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Detection of paradigm shifts and emerging fields using scientific network: A case study of Information Technology for Engineering

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ABSTRACT

Detection of emerging fields in any industry is of great importance to the industrialists, engineers and policy makers of business as well as state administration. Exact awareness of the paradigm which governs current research activities and chances of likely paradigm shifts which could redefine the research approaches, is very crucial for the actors of scientific community and policy makers. Excellent technologies in IT, even accelerated the scientific and applied ontological pursuit in both academia as well as industry. In this work, network approach is advocated for the identification of innovations, new paradigms and emerging fields in the IT industry in the research area 'engineering'. The network is a scientific network of research publications which reflects the volume and flow of scientific activities. Centrality analysis, path analysis, cluster analysis, etc. are used to identify the key papers of paradigm shifts, emerging fields, relatively important clusters and works respectively. A new metric, flow vergence index is devised for cluster analysis. The paradigm shift identified from this network is RFID technology, related with the supply chain management. With proper economic and policy supports, there are some good reasons to look forward for more wonders from the industry.

1. Introduction

Almost all the industries ranging from healthcare, medicine and pharmaceuticals, banking, biotechnology and biomedical engineering, automotive, operations and manufacturing, building and construction, distribution, food processing, space sciences, weather monitoring, and disaster management are directly or indirectly using the advancements in IT for their daily and strategic functioning. It renders a ubiquitous presence in the life of people through technologies embedded in various devices of different levels of sophistication and applications. Information technology industry being one of the sub-industries of the engineering industry, also have almost the same spread and reach. Detection of emerging fields, paradigms [1] associated with the scientific researches which directly or indirectly affect any industry is very important for industrialists, academic researchers, engineers, policy makers in business organisations as well as in state administration. Mulkay et al. [2] argued that emergence of a new research network occurs through the invasion of other research areas over one which holds room for development where theories and techniques of the former are readily transferable for answering the unsolved questions in the latter. Whitley [3] argued that Kuhn's model of dynamics of science fails to provide an insight about the creation of different sorts of knowledge in different social contexts. Perry and Rice [4] favoured evolutionary branching theory of Mulkay over Kuhnian model as their evidence points to divergence of research areas instead of convergence. In this work instead of considering the research areas, the flow of knowledge at individual work level is considered and the concept of flow vergence (divergence or convergence) is introduced. The flow divergence tendency of a

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work within a cluster indicates its cohesive potential to other research clusters. While convergence and passive flow indicate the tendency to grow incrementally within the confinement of the research area addressed by the cluster. Thus divergence indicates the radical nature of work and convergence indicates incremental flavour. Results point out that most of the works and research fields (clusters) in an evolved network show a convergence dominant mode of growth and thus agree to Mulkay model. The occurrence of paradigm shifts is also identified in this work and hence the evidence towards Kuhnian model with the advantage of identification of the emerging fields is presented.

Economic growth of most of the industries depends largely on the development of operating technologies within the industries. A lot of works were concentrated on the high technology industries, viewing an industry as a collection of its relevant technologies [5]. Many methods can be found from the literature, which were either intended to identify the technologies of good performance via clustering based on growth curves [6,7] or predict their development so as to help in planning. Clustering based on growth curves, a parametric method, attempts to fit a common growth curve model to all the technologies and then those showing similar patterns are grouped together by comparing their parameter values. However, their disadvantage lies in the fact that all the technological growths can't be explained by one predetermined growth model. They are more of a quantitative approach and fail to capture the qualitative aspects of the works. The importance of network of publications analysis lies in the fact that, being a knowledge flow based approach, direct relationships between the intellectual works are reflected. Indirect relationships can also be modelled by using derived networks such as collaboration networks and co-citation networks [8]. Various tools are available for complex network analysis and visualisation. Popular software packages are PAJEK [9] and GEPHI [10]. Histcite [11], an online bibliometric analysis and visualisation tool by Eugene Garfield can visualise the networks of publications as historiographs [12], which shows the historical evolution of the networks. Large network visualisation and analysis can also be done in a lot of other bibliographic management software packages.

In this work, we intend to identify important innovations (radical) and paradigm shifts that occurred in the IT for engineering during the early years of 21st century (the span of our research is from Jan. 1st 1999 to Feb. 28th 2013). This period is important because it has witnessed the downswing of the 5th Kondratieff cycle of development (K-cycle) [30], driven by information technology, networking and communication technologies. Interestingly, the growth of IT in developing countries (like India) during this period was remarkable [45] and might have far reaching impacts. Therefore, the developments in the industry during this period of the current cycle might be crucial for the future of industry, especially in the 6th K-cycle. Our research goal also includes the identification of different important fields (research clusters) in the industry. The evaluation of their performance (based on the knowledge flow characteristics) and ranking based on their performance is the main concern of this work. The identification of emerging fields in the industry is another important aim of our work. All these identifications: i.e., radical innovations, paradigm shifts, different fields of research, relatively more important fields among those research clusters, emerging research clusters, etc. is very much handy for the scientific community, other researchers, investors, policy makers, etc. Plausible implications of these identifications to various target groups are given in discussions (Section 4).

1.1. Organisation of the work

Detailed literature review about the analysis of scientific publications using network approach is given in Section 2. Section 3 specifies about the data collection, important concepts for networks and the methods used for this investigation. Results of the analysis and the discussions are given in Section 4, which includes identification of important network characteristics. The important analyses include centrality analysis, path analysis and cluster analysis. Centrality analyses helps to identify the innovations (both radical and incremental) and also the key papers of paradigm shift. Path analyses reveal the historical development of the main and critical theme of the network. Cluster analysis using FV model identifies emerging fields and the relative importance of clusters as well as the works. Discussions, findings and implications are also covered in this section. This section is followed by Section 5 which consists of conclusion. Limitations of current work, directions for future works, etc. are given in Section 6.

2. Network approach

In many scientific fields, the advancement of the field through accumulation of knowledge is tremendous so that the researchers are forced to depend on comprehensive surveys and literature reviews to remain updated about the field [13]. Several approaches can be found in the literature to study about the progress of science. Being rewards for introducing novel design, method or solution to certain problems or set of problems, patents are well regarded as proxy measures of technological advancements [31]. Hence they are widely used for evaluation of developments in research areas and even prediction of progress. Apart from patents, other intellectual properties like trademarks are used as indicators of technological growth (especially in high technology industries) by agencies like WIPO (World Intellectual Properties Organization) [32]. Business always plays an important role in delivering value of innovations and even controls the diffusion of innovations. Radical innovations often forces players in the market to forge suitable business model innovations. A recent study with the case of music industry also affirms this observation [33]. It can be found that the concept of 'business models' needs more thorough understanding by the researchers. An attempt to provide more clarity about business models had been done by Osterwalder et al. [34]. After an exhaustive research on the literature about the comparatively young concept of 'business models' they proposed the definition of business model — "A business model is a conceptual tool that contains a set of elements and their relationships and allows expressing the business logic of a specific firm. It is a description of the value a company offers to one or several segments of customers and of the architecture of the firm and its network of partners for creating, marketing, and delivering this value and relationship capital, to generate profitable and sustainable revenue streams". Works exploring the methods of value creation from business models (especially in e-commerce) which are patentable [35] can be also be found. The potential of business models in assessing the associated technological progress has not been uncovered till now and the study of business models is emerging as a management discipline. Scientific publications about high technological research fields could provide insight about the technological progress in associated industries. The importance of published articles is that, they are valuable resources which can be treated as a proxy measure of the volume of scientific activity and innovative researches in the scientific community. Another advantage of scientific publications is that it provides the analysts with a large volume of data (from lots of published works). However, immensity of information from literature is one factor which makes it difficult for researchers to identify the most relevant works for their research pursuits. The need for systematic methods for identification of relevant works including the state-of-the-art publications from the large corpus of prior literature is gaining more importance. Network analysis approach is a systematic approach which combines the power of information analysis and network theory (which has its roots in graph theory).

Network analysis approach, now has applications in many fields like social network analysis [36], transportation network analysis (for traffic assessment and control) [37], webgraphs analysis (for the structure of world-wide web) [38] and epidemiological modelling (for modelling the spread of epidemics) [39]. Patent networks, when analysed through the network approach (i.e., patent citations network), provided very encouraging results [40]. Business models and associated studies are still under the evolution process as a core research area in the management science. Consequently researches using network approach for the analysis of business models patent citations are not known. However, network approach is found fruitful for the analysis of scientific literature. The history of the quantitative study of publication patterns traces back to the Lotka's discovery (1926) of the *Law of Scientific Productivity* [41]. This ground breaking theory states that "the distribution of number of papers written by individual scientists follows a power law". During that time, the notion of *scalefreeness* [14] was not introduced. Today, most of the natural networks and also 'nature inspired' man made networks are identified to be executing a preferential attachment, which was wisely termed as 'scalefreeness' by Albert and Barabási [14]. As the power-law distribution of authors with their published works suggests, in most of the research fields, a few authors habitually publishes more work than the rest. Other notable works from the literature includes the discovery of the distribution pattern of indegrees and outdegrees [16] of papers in scientific publications network by Price [42]. He observed that these distributions also obey the power law. This was also before the introduction of term 'scalefreeness'. However, in order to verify the 'scalefreeness of the scientific networks', one could simply examine the indegree and outdegree distributions of the nodes. The notions indegree, outdegree, etc. are described in Section 3. The indirect relationships among the actors (such as authors and journals) of the scientific citation network also roused interests of researchers. The indirect or derived network analysis such as collaboration networks [43] and co-citation networks [44] are also widely explored these days.

Inspired by the increasing importance and potential of network approach for the analysis of scientific publications, we had chosen the same for our analysis of 'IT for the research area engineering', an important industry which was one of the greatest drivers of the 5th Kondratieff cycle and contributed highly to the progress of mankind in the twentieth century. This paper deals with the detection of innovations, emerging fields and paradigms in the IT field using the network. Our network obtained with the keyword search is large and dense (with 11,645 nodes and 4576 links), and suggests the bulk of knowledge accumulated in the IT field and also the intensity of flow of the information. This network indicates the direct relationships among the field papers (i.e., papers listed by the keyword search). The reduced network extracted from the network considering nodes with at least one directed arc (either incoming or outgoing) is the minimal core (of order 1), is shown in Fig. 1. It consists of 3705 papers and 4576 arcs. The 11,645 papers in the IT field cite various other papers (from various fields) so that the *citation network* consists of 286,726 nodes and 355,213 edges. This is also a direct network, but the knowledge contained in these need not be restricted to the domain indicated by the keyword used. The analyses on the citation networks of IT for engineering and its derived networks (created using the software WoS2Pajek [8]) are not included in this paper. We reserve these for future works. The IT for engineering is found to be a *scale free network* [14] which is currently in *convergence driven* growth (verified through FV model) mode and hence needs some breakthroughs in the near future. The important analyses which were done in this paper along with the interpretation of their results are given in Section 4.

3. Data, concepts and methods

In this work, network on the IT (*Information Technology*) industry in the research area *Engineering Science* is done. Papers published in top journals related to the IT for Engineering Science are collected from ISI Web of Science (WoS) [28], an online academic service provided by Thomson Reuters. Through WoS, one can access world's seven leading citation databases namely, Science Citation Index, Index Chemicus, Current Chemical Reactions, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index: Science, and Conference Proceedings Citation Index: Social Science and Humanities. Through WoS, full information, a record about an article, a book or other work, its title, authors, abstract, keywords, publication properties (keywords, journal, volume, pages, publication year, etc.) and its cited references can be obtained. The data of our work covers scientific publications in the area of interest for the span starting from 1st Jan, 1999 to 28th Feb, 2013, the crucial period of growth in IT, which could determine the future of the industry in the 6th Kondratieff cycle.

