Infrastructure
HITS	Hypertext Induced Topic Search
IDBROK	Inter-Dealer Brokerage Firms
IMF	International Monetary Fund
LVPS	Large-Value Payment System
MEC	Colombian Electronic Market (Mercado Electrónico Colombiano)
RTGS	Real-Time Gross Settlement System
RPS	Retail Payment Systems
SEN	Electronic Trading System (Sistema Electrónico de Negociación)
SIFI	Systemically Important Financial Institution
SIFMI	Systemically Important Financial Market Infrastructure
SSS	Securities Settlement System[4]
SET-FX	Electronic Foreign Exchange Trading and Registration Platform
TP	Trading and Registration Platform

[4] Following CPSS (2003) definitions, please note that a security settlement system (SSS) is a "system used to facilitate the settlement of transfers of funds or financial instruments". Hence, a SSS may (not) provide the services of a settlement institution, which is defined as "the institution across whose books transfers between participants take place in order to achieve settlement within a settlement system".

1. Introduction

One of the main lessons of the recent financial crisis is the importance of systemic risk. Moreover, as documented by León and Machado (2011), those lessons have pinpointed the convenience of financial authorities shifting their approaches to systemic risk from estimating frequencies or probabilities to assessing impacts or severities. This has resulted in the urge to identify so-called Systemically Important Financial Institutions (SIFIs) [5].

Identifying SIFIs is a complex task. For instance, the International Monetary Fund (IMF), the Bank for International Settlements (BIS) and the Financial Stability Board (FSB) developed a set of guidelines and recommendations on how national authorities can assess the systemic importance of financial institutions, markets or instruments (IMF et al., 2009), where three main criteria (i.e. size, connectedness and substitutability) should serve as the mainstay of any methodological approach to SIFIs.

Hence, as in IMF et al. (2009) and Manning et al. (2009), SIFIs share a distinctive feature: due to their size, degree of substitutability or interconnectedness, any failure or impairment (e.g. bankruptcy) could trigger greater disruptions in the financial system and economic activity.

Consequently, some methodological efforts for assessing and identifying SIFIs have recently emerged; for instance, the BIS (2011) proposed a Global-SIFIs framework based on accounting figures for size, connectedness and substitutability.[6] In the Colombian case several studies have also addressed the systemic importance issue, but with a mix of data from financial institutions' balance sheet and financial markets infrastructures statistics, where the latter data source has encouraged the application of methodologies such as network analysis and intraday payments simulation models for assessing connectedness and substitutability; this is the case of Cepeda (2008), Machado et al. (2011), León and Machado (2011), León et al. (2011), León et al. (2012) and León and Murcia (2012).

It is rather evident from the recent financial crisis that methods able to effectively aid financial authorities to identify SIFIs are particularly valuable to enhance their policy-making (e.g. prudential regulation, oversight and supervision) and decision-making (e.g. resolving, restructuring or providing emergency liquidity) capabilities. Despite a proper understanding of financial institutions' linkages is vital for the corresponding authorities, there is a source of financial connectedness not equally addressed by systemic risk literature: the Financial Market Infrastructures (FMIs).

A FMI is a multilateral system among participating institutions used for the purposes of executing, exchanging, clearing, settling or recording payments, securities, derivatives, or other

[5] For this document the authors embrace the term "financial institution" as comprising depository institutions, broker-dealers, investment companies (e.g. mutual funds), insurance companies and credit unions.
[6] BIS (2011) also includes cross-jurisdictional activity and complexity as relevant criteria.

financial transactions.[7] Or, as defined by Bernanke (2009), FMIs may be regarded as the “financial plumbing” that allows for interactions among financial institutions by supporting trading, payments, clearing and settlement.

In this sense, following Berndsen (2011) and DNB (2011), there is an infrastructure-related systemic risk: the component of systemic risk that can be brought about by the improper functioning of financial infrastructure, or where financial infrastructure acts as the conduit for shocks that have arisen elsewhere.

The financial crisis demonstrated the importance of FMIs. Dudley (2012) highlights that FMIs were a source of strength during the crisis because they enabled market participants to settle obligations in a timely manner, whereas FMIs’ robustness gave confidence to market participants that they could continue to trade, knowing that the transactions would almost certainly be settled and cleared without difficulty. Likewise, CPSS-IOSCO (2012) emphasizes that FMIs play a critical role in the financial system and the broader economy, where safe and efficient FMIs contribute to maintaining and promoting financial stability and economic growth, but where improperly managed FMIs can become sources of financial shocks, or a major channel through which these shocks are transmitted across domestic and international financial markets.

Thus, concurrent with contemporary emphasis on the identification of SIFIs, acknowledging the existence of infrastructure-related systemic risk urges for the identification of systemically important financial market infrastructures (SIFMIs). Regulatory efforts to design a proper framework for SIFMIs by multilateral agencies (e.g. CPSS-IOSCO) and local establishments (e.g. the U.S. Congress by means of the Dodd Frank Act) provide clear evidence of the novel relevance of both FMIs and SIFMIs for the safe and efficient functioning of financial markets.

In this context, this paper aims at extending the use of network analysis from the identification of SIFIs to the identification of SIFMIs, where the latter will be broadly defined as those providing trading, payments, clearing and settlement services to financial institutions, whose failure or impairment could trigger greater disruptions in the financial system and economic activity due to their *centrality*.

Despite it is tempting to use standard metrics for *centrality* (e.g. *degree* or *eigenvector*), some particularities of FMIs’ networks render these metrics inconvenient or useless to identify SIFMIs under the *too-connected-to-fail* criteria. The main particularity of FMIs’ networks is their strictly

[7] This is a definition similar to the one proposed by CPSS-IOSCO (2012). However, please note that CPSS-IOSCO (2012) limits the application of the Principles for Financial Markets Infrastructures to a narrow definition of FMIs (i.e. multilateral systems among participating institutions used for the purposes of clearing, settling, or recording payments, securities, derivatives, or other financial transactions). However, CPSS-IOSCO (2012) recognizes that other market infrastructures exist (e.g. trading exchanges, trade execution facilities), and that broadening the definition of FMIs for the application of the aforementioned Principles is to be decided by the relevant financial authorities; thus the authors’ choice is a rather wide definition of a FMI.

hierarchical pattern, which results in a precise type of network to work with: a directed acyclic network.

In order to tackle the particularities resulting from this type of network, this paper addresses the assessment of systemic importance for FMIs by means of the estimation of *authority centrality* and *hub centrality*. These two metrics, first proposed by Kleinberg (1998) for *information retrieval* purposes, are suitable for FMIs' networks since they (i) are designed for directed networks, even in the case of directed and acyclic networks, and (ii) are capable of simultaneously measuring mutually reinforcing *centrality* arising from nodes pointing to other nodes (i.e. *hubs*) and from nodes being pointed-to by other nodes (i.e. *authorities*).

