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Analysis of the intellectual structure of human space exploration research using a bibliometric approach: Focus on human related factors

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ABSTRACT

Human space exploration (HSE) is an interdisciplinary field composed of a range of subjects that have developed dramatically over the last few decades. This paper investigates the intellectual structure of HSE research with a focus on human related factors. A bibliometric approach with quantitative analytical techniques is applied to study the development and growth of the research. This study retrieves 1921 papers on HSE related to human factors from the year 1990 to the year 2016 from Web of Science and constructs a critical citation network composed of 336 papers. Edge-betweenness-based clustering is used to classify the citation network into twelve distinct research clusters based on four research themes: "biological risks from space radiation," "health and performance during long-duration spaceflight," "program and in-situ resources for HSE missions," and "habitat and life support systems in the space environment." These research themes are also similar to the classification results of a co-occurrence analysis on keywords for a total of 1921 papers. Papers with high centrality scores are identified as important papers in terms of knowledge flow. Moreover, the intermediary role of papers in exchanging knowledge between HSE sub-areas is identified using brokerage analysis. The key-route main path highlights the theoretical development trajectories. Due to the recent dramatic increase in investment by international governments and the private sector, the theoretical development trajectories of key research themes have been expanding from furthering scientific and technical knowledge to include various social and economic issues, thus encouraging massive public participation. This study contributes to an understanding of research trends and popular issues in the field of HSE by introducing a powerful way of determining major research themes and development trajectories. This study will help researchers seek the underlying knowledge diffusion flow from multifaceted aspects to establish future research directions.

1. Introduction

According to the 2015 NASA Technology Roadmaps [1], before the first boot print is left on Mars, creating an environment in which humans can live and work in space, navigating and traveling to distant locations, manufacturing products in space, landing on and departing from planetary surfaces, and quickly communicating between the Earth and space systems are some of the formidable technology hurdles to be conquered. Thus, human attempts to explore space have been addressed by a multidisciplinary and interdisciplinary approach to the benefit of both natural and social sciences and humanities. For studies based on these approaches in the field of space exploration, bibliometric investigations have assessed the interdisciplinarity of research produced by various global space research institutes. Nederhof [2] examined the methodological assumptions behind bibliometric indicators and bibliometric data collection in the space life and physical sciences. Gowanlock and Gazan [3] assessed the interdisciplinarity of research produced by the University of Hawaii NASA Astrobiology Institute by combining bibliometric techniques with a machine learning algorithm. Taşkın and Aydinoglu [4] also undertook a bibliometric investigation of the NASA Astrobiology Institute (NAI)-funded research based on the inventory of publications co-authored through NAI funding and investigated journal preferences, international and institutional collaboration, and citation behaviors of researchers to obtain a better understanding of interdisciplinary and

Abbreviations: BC, between centrality; BCM, biological countermeasures; BP, Bonacich power centrality; CC, closeness centrality; CPM, critical path method; D, degree; DC, degree centrality; EDL, entry, descent, and landing; GCR, galactic cosmic rays; HSE, human space exploration; ISRU, in-situ resource utilization; ISS, international space station; LEO, low earth orbit; LSS, life support system; PR, pagerank; SNA, social network analysis; SPC, search path count; SPE, solar particle event; SPLC, search path link count; WOS, web of science.

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collaborative astrobiology research funded by the NAI. Eito-Brun and Rodríguez [5] reported the conclusions of a bibliometric analysis of the European Space Agency's (ESA) scientific and technical bibliographic production.

In many scientific fields, the advancement of the field through the accumulation of knowledge is substantial, and researchers are forced to depend on comprehensive surveys and literature reviews for updates in the field [6,7]. The bibliometric approach is one of the methodologies that quantitatively analyzes academic literature and can manage a large number of studies [8]. Network analysis through bibliometric tools can prove powerful in identifying established and emerging topical areas [9]. Recent bibliometric and network-based analyses have been widely adopted to explain the research trends and intellectual structure by identifying research themes and mapping the corresponding relationships in various research areas such as nanotechnology [10], cloud computing research [7], and patenting research [8].