Data retrieval from WoS (for this work) is done using the advanced search option [28]. One can refine the search using various optional keywords such as authors, country, research area, organisation etc. in addition to the primary search keyword which is the topic around which scientific papers data has to be retrieved. The primary keyword (topic) and the optional keywords have codes of identification for entering the query. The Boolean operator AND combines the query terms refines the search. In this work, we used the query $TS =$ (*information technology*) *AND* $SU =$ (*engineering*), where TS is the code for topic and SU represents the code for research area. Retrieval was done on 28th February 2013. The time span for data retrieval is

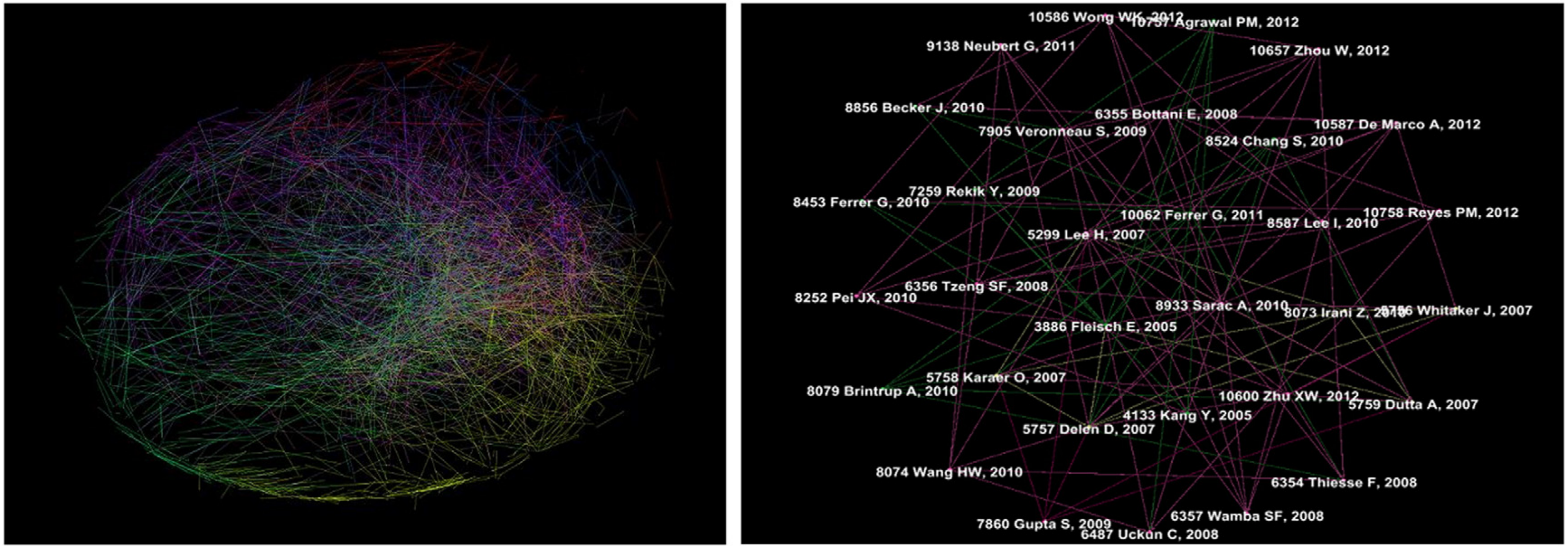

Fig. 1. (Left): Order 1 core (minimal core) of the network & (right): main core (order 5) of the network.

selected using 'all years' button because of the above mentioned importance of period. This query returned 11,645 hits in the period 1st Jan, 1999 to 28th Feb, 2013 from 1075 journals (which includes various engineering, computer science, expert systems, industrial management journals, etc.).

3.1. Important concepts

The graph theoretic concepts used to analyse the network and to conjure inference are given below for better understanding and to fix notations.

3.1.1. Core or generalised core

The core or generalised core of the network was conceptualised as a notion in 1983, by Seidman [15].

3.1.1.1. Core. Let $G = (V, L)$ be a simple directed graph. V is the set of *vertices* and L is the set of *lines* (*edges or arcs*). Let $n = |V|$ and $m = |L|$. Then, the subgraph $H = (C, L|C)$ induced by the set $C \subseteq V$ is a *k-core* or a *core of order k* if and only if $\forall v \in C : deg_H(v) \geq k$ and H is a maximum subgraph with this property.

The highest order core i.e., core of maximum order is also called the *main core*. In this paper, we take core of order 1, i.e., the core with $k = 1$ value.

3.1.2. Centrality measures

3.1.2.1. Degree centrality. Degree centrality [16] is the simplest of all topological indices and corresponds to the number of nodes adjacent to a given node v where, adjacency indicates direct linkage. Degree can be used as a measure to instantly evaluate the regulatory relevance of a node. Also it indicates a network node's interconnectedness. *In-degree* of a node u is the number of neighbours when the node u act as target for the neighbours through incoming or approaching links. *Out-degree*, on the other hand is that number of neighbours when the node u act as a source node and targets the neighbours through outgoing links. The degree centrality $deg(v)$ of a vertex v of a network with adjacency matrix $A = (a_{ij})$ is given by:

$$deg(v) = \sum_{i=1}^{n} a_{iv}. \tag{1}$$

The concept of degree centrality is that the more ties or connections a node has then, the more power or importance that node has in the network.

3.1.2.2. Eccentricity. Eccentricity [17] of a node v of a network is the distance from v to a node farthest from v. The distance of a vertex v to another node u is the number of edges in shortest v–u path in the network.

$$ecc(v) = max_{u \in V}\{d(v, u)\}. \tag{2}$$

The periphery of a graph G (network) is the subgraph of G induced by vertices that have graph eccentricities $ecc(v)$ equal to the graph diameter $d(G)$. The radius $r(G)$ is the minimum eccentricity of the nodes, whereas the diameter $d(G)$ is the maximum eccentricity. Eccentricity of a vertex indicates the position of the vertex in the network. The higher the eccentricity, the greater the likelihood to find the node in the periphery of the network.

3.1.2.3. Closeness centrality. The closeness [16] is another node centrality index, a proximity index. Proximity or closeness is treated as the reciprocal of *farness* and is calculated by computing the distances of all the shortest paths between the node and all other nodes in the network (graph), and then calculating the reciprocal of their sum.

$$C_{clo}(v) = \frac{1}{\sum w \in V dist(v, w)}. \tag{3}$$

Here, higher the values of closeness of a node, greater it make sense of node proximity. In case of closeness centrality, high and low values are more meaningful when compared to the average closeness of the graph G calculated by finding average of the closeness values of all nodes in the graph. The closeness value can be considered as an indicator of tendency of node proximity or isolation.

3.1.2.4. Betweenness centrality. The concept of betweenness centrality or S.P. betweenness was introduced by L.C. Freeman [18]. According to Freeman, "These measures define centrality in terms of degree to which a point falls on a shortest path between others and therefore has a potential for control of communication". It is a node centrality index which is considered as a crucial and informative centrality index. It is calculated considering node pairs (s_1, t_1) and counting the number of shortest paths between s_1 and t_1 and passing through a particular node v. Then, the value is compared against the total number of shortest paths from s_1 to t_1 to obtain ratio. This procedure is repeated for all the node pairs (s, t) and the summation of all the ratios gives the betweenness value for a particular node v. It can be expressed as:

$$C_{spb}(v) := \sum_{s \neq v \in V} \sum_{t \neq v \in V} \delta_{st}(v) \tag{4}$$

where, $\delta_{st}(v) := \frac{\sigma_{st(v)}}{\sigma_{st}}$, σ_{st} is the total number of shortest paths from node s to node t and $\sigma_{st}(v)$ is the number of shortest paths that pass through v.

Thus, a high S.P. betweenness score means that the node is crucial to maintain node connections for most of the paths. Shibata et al. stated that: "A paper with a large betweenness centrality bridges unconnected papers, and is therefore anticipated as a previously unexplored seed of innovation" [19]. Betweenness centrality holds the reputation for being successfully used to identify the pivotal papers of paradigm shifts [20]. Thus, in this work the major metric which is used to identify the radical innovations as well as the key papers of paradigm shifts is betweenness centrality.

3.1.2.5. Eigenvector centrality. The eigenvector centrality is based on the idea that the importance of a node depends both on number and quality of connection [21]. Larger number of connections definitely attributes to the influence it exercise on the connected nodes. However, smaller number of high quality connections may contribute to the relative importance over medium or low quality connections. Here, high quality connection means linkage to influential and important nodes in the network. The eigenvector centrality x_i of a vertex i of a network with the adjacency matrix A is given by:

$$x_i = \frac{1}{\lambda}\sum_{j=1}^{n} a_{ij} x_j \tag{5}$$

where λ is the largest eigenvalue of the adjacency matrix. Thus x_i of a vertex i corresponds to the average of the centralities of i's neighbours. In the vector notation this can be rewritten as: $\lambda\mathbf{x} = \mathbf{A}\cdot\mathbf{x}$, where $\mathbf{x}$ is an eigenvector of the adjacency matrix with eigenvalue λ. Largest eigenvalue of the adjacency matrix λ ensures that all the entries of centrality scores in the eigenvector, $\mathbf{x}$ is non-negative. The eigenvector centrality is found to be a very useful measure, especially for ranking based on importance. Search engine giant, 'Google' employed a variant of the eigenvector centrality to rank web pages, namely the 'page rank' algorithm which turned out to be of billion dollars worth and very crucial for the growth of Google.

3.1.3. Paths

3.1.3.1. Main path. The main path of a network is a path from the source (initial vertex) to the sink (terminal vertex), starting with the arc with largest weight and selecting at each step the arc to the neighbours with the largest weight [8]. The basic idea of computation of main path within a network is that of Humman and Doreian's [22]. It corresponds to the assignment of weight to each citation link based on the position in the overall network structure, which in turn is based on the existence of different search paths in the network. A *search path* is a sequence of citations which extends from a latest paper to oldest ones through intermediate papers and represents the knowledge flow through them. The metric used for assigning this weight is the SPLC (Search Path Link Count). Batagelj et al. advocated SPC (Search Path Count) [29] method for computing the Hummon–Doreian's SPLC weights in an efficient way and made it available in PAJEK. The higher the number of paths passing through the link, the more SPC weight will be assigned and hence more importance to the link.

3.1.3.2. Critical path. The critical path of a network is longest path in the network which consists of the papers which are critical to the network. Critical path method (CPM) determines the source–sink path(s) with the largest total sum of weights [7] where, weights are calculated using SPC algorithm. Successful papers are more likely to be found in the critical path.

3.1.4. Islands

Islands [27] are used to determine the 'important' subnetworks in a given network. Line islands are groups of vertices that locally dominate according to the values of lines in the network. Let $N = (V, L, w)$ be a network with line weight $w : L \rightarrow \mathbb{R}$. Non-empty subsets of vertices $C \subseteq V$ is called a *line island* of the network N if there exists a spanning tree T in the corresponding induced subnetwork, such that the lowest line of T has larger or equal weight than the larger weight of lines from C to the neighbouring vertices.

$$\max_{(u,v)\in L,\ u\notin C,\ v\in C} w(u,v) \leq \min_{(u,v)\in T} w(u,v). \tag{6}$$

Line islands are formed using line island formation algorithm [27]. Islands are used to detect emerging groups and identify locally important subnetworks (clusters).