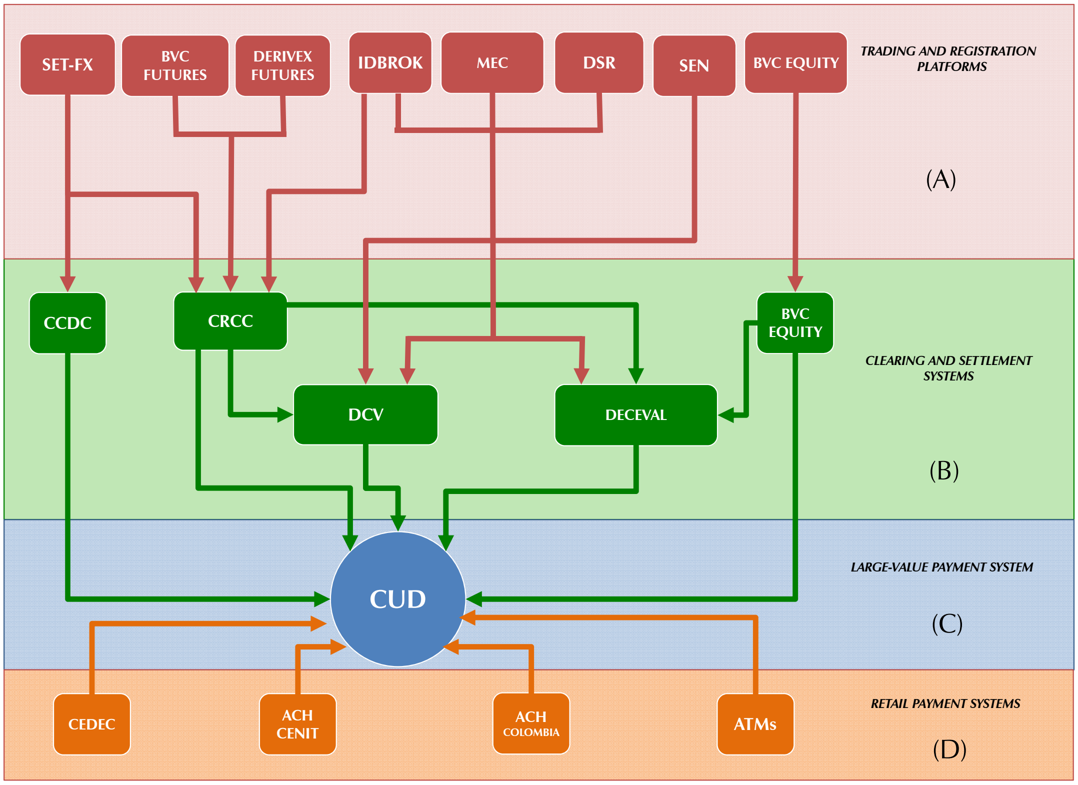
Results are valuable since they quantitatively support financial authorities' efforts to identify systemically important financial infrastructures (SIFMIs) under the too-connected-to-fail concept. In the Colombian case the systemic importance is strongly dominated by the only large value payment system (CUD) and sovereign securities' main settlement system and central depository (DCV). This confirms (i) the preeminence of the sovereign debt market as the most important contributor to local financial system's liquidity; (ii) the supremacy of sovereign securities as sources of liquidity for financial institutions in the local market, either provided by the central bank (i.e. via intraday or overnight repos) or by other financial institutions (i.e. via repos and sell/buy backs); and (iii) the significance of the impact on liquidity arising from RTGS systems interrelated continuously with other real-time based systems, as acknowledged by CPSS (1997). It is worth highlighting that both CUD and DCV are owned and operated by the Central Bank of Colombia (BR), as is customary in many other countries, presumably due to the importance of their proper functioning for financial markets.

This paper is structured as follows. The second section briefly describes the Colombian FMIs. The third section introduces basic *centrality* measures (i.e. *degree* and *eigenvector centrality*), along with the metrics herein suggested: *hub centrality* and *authority centrality*. The fourth section presents the main results of applying both basic and suggested *centrality* measures to the Colombian FMI's network. The final section summarizes results, the advantages and disadvantages of the proposed approach to assessing FMIs' *centrality*, and identifies some challenges ahead.

2. An overview of Colombian FMIs

Under the definition of FMIs as those multilateral systems among participating institutions used for the purposes of executing, exchanging, clearing, settling or recording payments, securities, derivatives, or other financial transactions, Figure 1 provides an overview of Colombian FMIs. Each level of Figure 1 relates to a specific type of infrastructure, corresponding to a broad classification of FMIs' duties or functions: (A) trading and registration, (B) clearing and settlement, (C) large-value payment systems, and (D) retail payment systems.

Figure 1
Colombian FMIs
(as of December 2011)



Source: Banco de la República (2012).

Level A comprises securities and currency trading and registration platforms[8] (hereafter referred as TPs). Regarding securities' TPs, the central bank (Banco de la República - BR) owns and operates SEN (Sistema Electrónico de Negociación), the main sovereign securities TP. Sovereign securities may also be traded in MEC (Mercado Electrónico Colombiano), which is owned and operated by the Colombian Stock Exchange (Bolsa de Valores de Colombia - BVC); MEC also provides a trading and registration platform for other types of fixed income securities such as corporate, municipal and commercial papers. The Colombian Stock Exchange also provides TP for equity and financial futures through BVC EQUITY[9] and BVC FUTURES, respectively.

DECEVAL REGISTRATION (DECEVAL / SISTEMA DE REGISTRO - DSR) is a TP owned and operated by DECEVAL central securities depository and securities settlement system (CSD+SSS), and provides registration services for fixed income securities. DERIVEX FUTURES provides TP services for the energy futures market. Local branches (subsidiaries) of international inter-dealer brokerage firms[10] (displayed as IDBROK) allow transactions between participants

[8] Registration platforms are used for collecting OTC markets' transactions.
[9] Local regulation does not allow OTC equity trading.
[10] In the local market these IDBROK are ICAP, GFI Group and Tradition.

through hybrid systems (voice and data). Regarding Peso/Dollar trading and registration platforms, SET-FX and IDBROKs provide TP services for foreign exchange market participants.

Level B corresponds to clearing and settlement systems. The central bank (BR) owns and operates DCV (Depósito Central de Valores), a FMI that is both the securities settlement system (SSS) and the central securities depository (CSD) for sovereign securities exclusively. DCV works under a Real-Time Gross Settlement System (RTGS) and a Delivery-versus-Payment (DvP) mechanism.[11]

Privately owned DECEVAL (Depósito Centralizado de Valores de Colombia) provides CSD and SSS services for corporate and public (non-sovereign) securities, along with CSD services for the equity market. Central counterparty (CCP) services for futures markets are provided by CRCC (Cámara de Riesgo Central de Contraparte de Colombia). The Colombian Stock Exchange (BVC) provides SSS services for local equity markets via BVC EQUITY.[12]

Regarding currencies, the CCDC (Cámara de Compensación de Divisas de Colombia) provides clearing and settlement for the Peso/Dollar spot market[13], whereas the CRCC offers clearing and settlement services for Peso/Dollar non-delivery forwards.

Level D comprises the only local large-value payments system (Cuentas de Depósito – CUD), where all cash leg's settlement (in local currency) takes place. The large-value payments system (LVPS), owned and operated by Colombia's central bank (BR), works under a Real-Time Gross Settlement System (RTGS) framework.[14]

Level E corresponds to retail payment systems. The central bank (BR) owns and operates both CENIT Automated Clearing House (ACH) and Cheques Clearing House (CCH), whereas commercial banks own ACH-Colombia. ATM provides clearing and settlement for transactions made through debit cards, credit cards, via POS (point of sale) and automated teller machines. Table 1 summarizes the above overview of Colombian FMIs.