3.1.5. FV model

We propose a new model for the temporal development of the network, flow vergence (FV) model. Knowledge propagation through network happens through flow of information from one work to another when the latter cites former. Thus the flow of knowledge happens in direction opposite to the direction of the link. This model aims to identify the type of knowledge progress in the research area. This also helps to identify the important papers in the network. The node which cites other one receives knowledge, i.e., exercises an inward flow of knowledge. Here we treat this as a convergent type flow. This will make more meaning when one node cites more than one node, i.e., receives knowledge from many works. Then, the knowledge contained in more than one work converges through flows or undergoes crossover to generate the knowledge level represented by the new work. However, the nodes which are cited by other nodes execute an outward flow of information, i.e., they provide information for the sake of growth of the research area. The type of flow in this can be treated as divergent one. A node is said to be in divergent mode when the *citations received* outnumbers the *citations made*. It is said to be in convergent mode if its outdegree outnumbers indegree. In case of a node where indegree and outdegree remains the same, the node is said to be in balanced flow vergence mode. Here the node can be considered as a passive node. This concept can be extended to determine the flow characteristics at the local cluster level where the nodes reside and also to the whole network. The local mode of knowledge accumulation can be identified by the average FV value of the cluster and the global mode of knowledge propagation can be found using network average of the FV values. Thus a new index is proposed as a metric for the identification of mode of flow vergence (either divergence or convergence of flow).

The workflow vergence indices can be calculated as follows:

$$W_{FV_{ij}} = \frac{indeg_{ij} - outdeg_{ij}}{\left(indeg_{ij} + outdeg_{ij}\right)} + \left(Eig_{ij}\right) \tag{7}$$

where $indeg_{ij}$ is the count of citations received to and $outdeg_{ij}$ is the number of citations made by the ith paper in the jth cluster, $i \in I_j$ and $j \in J$. I_j is the total number of papers in jth cluster and J is the total number of clusters. Eig_{ij} is the value of Eigenvector centrality of the node which represents the ith paper in the jth cluster. Information about the fundamental graph parameters which reflects the structure of a graph [48] can be obtained using the eigenvalues. Adjacency matrix of the graph is involved in the computation of eigenvalues and consequently the eigenvectors. This information about the topology based on connectivity is important. Since eigenvector indicates the influence of neighbours over a node in question and vice-versa, they are indicators of quality of connections too. Eigenvectors are included in the FV model in order to incorporate the quality of flow (i.e., whether the knowledge is received from or passed to a good quality work or not). The importance of quantity parameter of flow and direction is equally important. This is identified by the degrees ratio part (i.e., $\frac{(indeg-outdeg)}{(indeg+outdeg)}$), and the ratio with a minus sign indicates that inward flow (i.e., convergence) is dominant. When the quantitative indicator of the flow alone is used (i.e. the degrees ratio part), it gives less information about the quality of flow. The proposed vergence index could reasonably rank the works and clusters based on their quality as well as quantity of knowledge flow potential as it indicates both the quantitative (through degrees ratio part) as well as qualitative (through eigenvector) aspects of flow.

The *cluster flow vergence index*, $Clus_{FV_j}$ is the average of workflow vergence of works which belongs to the *j*th cluster and can be calculated as:

$$Clus_{FV_j} = \frac{\sum_{i=1}^{I_j} W_{FV_{ij}}}{I_j} \tag{8}$$

where, I_j is the total number of works in the *j*th cluster.

The *network FV index* can be calculated as:

$$N_{FV} = \frac{\sum_{k=1}^{K} W_{FV_k}}{K} \tag{9}$$

where, *K* is the total number of nodes in the minimal core of the original network.

The methodology for finding the relative importance of cluster and the relative importance of papers with in the cluster is as follows:

1) Find out the network FV index using Eqs. (6) and (8).
2) Find out *J*, the number of clusters and I_j (where $j \in \{1, \ldots J\}$), the number of papers with in each clusters after clustering using island formation algorithm.
3) Take $j = 1$, the first cluster.
4) For $i = 1, 2, \ldots, I_j$, find all the work FVs using Eq. (6).
5) Find cluster potentiality for *j*th cluster using Eq. (7).
6) Repeat 3 and 4 for $j = 2, 3, \ldots, J$.
7) Decision making based on *criteria for relative importance*:
   a) If cluster FV indices of cluster j > network FV index, cluster *j* is important for the network.
   b) If work FV for (i, j)th work > cluster FV of *j*, (i, j)th paper important for the cluster *j*.
   c) If Clus FV_j > Clus FV_n, *j*th cluster is more important than the *n*th cluster in the network.
   d) If W FV_{ij} > W $FV_{r,j}$, (i, j)th work is more important than the (r, j)th work in the *j*th cluster.
   e) If two clusters have same FV value, the latest one is to be treated as more important.
   f) If two works have same FV value, the latest one is to be treated as more important.

The major limitation of this approach is that the future potential of recent works cannot be predicted. So do the potential of emerging clusters. The FV model ranks the works within clusters and the clusters within the main research topic. This ranking is based on the performance which is dependent on the flow vergence mode at the end of the span of our interest. Identification of methods to estimate the potential of works (within the clusters) and clusters in the network, using FV model is reserved for further research.

4. Results and discussions

The main network of IT (for the span Jan 1, 1999 to Feb 28, 2013) is shown in Fig. 1 (left). It consists of 3705 papers (nodes) and 4576 reference links (arcs). The densest part of the network, given by the highest order core is shown in Fig. 1 (right). As mentioned earlier, the number of nodes (works) represents the volume of scientific activity in the field. The links which contribute to the density of the network represent the knowledge flow within these information network. Since the densest part of the original network is represented by its maximal core, the important papers of the network with high connectivities might be present in this sub-network.

While analysing the papers in densest part of the network, it is found that most of the papers deal with topics related to radio frequency identification (RFID). There are 30 papers and they are listed below:5299 Lee H, 2007, 5756 Whitaker J, 2007, 5757 Delen D, 2007, 5758 Karaer O, 2007, 5759 Dutta A, 2007, 6354 Thiesse F, 2008, 6355 Bottani E, 2008, 6356 Tzeng SF, 2008, 6357 Wamba SF, 2008, 6487 Uckun C, 2008, 7259 Rekik

Table 1
Top 13 papers with high indegree and outdegree.

Label of works	In-degree (>15)	Label of works	Out-degree (>11)
5299 Lee H, 2007	29	10,546 Xue XL, 2012	28
2901 Jaselskis EJ, 2003	26	10,089 Hernandez-Ortega B, 2011	18
2849 Yi MY, 2003	22	8933 Sarac A, 2010	16
3886 Fleisch E, 2005	21	5143 Chow HKH, 2007	15
3351 Nitithamyong P, 2004	20	3351 Nitithamyong P, 2004	13
4871 Thong JYL, 2006	19	5132 Muller M, 2007	13
2737 Gefen D, 2003	18	5179 Gunasekaran A, 2007	13
5757 Delen D, 2007	18	9065 Vancza J, 2011	13
6356 Tzeng SF, 2008	18	10,705 Kang Y, 2012	13
970 Mitropoulos P, 2000	16	9094 Cheng LC, 2011	12
5759 Dutta A, 2007	16	7860 Gupta S, 2009	11
6355 Bottani E, 2008	16	9044 Kuo RZ, 2011	11
385 Brewer A, 1999	15	9125 Xu X, 2011	11

Y, 2009, 7860 Gupta S, 200, 7905 Veronneau S, 2009, 8073 Irani Z, 2010, 8074 Wang HW, 2010, 8079 Brintrup A, 2010, 8252 Pei JX, 2010, 8524 Chang S, 2010, 8587 Lee I, 2010, 8856 Becker J, 2010, 8933 Sarac A, 2010, 8453 Ferrer G, 2010, 9138 Neubert G, 2011, 10,062 Ferrer G, 2011, 10,586 Wong WK, 2012, 10,587 De Marco A, 2012, 10,600 Zhu XW, 2012, 10,657 Zhou W, 2012, 10,757 Agrawal PM, 2012, and 10,758 Reyes PM, 2012.

The other two papers 3886 Fleisch E, 2005 and 4133 Kang Y, 2005 tackles the problems '*inventory inaccuracy and supply chain performance*' and '*information inaccuracy and information systems*'. The former states in its conclusion that automatic identification technologies (which were gaining popularity those days) has potential to offer inventory accuracy, while later, concluded that even without automatic product identification, inventory inaccuracy problem can be effectively addressed. The paper 5299 Lee H, 2007 which is intended to *unlock the value of RFID* shows reference links to the above two papers and received 29 citations by followers. This paper proves to be a very crucial one in the case of information flow about RFID technology. The latest paper in the list, 10,758 Reyes PM, 2012 is all about assessing antecedents and outcomes of RFID implementation in health care. It is identified that, for future implementers and current implementers of RFID in health care, the barriers of RFID appears to get lower and benefits tends to be higher compared to the non-implementers.

4.1. Centrality analysis

Other important analyses done in the network (minimal core of the original network) devices the centrality measures. For example, let us start with the degree centrality. The papers arranged (in descending order) according to in-degree centralities and out-degree centralities are given in Table 1 (only values ≥ 15 for in-degree and ≥ 11 for out-degree are shown). The papers arranged in this fashion for all the other centrality measures are given in Table 2.

From the in-degree and out-degree tables, many important things can be learned. The topmost entry in the in-degree table is 5299 Lee H, 2007 with in-degree centrality value 29. The indication is that, the paper is the most cited paper among the original works network. As earlier mentioned, this paper which unlocked the value of RFID proved to be very crucial one in the last decade to the industry. The paper which cited most number of other papers from the original information network is 10,546 Xue XL, 2012 whose out-degree is 28. The title of that paper is '*IT supported collaborative work in the A/E/C Projects: A ten year review*'. The significance of the papers with highest out-degree centrality in the original networks lies in the fact that those are most likely to contain almost all the relevant and up-to-date information (taking into account the time of publication) about the theme it addresses. This fact is established by the paper with label 10,546 Xue XL, 2012 which turned out to be a review of the collaborative project works over the last 10 years, supported by IT. The work which is published in the journal Automation in Construction, demonstrates the influence of IT in the engineering field '*construction*'. The RFID related innovations in the IT field demonstrates its influence in most of the industries. These two evidences points to one fact — "the role of IT as a supporting industry to all other industries is gaining more importance over the last decade".

Fig. 2a and b indicates that for IT, the in-degrees as well as out-degrees are distributed according to power law.

$$Count = 1251 \times indeg.^{-1.718} \quad (10)$$

$$Count = 1288 \times outdeg.^{-1.644} \quad (11)$$

where, $indeg = 1, 2, 3, \ldots, 29$ and $outdeg = 1, 2, 3, \ldots, 28$.

The power-law based distribution of both in-degree and out-degree indicates the *scale free* nature of the network. According to Barabási and Albert, scale free networks often originate from a process that each new node tends to get connected to the nodes with high connectivity. The rate of decay of outdegree seems to be more gradual compared to the indegree. In other words, citations received by nodes are slightly more localised (i.e. less distributed) than the citations they made. This particular nature of network corresponds to the flow characteristics of knowledge in the network. Flowvergence analysis is devised to get more insight in this regard and is given in one of the following sections.

The list of labels of top 10 papers according to the eccentricity can be identified from Table 2. They consist of the latest papers in various fields of IT and occupy the periphery of the network. The nature of innovation (whether incremental or radical?) in these cannot easily identified. The innovations in them may exhibit a cross-over nature as observed in the first paper 10,334 Lao SI, 2012 whose title is *An RFRS that combines RFID and CBR technologies*. Here, a technological crossover between RFID and CBR technologies is visible. For more insight about the nature of this innovation, these values has to be compared with other metrics (closeness and betweenness

Table 2
Top 10 papers with high values for eigenvector centrality, eccentricity, closeness centrality and betweenness centrality.

Eigen vector centrality	Eccentricity	Closeness	Betweenness
3886 Fleisch E, 2005	10,334 Lao SI, 2012	10,356 Rampersad G, 2012	5756 Whitaker J, 2007
2901 Jaselskis EJ, 2003	10,337 Ojiako U, 2012	6946 Balocco R, 2009	5413 Stratman JK, 2007
5299 Lee H, 2007	10,347 Martin SS, 2012	11,636 Lee CKH, 2013	5757 Delen D, 2007
4133 Kang Y, 2005	10,353 Chang CC, 2012	10,336 Perez-Arostegui MN, 2012	3789 Buhman C, 2005
5757 Delen D, 2007	10,354 Sila I, 2012	11,357 Dai H, 2012	8933 Sarac A, 2010
2849 Yi MY, 2003	10,356 Rampersad G, 2012	8779 Choi TM, 2010	9094 Cheng LC, 2011
5756 Whitaker J, 2007	11,080 Hameed MA, 2012	9555 Delen D, 2011	4358 Lin CH, 2006
1948 Mcafee A, 2002	11,614 Laosirihongthong T, 2013	10,353 Chang CC, 2012	2731 Liao SH, 2003
385 Brewer A, 1999	6946 Balocco R, 2009	10,347 Martin SS, 2012	8417 Shen WM, 2010
4613 Cotteleer MJ, 2006	8017 Park KS, 2010	9106 Hill SR, 2011	5133 Lee SM, 2007

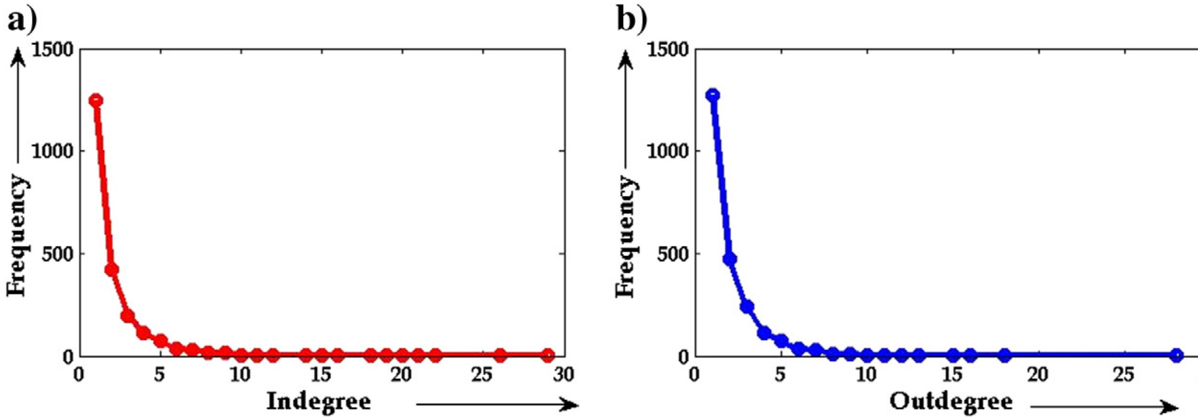

Fig. 2. a) In-degree distribution & b) out-degree distribution.

values) of the same paper which will be illustrated in following sections.

In this work the closeness centrality is used as an indicator for identifying the incremental innovations in the technology networks. High value of eccentricity indicates the peripheral position of the node in the graph. Thus, closeness value together with eccentricity value help to identify incremental innovations in the periphery in a network. The papers with top 10 high values of closeness centrality are given in Table 2. Here, it can be viewed that 4 papers which are appearing on both the tables as given below (the values in brackets indicates their eccentricity values as well as closeness as ordered pairs).

10,356 Rampersad G, 2012 (7,4.0338), 10,353 Chang CC, 2012 (7,3.6), 10,347 Martin SS, 2012 (7,3.5818) and 6946 Balocco R, 2009 (6,3.9444). The first one advocates the qualitative assessment of drivers of Inter-Organisational Systems (IOS) for aiding the creation of a network frame work rather than the conventional approach focusing individual-organisation. The second one is intended to explore the dynamic capabilities required for IT entrepreneurs and identified *market-oriented sensitivity*, *the ability to absorb knowledge*, *social-networking capability*, *and the integrative ability to communicate and negotiate*, etc., as the essential qualities of an IT entrepreneur for building competitive advantage. The purpose of third work was to identify the factors which impact firm's perceived performance of M-commerce. The fourth paper focused on the adoption of business to employee (B2e) mobile internet (MI) applications in Italian small and medium enterprises (SMEs). The themes handled in other incremental innovations which are not found at the periphery are: *a review of innovative quick response programmes*, *broadband adoption in rural Australia*, *RFID based sensors in perishables supply chain*, *information technology-enabled quality performance*, *impacts of RFID implementation on reducing inventory inaccuracy in multi-stage supply chain*, and *RFID based resource allocation system for textile manufacturing*.

In this work, betweenness centrality is used as the metric that signifies the radical innovations in technological networks. The papers with high betweenness centrality imply their relevance as regulatory centre in the network so that they could bridge the knowledge gap in the innovation networks and maintain the continuity. Also here, high and low values are more meaningful when compared to the average S.-P. betweenness value of the network. In Table 3, the top 6 papers carrying themes of information of radical nature are listed with titles and betweenness values (>200).

The top-on-the list paper, 5756 Whitaker J, 2007, proposed a theoretical framework for RFID adoption and benefits and tested the same on data from U.S. firms. Whitaker et al. established that a positive association can be seen between IT application deployment and RFID adoption. The theme surely qualifies as a radical innovation since the technological innovation and business model innovation are on an upper scale. The framework for RFID adoption is discussed. This can be viewed as the proposal for setting up of new framework for research and allied activities based on the scientific and technological breakthrough namely '*radio frequency identification*'. To top it all, an important suggestion — *firms with broad IT application deployment and a critical mass of RFID implementation are more likely to report the returns earlier* [23] is given. This important piece of information proved very vital for the later developments in the field and enhancement of RFID adoption. 5413 Stratman JK, 2007, deals with the theme '*realisation of ERP benefits and the role of strategic objectives behind the implementation for such*

Table 3
Top 6 papers, their titles and betweenness values.

Label	Title	Betweenness value
5756 Whitaker J, 2007	A field study of RFID deployment & return expectations	573.333
5413 Stratman JK, 2007	Realizing benefits from enterprise resource planning: & does strategic focus matter?	347
5757 Delen D, 2007	RFID for better supply chain management through enhanced information visibility	301.333
3789 Buhman C, 2005	Interdisciplinary and inter organisational research: establishing science of enterprise networks	226.833
8933 Sarac A, 2010	A literature review on the impact of RFID technologies on supply chain management	222.483
9094 Cheng LC, 2011	A technology centric framework for investigating business operations	200.5

benefits'. One of the hypotheses — *firms with different strategic objectives will realise different operational benefits from ERP systems adoption*, was tested and the result from survey on North American manufacturing firms implies that ERP adopters who seek operational performance improvement are likely to realise these benefits. 5757 Delen D, 2007, used the identified performance metrics on the data of cases supplied to one retailer by its major supplier, which represented mean time of movements at different locations. A discussion was followed, emphasising how these could assist in improving logistical performance of micro level supply chain and how such information could be valuable for both retailer and the supplier.

The fourth one proposes an operations management research focus which is based on a new business model — *organisation as a network*. Ubiquitous information sharing through the network enabled by IT is the key factor which determines the formation and sustainability of this framework. This helps member firms to harness the benefits of interdisciplinary and inter-organisational research in the operations management activities. It establishes that the future of operations management lies in the scientific activities from an interdisciplinary perspective [46]. The fifth work in Table 3 which deals about the potential impacts of RFID technology on supply chain management uses literature review and surveys to identify the same. Value creation benefits such as reduction of inventory losses, increase of the efficiency and speed of processes and improvement of information accuracy could be achieved in supply chain management, according to this work. The work identified various RFID systems (with differences in tags, readers, frequencies and levels of tagging) and suggests that cost and potential of each system change in a wide range. Brief survey was employed to study potential benefits against inventory inaccuracy problems and other challenges. Literature review covered various works which addressed analytical modelling, simulations, case studies and even ROI (return on investment) analysis [47]. The work is concluded that in order to gain more out of RFID, the firm has to choose right technology and environment. The sixth work in Table 3, found out that in industrial management research, technology centric framework poses great advantage over traditional process-centric and organisation-centric view and presented a 'trinity framework' where technology, organisational structure and business processes impacts one another for investigating business operations. Their key finding is very much relevant for the future progress of the firms which can be pronounced as "today's technology-intensive environment, organisational structures and business processes need to be developed or modified in coordination with technological development " [24]. They concluded that any firm which devices this innovation, i.e., technology centric framework, may gain the potential to harvest most benefits out of it.

From the table, most of the works with high betweenness values are related to industrial and operational performance enhancement through IT. These radical innovations are found to carry themes which revolve around RFID adoption for revolutionising business processes. This can be viewed as evidences for the *paradigm shift* in industrial applications especially supply chain management. RFID adoption for supply chains has not only revolutionised the supply chain management activities but also set new higher industrial standard practices. Bagchi et al. recognised RFID as a new paradigm in identification and tracking technology which is much superior to other identification technologies as they reduce mean and variance of inventory cycle times to an impressive extend [25]. Wal-Mart and other companies had seen the great benefits of RFID [47] so that their supply chain efficiency could be improved and even the suppliers could also benefit in the long-run [26]. The papers which played pivotal roles (all belongs to the main island which is the giant component) in the paradigm shift related to supply chain management through RFID technology are shown in Fig. 3. The important papers of the paradigm shift also appear in the critical path of the network (Fig. 4).

4.2. Path analysis

The path analysis of the network may reveal the evolution of some important themes in the IT field. The propagation of knowledge through these can be traced and more insight about the industry and the scientific drivers of the progress of the industry can be understood using the path analysis. The important paths of the networks — main path and critical path can be of help. Humman and Doreian [22] argued that by identifying the main paths of a network, one is thereby identifying the relationships between pieces of knowledge and therefore, they should be viewed as 'main flows of knowledge' in the network. Critical paths are also very crucial for the network and are likely to contain the critical pieces of knowledge most of which could qualify as breakthrough works.

4.2.1. Main path analysis

The main path of the original network is obtained by the SPC algorithm [29]. It consists of 9 nodes and 8 links. It is shown in Fig. 4. The green arrows represent the knowledge flow, which takes a direction opposite to that of reference links. The structural analysis reveals that the path appears to hold two branches. This almost symmetric branching indicates three things: 1) the crossover of two ideas at the top, 2) the propagation of the idea with information accumulation through the middle and 3) the divergence i.e., burst of new ideas at the bottom.