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[11] DCV working on a RTGS framework means that there is a continuous (real-time) settlement of securities, where each transfer is processed individually on an order-by-order basis (without netting), conditional on the existence of funds in the LVPS (CUD). However, DCV also includes liquidity saving mechanisms in the form of liquidity optimization algorithms; Banco de la República (2012) describes DCV's functionality.

[12] Following CPSS (2003) the settlement institutions (i.e. institutions across whose books transfers between participants take place in order to achieve settlement) for the equity market are the local large-value payment system (CUD) for the Peso leg and DECEVAL for the equity leg. The settlement system (i.e. a system used to facilitate the settlement of transfers of funds or financial instruments) is provided by BVC.

[13] Following CPSS (2003) the settlement institutions for the foreign exchange market are the local large-value payment system (CUD) for the Peso leg and Citibank-New York for the Dollar leg. The settlement system is provided by CCDC.

[14] CUD working on a RTGS framework means that there is a continuous (real-time) settlement of funds, where each transfer is processed individually on an order-by-order basis (without netting), conditional on the existence of the corresponding securities or currencies in the related clearing and settlement systems (e.g. DCV, DECEVAL). However, CUD also includes liquidity saving mechanisms in the form of liquidity optimization algorithms; Banco de la República (2012) describes CUD's functionality.

Table 1
Summary of Colombian FMIs
(as of December 2011)

Type [b]	FMI	Description
TP	SEN [a]	Trading and registration system for sovereign securities.
	MEC	Trading and registration system for fixed income securities (e.g. public debt, corporate debt and commercial papers).
	IDBROK	Trading and registration hybrid systems for fixed income and foreign exchange markets.
	SET-FX	Electronic trading and registration system for foreign exchange.
	BVC EQUITY	Trading for common and preferred equity shares.
	BVC FUTURES	Trading and registration system for financial derivatives (i.e. equity, foreign exchange and notional bonds).
	DERIVEX FUTURES	Trading and registration system for energy derivatives (i.e. electricity, gas or oil).
	DSR	Registration system for fixed income (includes public debt, corporate debt and commercial papers). Owned by DECEVAL.
CSD+SSS	DECEVAL	Provides safekeeping, asset service and settlement for corporate and government (non-sovereign) securities. Also serves as the settlement institution and CSD for the equity market.
	DCV [a]	Provides safekeeping, asset service, securities lending and clearing and settlement for sovereign securities.
SSS	BVC EQUITY	Clearing and settlement system for common and preferred equity shares.
CCP	CRCC	Clearing and settlement process for futures markets and Peso/Dollar non-delivery forwards.
CSS	CCDC	Clearing and settlement (system) services for foreign exchange spot transactions.
LVPS	CUD [a]	Provides funds transfer services among financial participants and settles the cash leg for other FMIs.
ACH	CENIT [a]	Provides funds transfer services for a large volume of relatively low-value payments, such as credit transfers and direct debits.
	ACH COLOMBIA	
CCH	CEDEC [a]	Clearing and settlement for cheques issued by banking institutions.
RPS	ATM	Clearing and settlement for transactions made through debit cards, credit cards, via POS (point of sale) and automated teller machine.

[a] Owned and operated by the Colombian central bank (BR). [b] Trading and registration platform (TP); central securities depository (CSD); securities settlement system (SSS); central counterparty (CCP); currencies settlement system (CSS); large-value payment system (LVPS); automated clearing house (ACH); cheque clearing house (CCH); automated teller machine (ATM). Source: authors' design.

3. *Authority centrality* and *hub centrality*

3.1. Basic *centrality* measures: *degree centrality* and *eigenvector centrality*.

A large volume of research on networks has been devoted to the *centrality* concept (Newman, 2010). The preeminence of *centrality* is also characteristic of research on financial networks, where *central* financial institutions are commonly regarded as too-connected-to-fail, and therefore systemically important. However, *centrality* is still an elusive concept that may be approximated from different perspectives, where different *centrality* measures are available.[15]

[15] This section briefly covers basic concepts of network analysis with emphasis on *centrality* measures used for financial networks. *Closeness centrality* and *betweenness centrality* are not considered since their ability to accurately

Centrality's most common and simple measure is *degree centrality*, which corresponds to the number of links (edges) connected to the participant (node or vertex) under analysis. *Degree centrality* assesses how intensely a node is connected to the network.

The standard case of network analysis applied to social relations or informational networks assumes that all edges or links are equally important. However, in some cases it is convenient to assign a value or weight to each edge, where such weight corresponds to the importance or strength of the connection; this is a *weighted network*. In financial networks it is common to use the monetary value of payments, as in León and Machado (2011).

The standard case also assumes that edges are undirected, where a connection exists between two nodes irrespective of the direction (incoming or outgoing) of the link (e.g. a network of friends), or where the link implies the existence of an equivalent exchange between the two nodes (e.g. exchanging money for a security). Yet, the direction of the edges may be informative for some networks. For instance, in the internet the existence of a link from webpage A to webpage B does not imply the existence of a link from B to A; likewise, in *bibliometrics* the citation of document X by document Y does not imply the citation of Y by X. In this case, as before, *degree centrality* may be easily adjusted to recognize the existence of a directed network, where two different *degrees* are to be considered: *in-degree* and *out-degree*.

However, *degree centrality* has some well-known limitations. The most evident is its inability to capture neighbor's importance; in this sense, *degree centrality* ignores that neighbors connected to *central* nodes should be awarded a higher importance. In order to overcome this shortcoming it may be useful to shift from *degree* to *eigenvector centrality*, where each adjacent node is assigned a *centrality* score proportional to the sum of the scores of its neighbors, and where *centrality* results from a node having many neighbors, or from having some *central* neighbors, or both (Newman, 2010).[16]

Eigenvector centrality may also be used with *weighted networks*. Nevertheless, since a directed network consists of an asymmetric adjacency matrix that yields two sets of eigenvectors, *eigenvector centrality* is usually applied to undirected networks. It is possible to apply *eigenvector centrality* to one side of the adjacency matrix in order to measure *in-degree* or *out-*

identify *central* nodes in payment systems is questionable (Soramäki and Cook, 2012). For a comprehensive review of *centrality* measures please refer to Newman (2010).

[16] Please note that the principal eigenvector of adjacency matrix Ω provides an index of the connectivity of the network, whereas the individual elements of the corresponding eigenvector indicates the *centrality* of each node within the network (Haining, 2004). In this sense, the *eigenvector centrality* (EC) of an i-node within an adjacency matrix Ω with elements $\Omega_{i,j}$ corresponds to the sum of the *centralities* of i's neighbors. As presented in Newman (2010), this measure is attained by means of the following formula, where κ_1 is the leading (i.e. largest) eigenvector of Ω, as follows:

$$EC_i = \kappa_1^{-1} \sum_j \Omega_{i,j} EC_j$$

degree centrality separately[17], but another issue arises: if a node has outgoing (incoming) edges only, estimating *in* (*out*) *eigenvector centrality* will result in that node displaying zero *in* (*out*) *centrality*, and it may result in other adjacent nodes exhibiting zero *in* (*out*) *centrality* because of being connected to this *non-central* node.