The main path reveals that two earlier papers — 548 Basu C, 2000 and 1706 Hedelin L, 2002 have undergone a crossover in terms of knowledge and the theme of paper 2340 Gelle E,2003 was developed. *Information quality for strategic technology planning* (the third paper) extends the information from *Diffusion of executive information systems in organisations and the shift to web technologies* and *IT strategic decision making*. Thus one of the main challenge and the purpose for which IT has been desperately used that days was in strategic decision making, strategic technology planning etc. and the use of information systems was one of the keys of success despite many problems. From there the evolution continued through themes of industrial management applicabilities like *Strategic information systems planning model for building flexibility and success*, *identification of role of strategies and IT application for excellent supply chains*, *reducing IT based transaction costs in supply chains* and *knowledge management systems adoption*. 2340 Gelle E, 2003 and these three papers show a chain like evolution and from the knowledge management systems adoption paper, the divergence is seen, first one seeks the

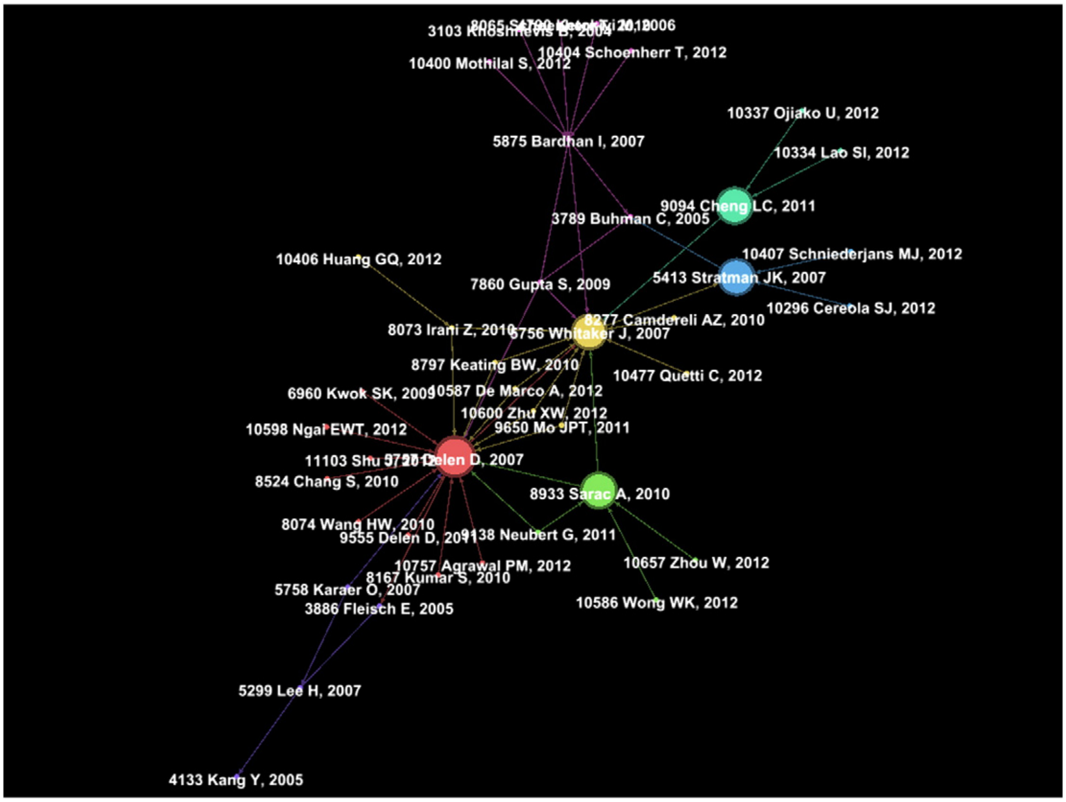

Fig. 3. Part of the main island of IT for engineering which shows important papers about the paradigm shift and the establishment of new paradigm — 'RFID for the supply chain management'.

usage of IS/IT to enhance service delivery and the other deals with an RFRS that combines RFID and CBR technologies.

4.2.2. Critical path analysis

The critical path consists of 17 nodes and 17 links. It is shown in Fig. 5. These papers are critical to the network. In other words, the backbone of the scientific network. The structure of this network fills one with the idea of the evolution of scientific knowledge as they are made up of important papers which can be treated as milestone events if they were in the project networks. The green arrows in the direction opposite to the directed network links indicate the flow of information through the network. The structure of the critical path is even more interesting as it not only holds branches like the main path but also the branches show different tendencies. One branch which has three vertices in common with the main path shows divergence which indicates emergence of new fields. The other branch shows a convergence (crossover) tendency which can likely lead to a new idea.

Starting with 1948 Mcafee A, 2002, the first part of critical path extends like a straight chain till 2007. 1948 Mcafee A, 2002 intended to empirically study the impact of enterprise IT adoption on operational performance. The work found the existence of a causal link between IT adoption and subsequent improvement in operational performance measures. The information has been flown to the second paper, 3517 Napoleon K, 2004 whose title is '*The creation of output and quality in services*: *A framework to analyse information technology–worker systems*'. The information chain then extends to the 2005 paper, 3789 Buhman C, 2005 titled as '*Interdisciplinary and inter organisational research*: *Establishing the science of enterprise networks*'. Their methodology devices the treatment of organisation as an IT enabled system, characterised by ubiquitous information sharing across traditional enterprise. In short, they proposed the new business model — organisation as a network. This one qualifies to be treated as an important bridge paper (radical innovation) as indicated by betweenness centrality value (226.833).

Next three papers — 5413 Stratman JK, 2007, 5756 Whitaker J, 2007 and 5757 Delen D, 2007 which are also of very high betweenness values, whose themes are already identified as business and operational enhancement by ERP and RFID, extends the chain further. These papers being present in the critical path prove to be very crucial for the industry. Though each of these triggers a huge number of paths of evolution, most critical branches are generated by the 5757 Delen D, 2007 (Fig. 4). The left branch consists of papers — 5758 Karaer O, 2007 which in turn shares its knowledge to two sub-branches through 8079 Brintrup A, 2010and 8933 Sarac A, 2010. The title of the first one is *Managing the reverse channel with RFID-enabled negative demand information* and that of the left sub-branch paper is *RFID opportunity analysis for leaner manufacturing*. The right sub-branch head paper whose title is already mentioned

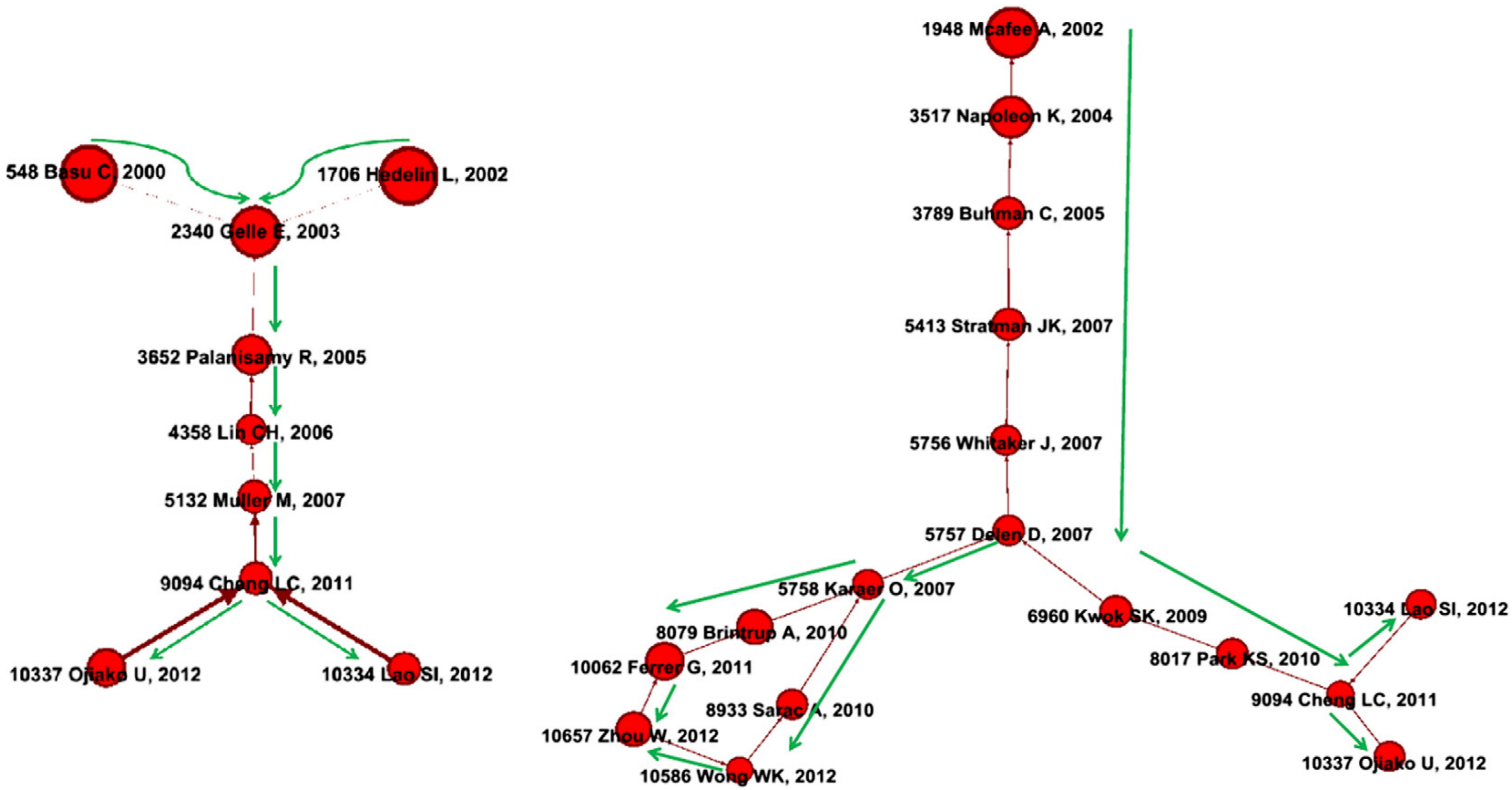

Fig. 4. (Left): Main path of the network and (right): critical path of the network.

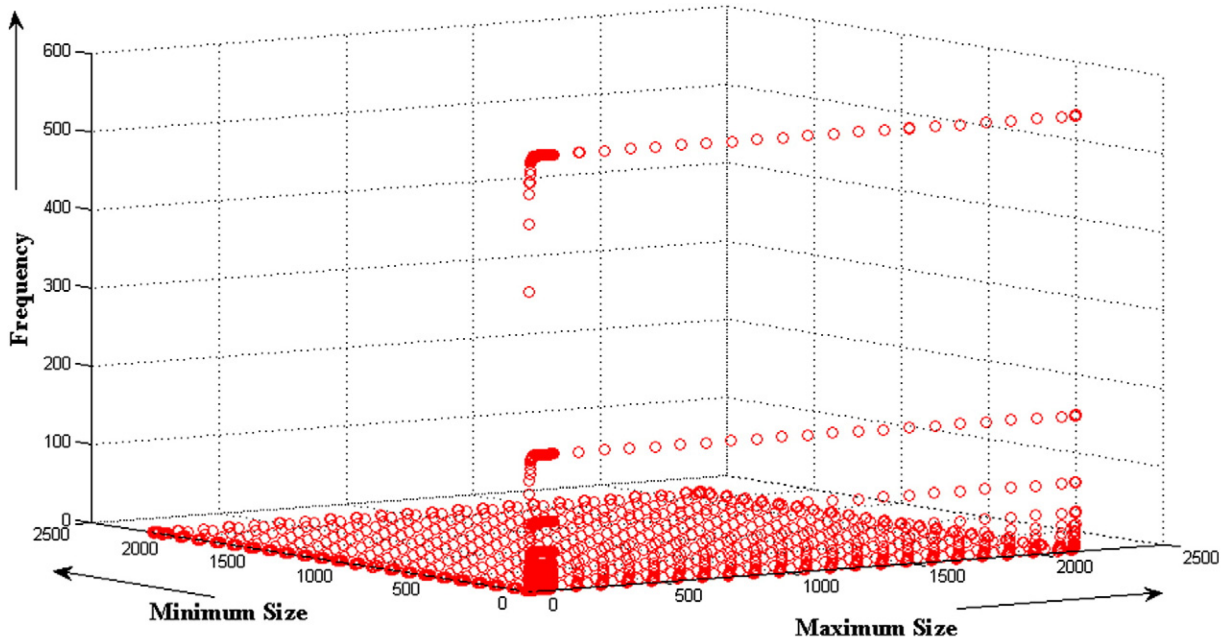

Fig. 5. 3-D plot of maximum and minimum size distributions of islands where size of giant component = 2156.

when it took its place in the betweenness table, however deals with a review on impact of RFID technologies on supply chain management. The left sub-branch extends with paper 10,062 Ferrer G, 2011 which deals with RFID application in large job shop remanufacturing operations while the right sub-branch advances with 10,586 Wong WK, 2012 which is all about an intelligent RFID based product cross-selling system for retailing. The left sub-branch is more focussed on RFID usage in manufacturing while the right sub-branch deals with RFID technology deployment in other post production functions. However, after the right sub-branch advancement on RFID usage for retailing in 2012, both the sub-branches tend to converge in 2012 itself for the 10,657 Zhou W, 2012. The title of the paper is *Manufacturing with item-level RFID information*: *From macro to micro quality control*. This indicates that to ensure quality in micro levels, both production and post production functions need to be carefully studied and the RFID technologies should be leveraged accordingly. The right branch of the critical path progresses with 6960 Kwok SK, 2009 whose title is *RFID-based intra-supply chain in textile industry* and 8017 Park KS, 2010 whose title is *Perceptions of RFID technology*: *a cross-national study*, finally reaches a branching node 9094 Cheng LC, 2011 which is also present in the main path. This paper and the branch papers from this node, 10,334 Lao SI, 2012 and 10,337 Ojiako U, 2012 are also present in the main path. The themes of these are already discussed and hence both the main path and critical path revealed timely evolutions of the important themes in the industry. Also the land mark papers in the paradigm shift are also present in the critical path.