This issue is especially important for a particular type of directed network: a directed acyclic network. This type of directed network, also known as DAG (directed acyclic graph), where no cycles between nodes exist[18], and where nodes non-strongly connected to two or more nodes exist, makes all nodes yield zero *eigenvector centrality*.[19] As stressed by Newman (2010), this makes standard *eigenvector centrality* completely useless for acyclic networks.[20]

3.2. Issues arising from measuring *centrality* for Colombian FMIs with *degree* and *eigenvector centrality*

Figure 1 displayed the functional connections between local FMIs, where links and nodes do not graphically represent their relative importance within the network. Figure 2 (below) corresponds to the topological network of local FMIs, where nodes' diameter is weighted according to the gross monetary value of the transactions managed by each FMI, and where edges' thickness is weighted according to the monetary value of the transactions flowing between FMIs.

Regarding the weights of the edges, the operational characteristics of the originating FMI determine whether the monetary values underneath the weights are gross or net. In Figure 2 FMIs that work under a netting operational framework (e.g. ACHs, CCP, CSS, CCH) generate net transactions (black edges), whereas FMIs that work under a gross settlement operational framework (e.g. SSSs+CSDs) or that merely capture financial firm's financial transactions (TPs), generate gross transactions (red edges).[21]

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[17] The right eigenvector corresponding to incoming edges in the lower part of the adjacency matrix, and the left eigenvector corresponding to outgoing edges in the higher part of the adjacency matrix.

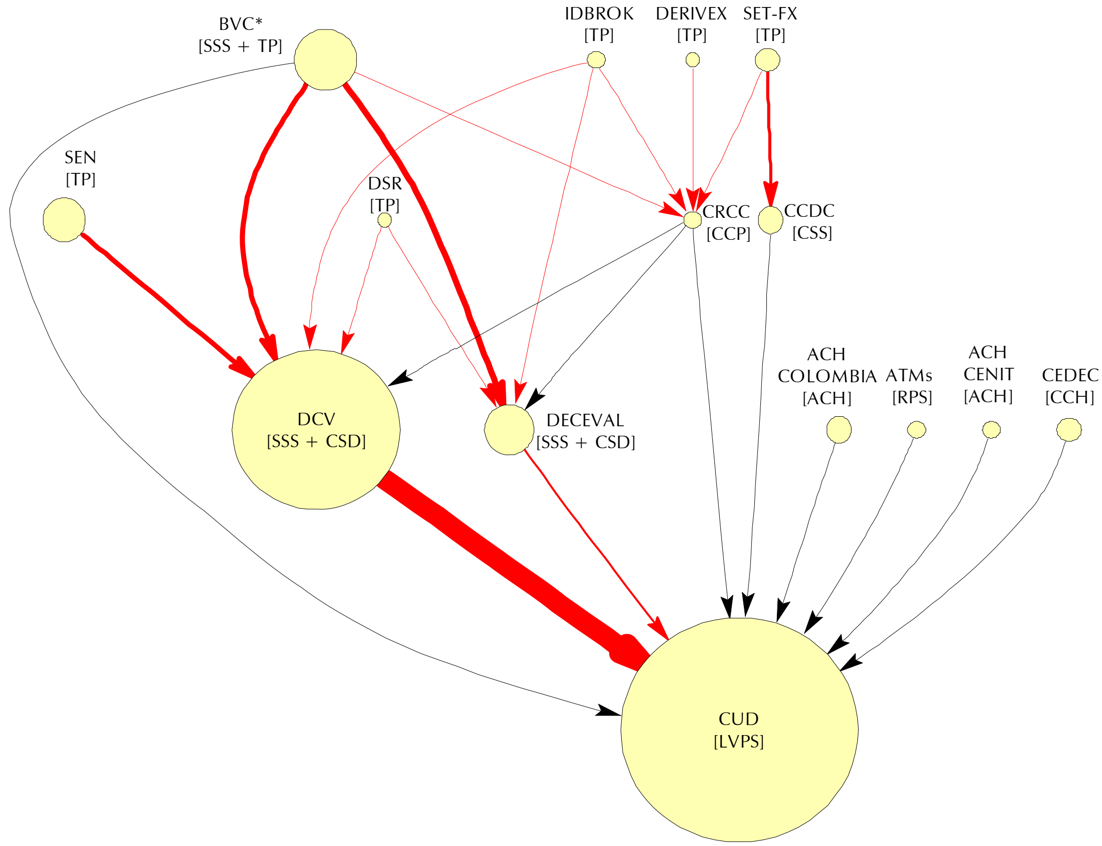
[18] Again, *bibliometrics* provide a typical case of acyclic networks. Because of their strict chronological content, the citation of –existing- document X by –new- document Y is plausible, whilst the inverse is impossible, making loops or cycles within citation networks impossible as well.

[19] A strongly connected node corresponds to a node that is reachable from and may reach other nodes in a directed network. In the presence of non-strongly connected nodes it is common to find non-zero *eigenvector centralities* due to the precision or iteration seeds of the algorithms; yet, *eigenvector centrality* in directed acyclic networks is inconsistent since it usually yields equal *centrality* to all nodes.

[20] Adjustments to standard *eigenvector centrality* are available. Two methods are worth mentioning: *Katz centrality* and *PageRank centrality*. *Katz centrality* avoids the issues regarding *eigenvector centrality* in directed acyclic networks by giving each node an initial amount of *centrality*; since this initial amount of *centrality* is arbitrary, this option is not considered in the herein case. *PageRank*, the algorithm behind Google's search engine, introduces a stochastic adjustment that randomly allows (i.e. creates) connections between nodes. Since FMIs connections are strictly hierarchical, where such randomly created connections are implausible, *PageRank centrality* is discarded; likewise, since it shares such stochastic adjustment, *SinkRank* (Soramäki and Cook, 2012) is also discarded.

[21] The only local FMI that generates both types of transactions (gross and net) is the Colombian Stock Exchange (BVC). It generates gross transactions under its sovereign and corporate debt trading and registering platform (MEC), which are settled by the SSSs+CSDs (i.e. DCV and DECEVAL). It generates net transactions under its equity trading, and settlement platform, which are sent to the LVPS (CUD) for the corresponding cash leg settlement.

Figure 2
Colombian FMIs' topological network [a,b]



[a] Nodes' diameter and edges' thickness correspond to the monetary value of transactions. [b] Edges representing net (gross) flows are in black (red). * BVC performs SSS (equity) and TP (fixed income, equity, futures) duties. Source: authors' design.

The main topological characteristic evident from Figure 2 is that the local IMFs' network is strictly hierarchical. Regarding securities, forex and derivatives transactions, they are captured or registered by TPs; afterwards, those transactions are cleared by the corresponding securities (SSSs and CSDs), currencies (CSS) or derivatives[22] (CCP) infrastructures, which concurrently interact with the RTGS-based LVPS to settle the corresponding leg and the cash leg. Transactions belonging to ACHs, RPS and CCH are settled in the LVPS directly.

The network in Figure 2 has no loops or undirected edges, and all edges are directed downwards, where there is a node that has incoming edges only and no outgoing ones (i.e. the LVPS), and several nodes with outgoing edges only and no incoming ones (i.e. TPs). Due to this strict hierarchical structure, the IMFs' network belongs to the particular case aforementioned: a

[22] Peso/Dollar futures and non-delivery forwards.

directed acyclic network.[23] It is important to realize that this strict hierarchical structure is not coincidental, but follows legal and operational considerations that tend to be stable overtime.[24]

Since FMIs' network is weighted, acyclic and directed, the usefulness of basic metrics for *centrality* (*degree* and *eigenvector*) is worth examining. As mentioned before, *degree centrality* would not be able to capture neighbor's importance, making all adjacent nodes equally important despite the origin of their preceding connections. This issue is particularly important in the case under analysis since some FMIs function as collectors or concentrators of other FMIs' edges, where this shortcoming is more acute in the case of FMIs that work under netting frameworks.[25]

Additionally, as already documented, standard *eigenvector centrality* for acyclic networks yields undesirable results: all nodes would have equal –zero- *centrality*. Hence, its application to the herein considered case is inconsistent.

Consequently, non-basic *centrality* measures should be considered for the Colombian FMIs case, where the network's topology (i.e. weighted directed acyclic network) should determine the choice of metrics. Next section addresses the implementation of two particular metrics: *authority* and *hub centrality*.

3.3. ***Authority centrality*** **and** ***hub centrality***

Unlike financial institutions' networks, which are composed by a myriad of nodes that interconnect in a rather non-hierarchical fashion[26], FMIs' networks are composed by a non-large set of nodes, with each FMI developing a specialized duty (e.g. LVPS, SSS, ACH, etc.) that clearly discriminates each node and defines its position within the network, and strictly determines the number and direction of all nodes' connections. In this sense, this strict hierarchy not only results in acyclic and directed networks, but also results in a particular challenge: to recognize that some FMIs are designed to serve as collectors or concentrators of

[23] The network acyclic property was tested according to the simple procedure described by Newman (2010): (i) find a node with no outgoing edges; (ii) if no such node exists, the network is cyclic; (iii) if such a node does exist, remove it and all its ingoing edges from the network; (iv) if all nodes have been removed, the network is acyclic; otherwise go back to step (i). Moreover, the fact that the graph could be drawn with all edges pointing downward also confirms that the network is acyclic.

[24] It is unlikely to find settlement systems sending transactions to trading platforms; LVPS sending transactions to ACHs; or CCHs sending transactions to TPs. The hierarchy clearly follows the operational role of each FMI.

[25] The inability of *weighted degree centrality* for capturing the importance of neighbor's precedent connections is evident in the present case. For instance, when using *weighted degree centrality* one SSS (i.e. DCV) would be more important than the only LVPS (CUD), which receives connections from all SSSs (i.e. DCV, DECEVAL and BVC), the CSS, ACHs, etc. Moreover, due to its netting framework, *weighted out-degree centrality* results in the only CSS (i.e. CCDC) being less *central* than SET-FX (the currency TP), despite the latter is the only contributor to the former. Using *non-weighted degree centrality* would yield odd results as well: the –recently established- CCP (i.e. CRCC) would be more *central* than any of the SSSs or the stock exchange (i.e. BVC), and the brokers would be more *out-degree central* than DCV and DECEVAL (both are SSSs and CSDs).

[26] This does not mean that the connections are completely random, or that tiered connections are not available. This means that each node's functions within the financial institutions network are not as strict as in the case of FMIs, where each node develops a rather specific duty (e.g. SSS, LVPS, ACH) that conditions its connections to other FMIs.

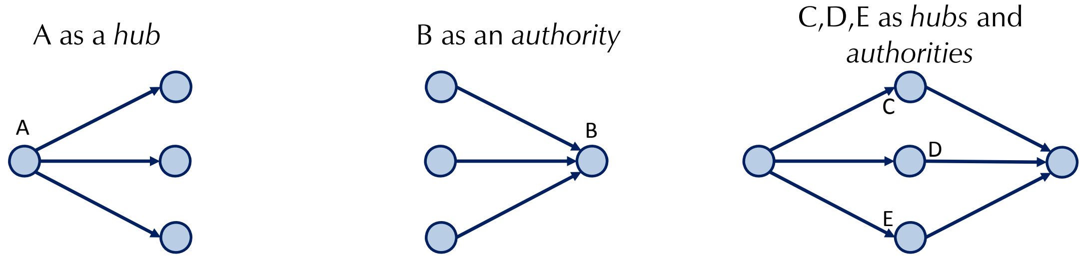
the transactions of other FMIs, whereas some others are designed to serve as originators of transactions, with some FMIs serving both purposes.

Kleinberg (1998) designed the HITS algorithm (Hypertext Induced Topic Search), which may be useful for simultaneously recognizing such dual role of FMIs (i.e, collecting and/or originating transactions) in a proper manner. The original use of the algorithm was *information retrieval* for *internet link analysis*[27], where the algorithm's main premise is to recognize that webpages serve two purposes: (i) to provide information on a topic, and (ii) to provide links to other webpages containing information on a topic. In this sense, the algorithm seeks an appropriate balance between these two purposes, which are related to *in-degree* and *out-degree centrality* in a directed network.[28]

Consequently, the intuition behind the algorithm is the existence of a mutually reinforcing relationship between two different types of pages within the Web: (i) *authorities*, which are commonly cited regarding a certain topic, thus they are informative and tend to exhibit a large *in-degree*; and (ii) *hubs*, which cite many related *authorities*, thus they are a useful resource for finding *authorities* and tend to exhibit a large *out-degree*.[29]

Figure 3 depicts both concepts, where nodes A and B strictly correspond to a *hub* and an *authority*, respectively. It is worth highlighting that a single node may concurrently display some level of *authority centrality* and *hub centrality*; this is the case of nodes C, D and E.

Figure 3
Authority centrality and *hub centrality* within a network



Source: authors' design.

[27] According to Langville and Meyer (2012) *information retrieval* is the process of searching within a document collection for a particular information needed (also known as a "query"), whereas *internet link analysis* corresponds to exploiting the additional information inherent in the hyperlink structure of the World Wide Web to improve the quality of the queries. The development of the HITS algorithm by Kleinberg was parallel to the most famous *internet link analysis* algorithm: *PageRank*, the algorithm behind Google's search engine (www.google.com), developed by Brin and Page (1998). HITS is the algorithm behind the search engines of Teoma (www.teoma.com) and Ask (www.ask.com).

[28] Please note that the dual relationship embedded in mutual reinforcement between *authorities* and *hubs* is manifested by their *in-degree* and *out-degree*, which results in a high correlation between HITS ranking and *in/out-degree* ranking. However, as reported by Ding et al. (2001), HITS (and Google's *PageRank*) is more efficient than simple *in/out-degree* metrics.

[29] Again, *bibliometrics* provides a practical example. A *hub* is a review paper that cites many original papers, while an *authority* is an original seminal paper cited by many papers (Ding et al., 2001). Please note that in all cases *authority centrality* and *hub centrality* only exist in directed networks (e.g. the World Wide Web, the FMIs in Figure 2).

In this sense, as stressed by Langville and Meyer (2012), Kleinberg's algorithm identifies popularity or importance based on a pair of interdependent circular thesis: (i) a webpage is a good *hub* if it points to good *authorities*, and (ii) a webpage is a good *authority* if it is pointed-to by good *hubs*. As a result, good *authorities* are pointed-to by good *hubs*, and good *hubs* point to good *authorities*, where each webpage has some *authority* score and some *hub* score.