4.3. Cluster analysis

The clusters in the industry are formed using the line island formation algorithm [27]. Islands are useful to identify the various themes of the network and hence the emerging fields. Theme identification is done using arc weights by choosing a connected small sub-network of size in the interval (k, K). Thus, islands can be chosen by specifying the minimum size as well as maximum size of the islands to be formed. Choosing different values for the minimum and maximum sizes, different number of islands can be formed. All islands, can be displayed with the choice $[k,K] = [1,|\Delta G|]$, where ΔG represents the vertex set of giant component and hence $|\Delta G|$ the size of giant component. In our network the number of nodes in the giant component, i.e. $|\Delta G|$ is found to be 2156. The distribution of number of islands with maximum and minimum chosen island sizes is given in Fig. 5. Here 19 themes of research activities associated with IT, engineering are identified using the selected size interval (8,2156). The largest island (19th cluster) obtained is the giant component with number of vertices 2156, the main island of the network. The main path, critical path, etc. belong to this island. Topmost works in most of the centrality tables also belong to this island. The islands other than the main island are shown in Fig. 6 and the themes of the 19 clusters are listed in Table 4.

The methodology for cluster analysis is based on an index of knowledge flow as well as connectivity, the *FV* (*flow vergence*) *index*. The relative importance of each cluster can be found using the *cluster FV index*. Within each cluster, the relative importance of the papers can be identified by using the index *workflow vergence*. The *work FV index* can be viewed as an indicator of the dominance in vergence i.e., divergence or convergence property of the work over the span of evolution under consideration (1999–2013). Cluster FV index indicates the overall dominant vergence trend i.e., either convergence or divergence of the cluster. Each cluster indices are compared against the *network flow vergence* index, N_{FV} to identify how important that cluster is to the industry.

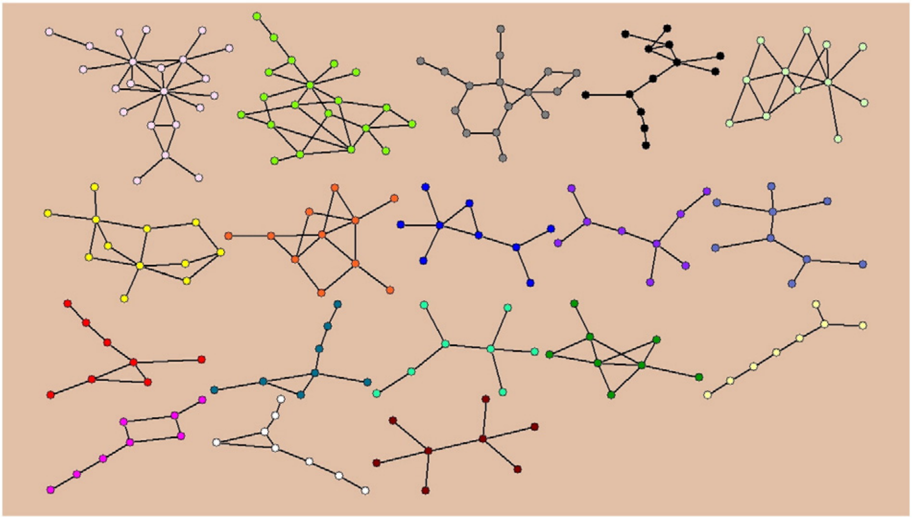

Fig. 6. 18 islands from core 1 network other than the main island.

The network vergence index is needed to be found out before moving for the analyses of various clusters. The value of the index is, $N_{FV} = \frac{-54.9802672}{3705} = -0.014839478$. The general trend of network can be found more skewed towards the convergence property. This indicates that there is less number of divergences than convergences. Convergences or information crossovers indicate the development of a new concept as a result of combination of two or works. Divergences often cause the emergence of large number of new fields from an innovation seed of radical nature. In the case of IT network, the convergences or crossovers which happen more frequently than divergence indicates the presence of a few radical innovations. Though, radical innovations occurred less frequently, they were generally of high *generative potential*, so that lot of contributions were made by them and their follow up works. The detailed analysis of the first cluster is as follows.

4.3.1. Cluster # 1

Cluster # 1 consists of 12 nodes and 15 links. The work FV indices are calculated as shown in Table 5. From the titles, it can be viewed that most of the papers deal with digital water marking techniques which are of prime importance in the case of digital rights management (DRM) and security. Rights for the owner or the proprietor of intellectual properties in the digital formats of audio, image, video and multimedia contents as well as security are attempted to be ensured by watermarking techniques. Some of papers also discuss the closely associated issues like data hiding and traitor tracing techniques which are also meant for enhancing security management of data, systems, etc. Thus the overall theme which guides this particular cluster is the "*digital watermarking, digital rights and security management*".

The knowledge flow index for cluster #1, FV index is calculated as shown:

$$Clus_{FV_1} = \frac{1.0358 + 1.0226 + \ldots - 1}{12} \approx -0.327 \qquad (12)$$

i.e., $Clus_{FV_1} < N_{FV}$, and hence cluster # 1 is relatively less important for the IT industry and its contributions have less effect in determining the industrial progress during the span 1999–2012. However, there are some works which contributed to the growth of the theme contained in the cluster # 1. Those are arranged in their order of importance, which is evaluated using the criteria $W_{FV_{i1}} > Clus_{FV_1}$ and can be found in Table 6.

The ranking of all the papers with their importance are shown in Fig. 7. One of the interesting things which can be noticed is that the present papers address both DRM and security issues as though they are related in grass root levels.

4.3.2. Cluster # 2

The second cluster consists of 20 works and 29 links. The work FV indices of various papers can be found out as mentioned above. While analysing the works in this cluster, we found that most of the works deals with researches related to tactile sensing technology. Most of works were on medical applications like minimum invasive surgery including robot assisted ones. The theme of the cluster can be "*Tactile sensing technology and its applications*". This cluster is of relatively less importance to the industry as a whole. More fail safe and accurate diagnosis to aid risk free surgeries and therapies can be anticipated in future with the developments in tactile sensing technology.

4.3.3. Cluster # 3

Cluster # 3 consists of works related to communications, especially conversational interfaces, speech and language technologies, wireless broadband related research etc. There are 9 papers and 8 links. Divergence dominance is executed by the cluster. The important papers which contributed to the cluster growth and made the cluster important to the whole industry are listed in the table. The overall theme which directs this cluster is that of *Audio, speech and language processing technologies for communication*. This is one of the fields where new revolutions are anticipated in the industry.

Table 4
Identified clusters and their themes in the core 1 network.

Cluster id.	Cluster theme
Cluster # 1	Digital watermarking, digital rights and security management
Cluster # 2	Tactile sensing technology and its applications
Cluster # 3	Audio, speech and language processing technologies for communication
Cluster # 4	Infrastructure and road safety management systems
Cluster # 5	Brain–computer interface technologies
Cluster # 6	Technology intelligence systems and technology management
Cluster # 7	Ergonomics: children and IT
Cluster # 8	Light Detection and Ranging (LIDAR) technology & its applications
Cluster # 9	Engineering computations and IT based monitoring & assessment
Cluster # 10	Intelligent distributed control systems and ontology generation
Cluster #11	Circuits and systems for biomedical applications
Cluster # 12	Information and communication technologies
Cluster # 13	Energy and e-waste management
Cluster # 14	Intelligent vehicle navigation systems
Cluster # 15	Carbon capture and storage technologies
Cluster # 16	Image & video processing technologies and standards
Cluster # 17	E-learning and education management systems
Cluster # 18	Smart grids: communication and security
Cluster # 19	IT applications in engineering and management

Table 5
Works in cluster # 1 and their FV values.

Labels	$indeg_{ij}$	$Outdeg_{ij}$	Betweenness centrality	$Eig._{i1}$	W_{FVi1}
330 Hartung F, 1999	6	0	0	0.035789	1.03579
331 Wolfgang RB, 1999	5	0	0	0.0226136	1.022614
1032 Hartung F, 2000	1	1	0.5	0.0045227	0.004523
1837 De Vleeschouwer C, 2002	0	2	0	0	−1
2309 Ejima M, 2003	0	1	0	0	−1
2610 Eskicioglu AM, 2003	1	1	0.5	0.0045227	1.004523
3124 Lin ET, 2004	0	2	0	0	−1
3188 Barni M, 2004	2	0	0	0.0090454	1.009045
4776 Frattolillo F, 2006	0	3	0	0	−1
7220 Ercelebi E, 2009	0	3	0	0	−1
8578 Nakayama H, 2010	0	3	0	0	−1
9579 Hsieh SL, 2011	0	1	0	0	−1

4.3.4. Cluster # 4

The works in cluster # 4 are related to an important engineering application in daily life. The road and infrastructure safety has been an important concern for man. Owing to the ever increase in the number of road accidents and the threat of natural disasters as well as anthropogenic accidents such as fire and short circuits in infrastructures, the concern will remain important. Hence, the theme of the cluster is identified to be *Infrastructure and road safety management systems*. The 9 works tackle with the management of safety of road and infrastructures and they are connected by knowledge flow through 9 links. Most of the works deal with RSMS (road safety management systems). The cluster is relatively important to the network and is divergence driven. The important papers of the cluster are listed in Table 7.

4.3.5. Cluster # 5

The works in cluster # 5 are mainly oriented towards the theme *Brain–computer interface technologies*. It is the largest cluster and consists of 22 works and 29 links. Despite the bulk of scientific activities, the overall cluster average vergence index is −0.48593. This indicates that the cluster is relatively less important as far as the industry is concerned. Most of these recent works are on EEG based BCIs and controlled Functional Electrical Stimulation system. This cluster, being convergence

Table 6
Important works in cluster # 1.

Cluster # 1 ($Clus_{FV_1} = -0.327$) work id.	$W_{FV_{i1}}$	Title of works
330 Hartung F, 1999	1.035789	Multimedia watermarking techniques
331 Wolfgang RB, 1999	1.022613	Perceptual watermarks for digital images and video
3188 Barni M, 2004	1.009045	Data hiding for fighting piracy
2610 Eskicioglu AM, 2003	0.004523	Security of digital entertainment content from creation to consumption
1032 Hartung F, 2000	0.004523	Digital rights management and watermarking of multimedia content for m-commerce applications

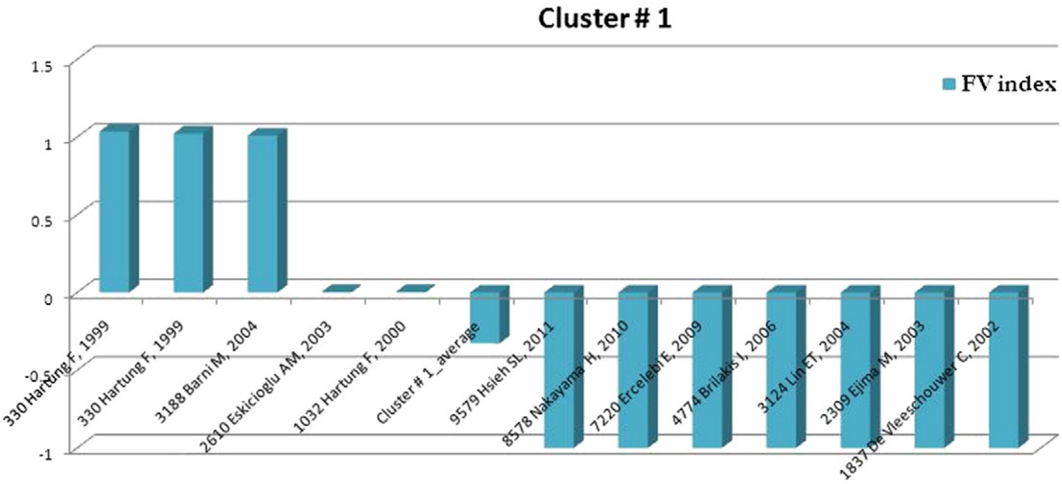

Fig. 7. Works in cluster #1, arranged in decreasing order of importance.

driven currently, awaits some radical innovations for its own revolutionary growth and for the sake of mankind.