This may be conveniently reduced for the case in hand as follows: *authority central* FMIs receive transactions from *hub central* FMIs, and *hub central* FMIs send transactions to *authority central* FMIs, where each FMI has some *authority* score and some *hub* score.

Kleinberg's original algorithm consists of an iterative procedure for simultaneously computing each node's *authority centrality* and *hub centrality*.[30] However, it does not rely on each node's *in-degree* and *out-degree* scores only. Due to the interdependent circularity aforementioned, the algorithm recognizes that the *authority centrality* of each node is defined to be proportional to the sum of the *hub centrality* of the nodes that point to it, and that the *hub centrality* of each node is defined to be proportional to the sum of the *authority centrality* of the nodes it points-to. In order to make such recognition the algorithm uses the *eigenvector centrality* previously presented, but it circumvents the documented equal –zero- *centrality* issue in directed networks by simultaneously and iteratively estimating the *authority centrality* and *hub centrality* for each node based on the circular (i.e. mutually reinforcing) premise that a node with zero *authority centrality* (i.e. not pointed by others) still can have non-zero *hub centrality* because of pointing to other nodes, and that those nodes it points to have non-zero *authority centrality*, and so on.

Kleinberg's iterative procedure may be summarized as the estimation of *eigenvalue centrality* on two modified versions of the original adjacency matrix, where these two matrices correspond to an *authority* matrix ($\mathcal{A}$) and a *hub* matrix ($\mathcal{H}$). Let Ω be the adjacency matrix resulting from a network, the *authority* and *hub* matrices ($\mathcal{A}$ and $\mathcal{H}$) are estimated as follows:

Authority matrix	*Hub* matrix
$\mathcal{A} = \Omega^T\Omega$	$\mathcal{H} = \Omega\Omega^T$

Multiplying a symmetrical adjacency matrix with itself allows identifying all nodes that can reach each other in two steps –second order adjacencies (Haining, 2004). However, in the case of non-symmetrical (i.e. directed) adjacency matrices, multiplying with a transposed version of itself allows identifying directed (*in* or *out*) second order adjacencies. Regarding $\mathcal{A}$, multiplying Ω^T with Ω sends weights backwards –against the arrows, towards the pointing node-, whereas multiplying Ω with Ω^T (as in $\mathcal{H}$) sends scores forwards –with the arrows, towards the pointed-to

[30] Kleinberg's original iterative algorithm is presented in Langville and Meyer (2012).

node (Bjelland et al., 2008).[31] In this sense, for a non-weighted network off-diagonal elements H_{ii} correspond to the number of nodes that node i points to, whereas elements A_{ii} correspond to the number of nodes pointing to i.

Since $\mathcal{A}$ and $\mathcal{H}$ are symmetrical nonnegative matrices (even if Ω is directed and acyclic), a unique *eigenvector centrality* of $\mathcal{A}$ and $\mathcal{H}$ may be estimated, and the resulting *authority* and *hub centrality* scores will be positive non-zero scores for each node; this contrasts with standard *eigenvector centrality* on a directed and acyclic adjacency matrix, where *eigenvalue centrality* will yield equal –zero- scores for each node.

Hence, *authority centrality* and *hub centrality* addresses two issues regarding the FMIs depicted in Figure 2. First, it provides a dual *centrality* score based on FMIs' role within the –directed and acyclic- network, where their collector and/or originator roles are measured. Second, as it captures the *authority centrality* and *hub centrality* of the FMIs connected to each FMI, it provides a dual *centrality* weighted measure of their importance within the network.

Table 2 provides a brief comparison of the centrality metrics previously addressed, where their advantages and disadvantages for the herein case are mentioned.

Table 2
Comparison of selected *centrality* metrics

Metric	Description	Advantages	Disadvantages
Degree	Number of links connected to the participant. Degree centrality assesses how intensely a node is connected to the network.	Simple and intuitive. May be adjusted to weighted and directed networks.	Ignores that neighbors connected to central nodes should be awarded a higher importance.
Eigenvector	By estimating the eigenvector of the adjacency matrix each node is assigned a centrality score proportional to the sum of the scores of its neighbors.	Centrality results from having many neighbors, or from having some central neighbors, or both. May be adjusted to weighted and directed networks.	May not be simple. Standard eigenvector centrality is completely useless for directed acyclic networks.
Authority & Hub	By estimating the eigenvector of the *authority* and *hub* matrices each node is assigned an *authority* and a *hub* centrality score proportional to the sum of the *hub* and *authority* scores of its neighbors.	Convenient for directed acyclic networks, even in the weighted case. Authority (hub) centrality results from being connected to many hubs (authorities), or from being connected to some central hubs (authorities), or both.	May not be simple.

Source: authors' design.

[31] In this sense, as in Bjelland et al. (2008), $\mathcal{H}$ allows nodes to send one another (via two hops) their *hub* scores; and a node j with a high *hub* score (i.e. it points to good *authorities*) will send (via the action of $\mathcal{H}$) larger *hub* weight to other nodes i which point to the same nodes (good *authority* nodes) as j does. Meanwhile, $\mathcal{A}$ allows nodes to send one another (via two hops) their *authority* scores; and a node j with a high *authority* score (i.e. it is pointed-to by good *hubs*) will send (via the action of $\mathcal{A}$) larger *authority* weight to other nodes i which are pointed-to by the same nodes (good *hub* nodes) as j does.

4. Main results

This section presents the main results from implementing *in/out-degree centrality*, *authority centrality* and *hub centrality*; since *eigenvector centrality* yields equal –zero- scores to all nodes due to the directed and acyclic features of the network under analysis, results are not reported. Table 3 presents the two metrics of *centrality* for the non-weighted and weighted versions of the adjacency matrix behind the network in Figure 2; weights correspond to the daily average gross monetary value of the transactions occurred during year 2011 between the FMIs herein considered.[32]

Table 3
Colombian FMIs' *degree*, *authority* and *hub centrality* [b]

Type	FMI	*Degree centrality*				*Authority* and *hub centrality*			
		Non-weighted		Weighted		Non-weighted		Weighted	
		In	Out	In	Out	*Auth.*	*Hub*	*Auth.*	*Hub*
TP	BVC [a]	0.000	0.167	0.000	0.220	0.046	0.139	0.000	0.010
	SEN	0.000	0.042	0.000	0.101	0.011	0.032	0.000	0.000
	IDBROK	0.000	0.125	0.000	0.002	0.031	0.092	0.000	0.000
	SET-FX	0.000	0.083	0.000	0.043	0.011	0.034	0.000	0.000
	DERIVEX F.	0.000	0.083	0.000	0.000	0.026	0.076	0.000	0.000
	DSR	0.000	0.083	0.000	0.000	0.021	0.063	0.000	0.000
SSS+ CSD	DCV	0.208	0.042	0.200	0.478	0.178	0.075	0.003	0.750
	DECEVAL	0.167	0.042	0.115	0.021	0.166	0.073	0.003	0.034
CCP	CRCC	0.167	0.125	0.008	0.008	0.158	0.131	0.000	0.007
CSS	CCDC	0.042	0.042	0.041	0.041	0.028	0.050	0.000	0.065
LVPS	CUD	0.417	0.000	0.636	0.000	0.261	0.045	0.994	0.000
ACH	ACH COL.	0.000	0.042	0.000	0.035	0.016	0.048	0.000	0.055
	ACH CENIT	0.000	0.042	0.000	0.010	0.016	0.048	0.000	0.016
RPS	ATMs	0.000	0.042	0.000	0.010	0.016	0.048	0.000	0.016
CCH	CEDEC	0.000	0.042	0.000	0.030	0.016	0.048	0.000	0.047

[a] BVC performs SSS and TP functions, for equities and local sovereign securities, respectively. [b] Scores are normalized (i.e. the sum of each column is 1.0). Source: authors' calculations.

As expected, using the non-weighted network yields less dissimilar results in cross section; differences between FMIs are less marked since all links and all neighbors are considered as being equally important. *In-degree centrality* on non-weighted connections regards the LVPS (CUD) as the most important, followed by SSSs+CSDs (i.e. DCV and DECEVAL) and the CCP (CRCC), whereas the most *out-degree central* is the BVC (TP+SSS), followed by the CCP (CRCC). *Authority* and *hub centrality* on non-weighted connections also display similar results in cross section: the most *authoritative* FMI is the LVPS (CUD), followed by SSSs+CSDs (i.e. DCV

[32] Data provided by FMIs is consolidated and examined in Banco de la República (2012), which is the main source of the aggregated data used in this paper's calculations. Gross monetary values are used for all calculations since particularly netting-efficient FMIs (e.g. CCP and CSS) resulted in –artificially- rather low centrality figures; authors seek to avoid misleading results arising from efficiency issues and, thus, prefer to make a fair comparison across FMIs.

and DECEVAL) and the CCP (CRCC), with BVC (TP+SSS) as the most *hub central* FMI, followed by the CCP (CRCC).

Hence, it is apparent that changing from the simplest measure of *centrality* (i.e. *degree centrality*) to a more elaborated measure (i.e. *authority* and *hub centrality*) adds little value to the analysis of FMIs systemic importance when working on the non-weighted version of the network; moreover, since differences are rather slight between FMIs, its informational content may be dubious. Again, this is intuitive since all links and nodes are deemed as equally important.

On the other hand, working on the weighted version of the network increases cross-section differences. In the case of *in-degree centrality* the LVPS is the most *central* FMI, followed by SSSs+CSDs (i.e. DCV and DECEVAL). Despite the ranking between the non-weighted and weighted *in-degree centrality* is nearly the same, differences are greater in the latter: the two most *in-degree central* FMIs in the non-weighted case account for 62.5% of the total score, whereas in the weighted case they account for 83.6%; the most *in-degree central* FMI (i.e. CUD) accounts for 41.7% and 63.6% of the total score in the non-weighted and weighted cases, respectively.

Cross-section differences for the weighted *out-degree centrality* are even more significant. Not only has the ranking changed (e.g. the most *central* position changes from BVC to DCV[33]), but the scores are more concentrated: in the weighted version the most *out-degree central* FMI (DCV) is assigned a 47.8% score, whereas in the non-weighted the three most *out-degree central* account for 41.7%.

Such increase in the cross-section differences is intuitive, and follows the value of the transactions between FMIs; thus, as expected, the weighted network may be considered as more informative than the non-weighted *in/out degree centrality*. However, the ability of the *in/out degree centrality* score to identify the sources of infrastructure-related systemic impact may be questionable since they contradict common knowledge regarding the functioning of the local markets. For instance, within the Colombian financial markets it seems implausible that the failure of the SET-FX (TP) platform (i.e. the fourth most *out-degree central* FMI) would halt the entire infrastructure network; it would compromise the foreign exchange market, but its impact on the settlement of other markets is rather limited. Moreover, SET-FX's (TP) *centrality* score being about five times CCDC's (CSS) is non-intuitive since the former sends about 96.2% of its transactions (i.e. their monetary value) to the latter.

Regarding *authority centrality* on the weighted network, it is clear that the LVPS (CUD) is the most *central* node, with a 99.4% score. Despite this may seem an extreme result, it is rather

[33] The *out-degree* ranking changes significantly when shifting from the non-weighted to the weighted network. The BVC loses its most *central* rank to DCV, which was formerly the seventh most *central*; IDBROKs, formerly the second most *central*, is now ranked twelfth; DSR, formerly the fourth most *central*, is now ranked thirteenth; SEN, formerly the seventh most *central*, is now ranked third; DERIVEX FUTURES, formerly the fourth, is now the fourteenth.

intuitive: in the absence of the local currency settlement –by the LVPS-, no other market (i.e. securities, foreign exchange, derivatives) or infrastructure (i.e. SSS, CCP, ACHs, RPS, CCH, etc.) would be able to settle its transactions. As evident in Figure 2, the LVPS is the ultimate collector of transactions –*authority*- within the FMIs' network; this is congruent with common knowledge of Colombian markets since the settlement of all other FMIs critically depends on CUD's proper functioning.

Two other FMIs have a non-zero *authority* score: DCV and DECEVAL (SSSs+CSDs). They act as collectors of the transactions captured by the most important local TPs (i.e. SEN and BVC), which both provide trading platforms for the most liquid local market: the local sovereign securities market.

This collector role by largest SSSs+CSDs (DCV), along with its direct and intense link with the most *authority central* FMI (i.e. CUD), results in its systemic importance as *hub* within FMIs' network: DCV's *hub centrality* score is 75.0%. This is intuitive since a critical and circular (i.e. mutually reinforcing) relationship between the local sovereign securities market and the cash settlement of all local financial markets is well-known; for instance, during 2010 and 2011 DCV's contribution to CUD's payments was about 46.9% and 44.1%, respectively.[34] In this sense, as it is locally acknowledged, the absence or failure of the most *hub central* FMI (i.e. DCV) would halt FMIs' network, especially because of its liquidity contribution to the CUD (i.e the most *authoritative* FMI), which includes the management of sovereign securities as collaterals for liquidity provision by the central bank (i.e. via intraday or overnight repos) and for money market liquidity via repos and sell/buy backs between financial institutions.[35]

It is worth highlighting that the strong mutually reinforcing link between DCV and CUD was expected because of (i) the aforementioned preeminence of public –sovereign- debt markets; (ii) sovereign securities being the most widely required collateral for money market operations, either with the central bank or between financial institutions; and (iii) both FMIs sharing a real-time DvP framework. Regarding the latter, as acknowledged by CPSS (1997), "when a RTGS system is interrelated continuously with other systems as in the case of real-time DvP systems, the impact on RTGS liquidity can be more widespread and significant".

The second most *central hub* is CCDC (CSS), with a 6.5% score. This is intuitive since the CCDC is the only FMI that combines the collector and originator roles for the local foreign exchange market. The third and fourth most *central hubs* are ACH Colombia (5.5%) and CEDEC (4.7%), which is also expected due to their role as the most important provider of low-

[34] This contribution corresponds to daily averages of large-value payments that were originated in DCV's sovereign securities settlement, including sell/buy backs and repos, as in Banco de la República (2012).