4.3.6. Cluster # 6

The sixth cluster consists of 8 papers and 8 links. Most of the works deal with technology intelligence systems. The cluster vergence index is found to be ≈0.088937705. This is a divergence driven cluster and also this cluster is relatively important in terms of its contribution to the growth of the network. The important works in the cluster are given in table. The importance and advantage of technology intelligence systems have been surprisingly started to gain acknowledgement from business strategists and other decision makers. This cluster which proved its generative potential is likely to have a very promising future.

4.3.7. Cluster # 7

Cluster # 7 consists of 11 papers and 15 links. One important thing which can be noticed is that most of the works are oriented towards ergonomic aspects of the computer usage, especially in children. Researches aim to ensure effective usage of computers with sufficient muscle activity by the children. This theme is of very much importance in terms of the social value. Important thing to be noticed about this cluster is that almost all the works are co-authored by Straker. Out of that most of them have Straker as the first author. More radical flavoured researches are welcome in this theme for ensuring its growth.

4.3.8. Cluster # 8

There are 8 works and 8 links in the 8th cluster. Most of them deal with researches on Light Detection and Ranging (LIDAR) and its various applications in fields like: transportation planning for *high way safety* and *floodplain delineation*. The important papers are listed in the table. The performance of this cluster for the span of our consideration has been satisfactory. Though the theme is not under urgent need for radical flavoured works, scope for more research is always out there since the problems dealt by the cluster are of prime importance to the mankind.

4.3.9. Cluster # 9

The 9th cluster consists of 9 works and 8 links. The papers address the problems which make use of engineering computations in risk assessment, monitoring and modelling various natural phenomena, natural resources and various systems which interacts closely with the natural resources. Some papers also deal with the development of advanced traveller information systems which are coming under intelligent transportation systems. The overall theme of cluster can be viewed as *Engineering computations and IT based monitoring and assessment*. The papers which contributed most to this cluster can be found in table. The progress of this cluster can be crucial to the mankind

Table 7
Important research clusters within the industry.

Cluster id	Cluster theme	Cluster FV value	Mode of growth
Cluster # 10	Intelligent distributed control systems and ontology generation	0.338372366	Divergence driven
Cluster # 4	Infrastructure and road safety based management systems	0.190669373	Divergence driven
Cluster # 9	Engineering computations and IT monitoring and assessment	0.190166849	Divergence driven
Cluster # 8	Light Detection and Ranging (LIDAR) technology & its applications	0.130063544	Divergence driven
Cluster # 6	Technology intelligence systems & technology management	0.088937705	Divergence driven
Cluster # 3	Audio, speech and language processing technologies for communication	0.042018701	Divergence driven
Cluster #19	IT applications in engineering & management	−0.006661218	Convergence driven

and for the same reason, sustained efforts should be there to ensure that.

4.3.10. Cluster # 10

The cluster # 10 consists of 8 works and 7 links. High relative importance of cluster, divergence driven knowledge accumulation can be understood from analysis. Here also, most of the works are originated during the later half of the time span. Important papers are listed in the table. Theme of the cluster is *Intelligent distributed control systems and ontology generation*. The applications of researches in this theme are of immense reach (even in robotics) and are of current as well as futuristic relevance.

4.3.11. Cluster # 11

The 11th cluster of the network consists of 8 works and 11 links. The works are generally on circuits and systems and the application areas include biomedical engineering. The cluster is found to be relatively less important in the network and also the flow of the knowledge in a convergence driven mode. Reiger et al. are the important authors who contributed to this theme and most of the works are new, they are more of incremental addition of knowledge and the theme need radical flavoured works for its progress.

4.3.12. Cluster # 12

The cluster # 12 consists of 16 papers and 18 links. Most of the works are oriented towards the assessment of impacts of ICT (information and communication technologies) on applications like social behaviour and social networks, transportation etc. The mode of knowledge accumulation is that of convergence. There are some important authors who contributed to the cluster, from which *Mosa A* is a prominent one. The cluster needs some radical flavoured research works to fuel its progress.

4.3.13. Cluster # 13

The thirteenth island consists of 13 papers and 13 links. The overall theme of the cluster is *Energy and e-waste management*. Recent works in the field includes *Radio frequency identification* (*RFID*) *and communication technologies for solid waste bin and truck monitoring system* also. More innovations which are of revolutionary capability should be encouraged and diffused for the practical usage as technologies so that the current crisis of energy and waste disposal can be avoided. This cluster is undoubtedly one of the clusters which need prime focus of researchers, policy makers and industrialists.

4.3.14. Cluster # 14

The works in this cluster are mostly about positioning and navigation technologies. There are 8 papers and 7 links. This convergence driven cluster is of less importance to the network. More radical flavoured works are welcome to improve the performance of the cluster so that in the coming years, the positioning and navigation systems can be incorporated in almost all the vehicles with comparatively low cost and ensure risk free and safe travels.

4.3.15. Cluster # 15

The fifteenth cluster consists of 12 papers and 15 links. Most of the works are oriented towards research topics with environmental concern, especially global warming issue. The role of green house gases in global warming is not second to any other factors affecting it. The most abundant green house gas, carbon dioxide has lot of natural as well as man-made sources. Researches are being conducted to reduce the emission of carbon dioxide from anthropogenic sources and control the concentration of atmospheric CO_2. The theme of this particular cluster is *Carbon capture and storage technologies*. Cluster desperately needs break through inventions and innovations.

4.3.16. Cluster # 16

The sixteenth cluster consists of 8 papers and 7 links. The papers are mostly of signal processing oriented research, especially image and video processing with applications in many fields including robotics. The cluster performance for the span under consideration has not been satisfactory and the mode of knowledge flow has been driven by convergence. The overall theme of cluster is of *Image and video processing technologies and standards*. Performance of cluster can be improved with some radical flavoured works.

4.3.17. Cluster # 17

The cluster # 17 deals with educational enhancement technologies using IT. The cluster has 8 papers and 8 links. This comparatively young cluster progresses through convergence style of knowledge flow. The cluster is relatively less important to the industry. The overall theme of the cluster is about *E-learning and education management systems*. This socially relevant, young cluster can evolve into a great potential one if research works are motivated and well directed towards revolutionary *breakthroughs*.

4.3.18. Cluster # 18

The 18th cluster is all about smart grids. Smart grids are the new generation power grids. These intelligent power grids, have the power consumption control capability. They make use of the state-of-the art technologies in all the important fields like sensing, communication from user to the network and back. The effective assessment of the power usage and effective communication is crucial for success of power grid. Security from all kinds of attacks including cyber attacks is another important challenge. The overall theme of this cluster is *Smart grids*: *Communication and security*. This cluster is comprised of 8 papers and 8 links and exhibits convergent driven knowledge accumulation mode. It may evolve out to occupy commanding position in the progress of mankind if fuelled by sustainable revolutionary research works.

4.3.19. Cluster # 19

This is the largest cluster with 2156 nodes and links. The most critical works as well as the critical and main flows of knowledge for the span of our concern can be found in this cluster as main path and critical path etc. belongs to this main line island. Most of the works associated with this island deals with the supply chain management and related issues and the IT advancements in addressing the challenges. Thus the theme of this cluster can be recognised as *IT applications in engineering and management*. Being the giant component and the home for critical works, the papers (shown in Fig. 3) associated with the paradigm shift — *RFID for supply chain management*, belong to

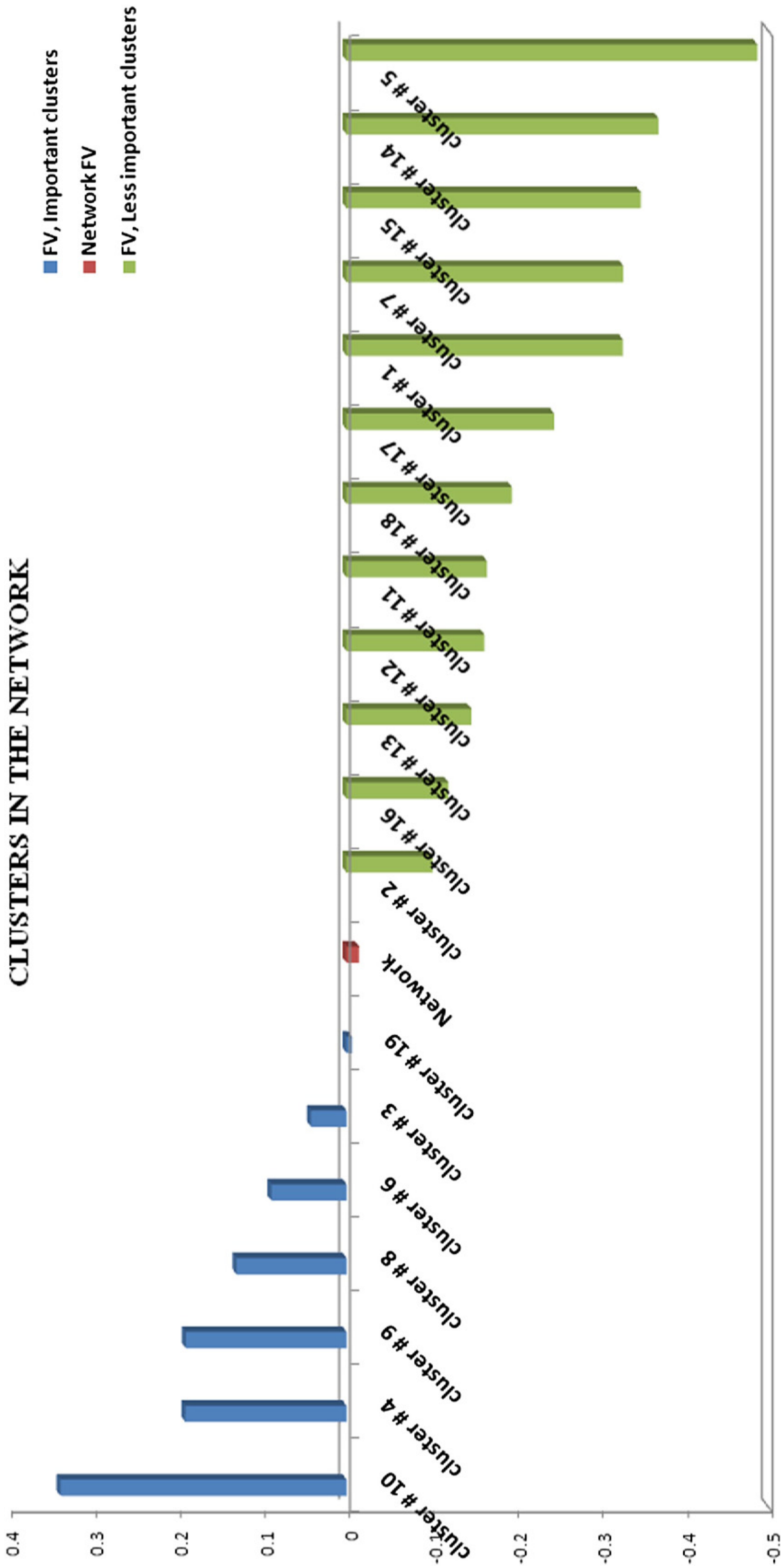

Fig. 8. All 19 clusters arranged in their decreasing order of importance.

this cluster. Effective management of supply chain had been one of the major challenges for the firms, whose business processes involve manufacturing. Our analyses (both centrality and path analysis) identified that certain works dealing with RFID are critically important to the cluster and invoked a paradigm shift as they influenced the later research activities in supply chain management and introduced a new research framework. The performance of the cluster during the span of our interest can be identified from the Cluster FV value. The value (−0.006661218) suggests that cluster performance is relatively important to the network. The cluster is currently in convergence driven mode of growth. This indicates that the cluster needs more rigorous and focussed research activities and the attention of funding agencies and decision makers.