[35] Sell/buy backs consist of two sell and buy transactions simultaneously contracted, with the same principal amount and security, with both parties obliged to take the inverse position at maturity (i.e. the buyer becomes the seller), where the property of the collateral is transferred to its buyer. Unlike repos, haircuts and mobility limitations are not imposed on collateral (León, 2012).

value transfer services in Colombia and the sole provider of clearing and settlement for cheques issued by banking institutions, respectively.

Other FMIs that have a systemic role as *hubs* are DECEVAL (3.4%), ACH Cenit (1.6%), BVC (1.0%) and CRCC (0.7%). In this sense, as expected, their systemic role within the FMIs' network is rather limited when compared to DCV's or CCDC's.

All in all, *authority* and *hub centrality* as metrics of systemic importance yield an intuitive result: two FMIs could seriously imperil the safe and efficient functioning of the local financial markets: CUD (LVPS) and DCV (SSS+CSD), which are both owned and operated by the central bank. Central banks owning and managing LVPS and CSDs is a rather widespread practice[36], which may be due to these FMIs' critical roles within financial markets.

Results display that other FMIs may threaten the safe and efficient functioning of local financial markets. The most evident is the CCDC, which is the second most *hub central* FMI due to the foreign exchange market being the second most important contributor to the CUD (LVPS), and because of its lack of substitutes within the local FMIs network.

Other FMIs' threats to the safe and efficient functioning of local financial markets could be contained or mitigated by the existence of a substitute, or could be managed due to the low monetary value of their operations and the corresponding low impact in the functioning of the FMIs' network. The relative low systemic importance of those FMIs follows the degree of development attained by the markets they serve (i.e. derivatives, corporate debt), which is still minor when compared to the local sovereign securities market. However, it is important to highlight that this does not mean that these FMIs are not capable of endangering the markets they serve, or even stressing the system as a whole because of financial institutions simultaneously participating in several markets and various FMIs.

5. Final remarks

Despite the importance of systemic risk management is a well-known fact, infrastructure-related risk is a rather unmapped source of systemic risk. In this sense, the safe and efficient functioning of FMIs is an important source of financial stability since financial institutions, non-financial firms and individuals count on the clearing and settlement of their transactions, even in the middle of a period of financial turmoil. Hence, notwithstanding that FMIs have been a source of strength during the crisis (Dudley, 2012), financial authorities should not limit their efforts of

[36] World Bank (2011) reports that in 39% of the 149 countries surveyed the CSD is operated by the central bank, with such involvement of the central bank as the CSD operator being more common for CSDs that handle government securities only. According to the report, central banks are usually heavily involved during early stages of setting up securities markets (as is the case in Colombia); for instance, in lower-middle income and low income countries CSDs operated by the central bank are 49% and 71%, respectively. The same report documents that 96.6% of RTGS based LVPS are operated by central banks.

identifying and managing sources of systemic importance to financial institutions: they should also identify and manage systemically important financial market infrastructures (SIFMIs).

Network analysis' *centrality* has been a common and interesting metric for identifying systemically important financial institutions (SIFIs) under the too-connected-to-fail concept. However, to the best knowledge of the authors, *centrality* has not been equally used for identifying SIFMIs. Therefore, concurrent with contemporary emphasis on the identification of sources of systemic importance and on infrastructure-related risk, this paper extended the use of *centrality* metrics from identifying SIFIs to identifying SIFMIs.

As examined in this paper, although using basic *centrality* metrics such as *degree* and *eigenvector centrality* is tempting, FMIs' networks exhibit particular structures (i.e. directed and acyclic) that render them inconvenient and useless, respectively. In order to overcome this issue this paper uses *informational retrieval* techniques typical of *internet link analysis* for assessing systemic importance arising from FMIs dual role as collectors and/or originators of transactions within their network. The authors' choice is to use Kleinberg (1998) HITS algorithm, which is specifically designed to identify two types of *centrality*: *authority* and *hub centrality*, corresponding to the collector and originator role, respectively.

Besides the theoretical and practical advantages of using *authority* and *hub centrality*, results are intuitive and match local market's functioning in a convenient manner. Results highlight the systemic importance of the LVPS (CUD) and the most important SSSs+CSDs (DCV), where their importance arises from their *authority* and *hub centrality*, respectively. Consequently, under the herein proposed approach, both CUD and DCV display the highest systemic importance for the Colombian financial markets; this is, unlike other local FMIs, (i) the malfunctioning of CUD or DCV may halt the entire financial circuit, triggering greater disruptions in the financial system and economic activity, or (ii) they may act as powerful conduits for transmitting shocks with the local financial system.

CUD and DCV being the local SIFMIs is intuitive and concurrent with market's functioning since DCV's sovereign securities settlements contributes with nearly half of the payments processed in CUD, and DCV depends on the existence of funds in CUD for settling its transactions. This is particularly important due to the sovereign securities market being the most liquid and important within the local economy, along with the documented (CPSS, 1997) enhanced interconnection arising from both working on a real-time DvP framework.

It is important to point out that the systemic importance of CUD and DCV may be validated by the fact that they both are owned and operated by the central bank. As documented by World Bank (2011), this is a widespread practice that may result from the critical nature of their roles, especially for low and middle-income countries.

Results are particularly useful for financial authorities. They may serve the purpose of assisting financial authorities in focusing their attention and resources –the intensity of oversight, supervision and regulation- where the infrastructure-related systemic impact is estimated to be the greatest. They may also serve the purpose of tracking the development of existing FMIs, or even identifying FMIs which are non-substitutable and large and thus may be a potential source of single-point-of-failure risk.

As it is always the case, it is important to highlight some caveats regarding the herein proposed model and its results. First, systemic importance is a relative (cross-section) concept, and the preeminence of CUD and DCV does not mean that other FMIs' systemic importance is null or negligible; CUD and DCV being those FMIs capable of critically impairing the financial system as a whole does not mean that other FMIs are not capable of endangering the markets they serve, or even stressing the system as a whole, as is the case of CCDC (CSS) due to its central and non-substitutable role for the local foreign exchange market. Second, results should not be regarded in isolation; they are not intended to substitute sound judgment by financial authorities, or to be regarded as the sole metric to use when deciding the systemic importance of a FMI. Third, despite the preeminence of CUD and DCV as SIFMIs matches local market's functioning and common-sense, the chosen algorithm (i.e. based on the mutually reinforcing relationship between *authority* and *hub centrality*) and the dominance of sovereign securities market may be underestimating other FMIs' systemic importance; hence, other metrics, such *as in/out degree centrality* may serve as a supplement to the herein proposed approach. Fourth, the model is specifically designed to capture the liquidity transmission channel across FMIs, but may fail to capture the market confidence transmission channel, which is especially relevant since financial institutions tend to simultaneously participate in several markets and various FMIs.

Finally, some challenges remain. First, financial institutions' and financial infrastructures' systemic importance have been assessed independent one from the other; a truly comprehensive view of financial markets' functioning may require merging both institutions and infrastructures in the same network, especially since financial institutions tend to simultaneously participate in several markets and various FMIs. Second, *authority* and *hub centrality* may be useful for identifying SIFIs as well, and may aid financial authorities to identify *hubs* and *authorities* within the entire financial system, and within each market (i.e. sovereign securities, corporate securities, foreign exchange, and derivatives). Third, due to the rapid evolution of local markets, the systemic importance of FMIs is also a dynamic concept that requires a periodic assessment and analysis. These challenges are part of the authors' research agenda.

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