All the clusters arranged in order of their importance to the network are shown in Fig. 8. From all the clusters the important ones are identified as given in Table 7 with their themes and vergence index.

The important works with in the emerging clusters are listed in Table 8. Table 9 shows important works with in relatively important clusters of the industry. The relatively less important clusters to the industry are listed in Table 10 with their cluster vergence indices.

4.4. Findings and major implications

Various findings of our analyses have different implications to various target groups. In general, the centrality analyses and path analyses identified the: i) radical innovations or critical works which played great role in the critical knowledge flows in the network, and ii) the paradigm shift occurred in one of the major industrial challenge of supply chain management, the RFID technology. Cluster analysis based on line island formation algorithm and FV model based performance ranking identified the: i) important research themes, ii) emerging research themes, and iii) the attention needed themes and the varying degree of attention required for their sustainability. These are given as follows.

4.4.1. Potential implications of the findings for various target groups

For *science and technology policy makers*:

1) Radical innovations and consequently the paradigm shift are identified in research related supply chain management (SCM). Considering industrial importance of SCM and the potential benefits RFID technology offers, special emphasis might be given to this area of research on policy formulations.
2) The cluster performances also indicates that for sustainability of the largest cluster which includes the supply chain management, more scientific and economic attention are required as it is currently in convergence driven mode of growth.
3) Emerging fields requires very intense scientific attention as well as R&D funding.
4) Environmentally important fields such as *carbon capture & storage* (CCS) *technologies*, and energy and e-waste management also require a drastic sequence of radical innovations which could trigger paradigm shifts. Directed R&D efforts should be employed.

For *industrialists and investors*:

1) Business firms associated with supply chain management might find great opportunities in RFID systems integration. Even though huge investment and technical difficulties might be encountered as the paradigm shift is still on the move, proper choice of technologies and management practices might turn the tide in their favour.
2) Six other relatively good performing clusters in the industry are also identified which could offer good profitable investment opportunities. Strategic decisions such as acquisitions and mergers also require an updated evaluation of importance of industrial fields just like the evaluation of the attributes of other firms.
3) Investors interested in emerging fields could go for funding the projects associated with *smart grids* and education management systems which could offer high returns on high risks.
4) In today's green conscious world, the choice of environmentally important research fields like CCS technologies will be a worthy choice for corporates. Energy and e-waste management, which are burning problems, could bring socio-environmental as well as monetary values.

For *researchers* (*academia as well as industry*):

1) In many management and engineering problems, the advancement of IT provided new leads. There are plenty of research opportunities in this subfield (19th cluster). Regarding the paradigm identification with the supply chain management, academic and industrial researchers in supply chain management are the most recognised, direct beneficiaries. The current paradigm in supply chain management which governs the research activities is RFID technology. This awareness provides a direction for their research and career.
2) The researchers who crave to extend their career with relatively high performing industries related to IT could chose any of seven research fields (currently 6 other clusters are ranked high than the largest cluster) for pursuing their research.
3) The researchers who are interested to work in relatively younger research fields associated with IT, smart grids

Table 8
Important works in emerging clusters.

Cluster id.	Cluster theme	Titles of important works (in decreasing order of importance)
Cluster # 18	Smart grids: communication and security	1) Toward intelligent machine-to-machine communications in smart grid, 2) Cognitive radio based hierarchical communications infrastructure for smart grid, 3) An early warning system against malicious activities for smart grid communications, 4) QoE-driven power scheduling in smart grid: architecture, strategy and methodology
Cluster #17	E-learning and education management systems	1) Permanent theoretical and practical education of teachers technical and information profile, 2) Human computer interaction model in educational software, 3) Education in the digital environment

Table 9
Most important 4 works in important clusters.

Cluster id.	Cluster theme	Titles of important works (in decreasing order of importance)
Cluster # 10	Intelligent distributed control systems and ontology generation	1) Internet-based teleoperation of an intelligent robot with optimal two-layer fuzzy controller, 2) ShareMe: running a distributed systems lab for 600 students with three faculty members, 3) Automatic fuzzy ontology generation for semantic help-desk support, 4) Distributing Internet services to the network's edge.
Cluster # 4	Infrastructure and road safety management systems	1) Information management at state highway departments: Issues and needs, 2) Enhancing pavement management systems using GIS, 3) Highway safety analysis using geographic information systems, 4) Geographical information systems aided traffic accident analysis system case study: city of Afyonkarahisar.
Cluster # 9	Engineering computations and IT based monitoring and assessment	1) Advanced traveller information system for Hyderabad City, 2) Risk assessment of a dam-break using GIS technology, 3) Assessing the effects of consumer involvement and service quality in a self-service setting, 4) Identification and monitoring of bridge health from ambient vibration data.
Cluster # 8	Light Detection and Ranging (LIDAR) technology	1) Application of light detection and ranging technology to highway safety, 2) Modelling road centerlines and predicting lengths in 3-D using LIDAR point cloud and planimetric road centerline data, 3) Impact of varied data resolution on hydraulic modelling and floodplain delineation, 4) Integration of light detection and ranging technology with photogrammetry in highway location and design.
Cluster # 6	Technology intelligence systems and technology management	1) Strategic forecast tool for SMEs: how the opportunity landscape interacts with business strategy to anticipate technological trends, 2) The choice of technology intelligence methods in multinationals: towards a contingency approach, 3) Broadband: a municipal information platform: Swedish experience, 4) Metadatabases in environmental information systems: the Locator and Communication Service (VKS-Umwelt).
Cluster # 3	Audio, speech and language processing technologies for communication	1) JUPITER: a telephone-based conversational interface for weather information, 2) Speech and language technologies for audio indexing and retrieval, 3) Speech and language processing for next-millennium communications services, 4) Wireless broadband communications: some research activities in Singapore.
Cluster #19	IT applications in engineering & management	1) Inventory inaccuracy and supply chain performance: a simulation study of a retail supply chain, 2) Implementing radio frequency identification in the construction process, 3) Unlocking the value of RFID, 4) Information inaccuracy in inventory systems: stock loss and stockout.

and educational management systems may hold many intellectual challenges in store for them. Those interested in futuristic energy solutions could also go for the research theme 'smart grids: communication and security'.

4) Other research fields with current as well as futuristic importance are CCS technologies and energy and e-waste management which hoards many hidden and open challenges.

5. Conclusion

The network analyses done in this paper were intended to reveal the important network growth characteristics of IT for engineering. The centrality analyses revealed the highly connected works and innovations of radical and incremental nature. A major paradigm shift has been identified in the field of supply chain management. The radical innovations which qualified as breakthrough works of the new paradigm — *RFID* for the supply chain management are also successfully identified. Evolution of the main flows of knowledge as well as critical knowledge flows which determined the industry for the span of our consideration are also revealed through path analysis. Various fields of research (clusters) within the network of our interest are found and most important ones are identified using the FV model. Seven technology clusters that contributed more to the growth of the field are: 1) *Intelligent distributed control systems and ontology generation*, 2) *Infrastructure and road safety management systems*, 3) *Engineering computations and IT based monitoring and assessment*, 4) *Light Detection and Ranging (LIDAR) technology & its applications*, 5) *Technology intelligence*

Table 10
Relatively less important clusters and their cluster FV values.

Cluster id	Cluster theme	Cluster FV value	Mode of growth
Cluster # 2	Tactile sensing technology and its applications	−0.101876167	Convergence driven
Cluster #16	Image & video processing technologies and standards	−0.120501795	Convergence driven
Cluster #13	Energy & e-waste management	−0.147502487	Convergence driven
Cluster # 12	Information and communication technologies	−0.163184099	Convergence driven
Cluster #11	Circuits and systems for biomedical applications	−0.166077125	Convergence driven
Cluster # 18	Smart grids: communication and security	−0.195655308	Convergence driven
Cluster #17	E-learning and education management systems	−0.245477284	Convergence driven
Cluster # 1	Digital watermarking, digital rights and security management	−0.326958834	Convergence driven
Cluster # 7	Ergonomics: children and IT	−0.327314376	Convergence driven
Cluster #15	Carbon capture and storage technologies	−0.347943739	Convergence driven
Cluster # 14	Intelligent vehicle navigation systems	−0.368879312	Convergence driven
Cluster # 5	Brain–computer interface technologies	−0.485926405	Convergence driven

systems & *technology management*, 6) *Audio, speech and language processing technologies for communication* and 7) *IT applications in engineering and management*. The emerging themes — *Smart grids*: *communication and security* and *E-learning and education management systems* are also identified using the cluster analysis. The emerging clusters (younger ones) are desperately in need for breakthroughs since they are currently in convergent mode of growth. The network as a whole is a scale free one and is currently skewed towards convergence dominant mode and requires more radical innovations. Paradigm shifts are also essential for fields like *carbon capture and storage technologies*. The implications of the findings which could feed the policy makers, industrialists and investors, researchers with valuable inputs for decision making are discussed. The potential of network analysis approach for the scientific publications has been attempted to be utilised for revealing several decision making aids for a variety of target groups. This work provided an insight about various interdisciplinary interactions and existence and emergence of various research fields. At the same time, evidence about progress of scientific fields through paradigm shifts was also unveiled. Thus, the work adheres to Kuhnian model of dynamics of science while overcoming its major challenge in identification of emerging fields and interdisciplinary knowledge domains.

6. Directions for future research

In this work, direct network obtained from keyword search is considered for the analysis. Bounded by scope limitations, we have chosen the size inputs for LIF algorithm as [8,2156]. The choice of this island size screened lots of smaller clusters (size less than 8 and can be obtained by choice of $[k \geq 2, K \leq |\Delta G|]$). Methods for a pre-cluster analysis to identify the important smaller clusters which could be considered for the clustering process should be devised and such a pursuit is reserved for future works. Another limitation is that, estimation of the future potential of papers in the emerging fields is not addressed by the FV model. The FV model based prediction is reserved for our following works. The study of the industry in the current work was based on the keyword search. FV model which has knowledge flow vergence as its basic idea, it could find similar or related applications in most of the directed communication networks. Patent citations network is one network where the model could be readily applicable. The significance and applicability of FV model on other networks such as protein interaction network, social networks and epidemiological networks needs to be carefully explored. More insights about many related fields, parallel evolutions as well as revolutions in them can be gained by the analysis of citation network (that includes external citations) of the current network. Moreover, the interdisciplinary interactions of various industries dependent on IT, engineering and vice versa are more likely to be revealed in an information rich perspective from the citations network analysis. Affiliations network (2-mode relationship) analysis could also reveal valuable information about the research field. The scope of FV model in affiliations networks is also an interesting research quest. The derived network analyses such as collaboration networks, co-citation networks which could provide very valuable inputs to policy makers, investors, scientists and other researchers etc. are also considered for further endeavours where the significance of FV model in such indirect relationships might also be explored.

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