The purpose of this study is to construct a network-based bibliometric analysis to understand the intellectual structure of human space exploration (HSE) research and to uncover underlying knowledge diffusion patterns from multifaceted aspects by (1) delineating the themes that constitute the intellectual structure of HSE discipline and mapping the relationships among the themes and (2) identifying influential papers in the HSE field.

This paper is organized as follows. The next section presents the methodologies used in this study. This study uses various bibliometric indicators to investigate the knowledge structure of HSE publications. Two major bibliometric types of analyses, citation analysis and co-word analysis, are combined to explore research subjects and important research papers in HSE research. After describing the methods and measures of each approach, a research procedure is drawn. Section 3 provides the data results of bibliometric analysis. Finally, Section 4 concludes with the findings, contributions, and a discussion of future perspectives.

2. Materials and methods

2.1. Bibliometric indicators

2.1.1. Citation analysis

Citations serve as a valuable instrument for the study of knowledge transfer in science and technology. In a citation network, each node represents an article, and the nodes are linked to other nodes that it references or is cited by Ref. [11]. Based on the citation network, scholars have applied social network analysis (SNA) to understand the intellectual structure of many fields [7,12]. This study uses SNA to understand the intellectual structure of HSE research by revealing how it is shaped by communication patterns among papers with the four following analysis metrics.

2.1.1.1. Edge-betweenness-based clustering. Grouping articles that address similar issues is an essential step in discovering research fronts. In a citation network, if two articles connect to (cite or are cited by) the same articles, it is highly possible that the articles address a similar issue. Thus, articles that address the same issues form a tightly knitted “community” in a citation network. The edge-betweenness of an edge is defined as “the number of shortest paths between pairs of vertices that run along it” [13]. Applying the modularity concept proposed by Newman [14], the division with the maximum modularity to obtain the optimal division of a network can be sought. Modularity is defined as “the number of edges (links) falling within groups minus the expected number in an equivalent network with edges placed at random.” A network with high modularity is dense in connections between nodes within groups but sparse in connections between nodes in different groups. The method involves iterative removal of the link with the highest edge-betweenness at each intermediate step. At the end of the iterative process, the division with the highest network modularity is selected as the final result. The process guarantees that each division has high coherence within groups, low connectivity among groups, and the selected division is the best among all alternatives [8,15,16].

2.1.1.2. Key-route main path analysis. To explore technological development trajectories through either patent or bibliographic citation data, many researchers have applied main path analysis. One of the more widely used extensions of main path analysis is the key-route main path approach [17]. A citation network includes many nodes (articles) and links (citation relationships). Thus, a citation network can have many main paths. Key-route main path analysis begins with identifying the most significant link (key-route) in the network. Main path analysis calculates the traversal weight for each link in the citation network and then explores the main path according to the traversal weights based on three specific search algorithms [18]: (1) the search path link count (SPLC) is the algorithm adopted by Refs. [7,15,16] to measure the significance of the links, which accounts for the number of all possible search paths through the network, emanating from an origin, to identify the global main path of the citation network. (2) The search path count (SPC) algorithm is applied to a small citations network that reconstructs the main path in the network of citations between scientific papers used by Refs. [6,12,19,20], which accounts for the number of times the link is traversed if the search from all the sources to all the links in a citation network is exhausted. (3) The critical path method (CPM), which comes from operational research, identifies the longest source-link path and provides a visual display of broader longitudinal connectivity than the SPC output, which identifies the backbone structure of the network [19,21].

2.1.1.3. Centrality indexes. Different centrality indicators have been used to measure the significance of a paper. The importance of a paper can be determined by its influence on the citation network, which can be measured by centrality indexes as described in Table 1.

2.1.1.4. Brokerage analysis. A highly-cited paper may not necessarily be a prestigious paper although, in some cases, there might be a strong positive correlation between the two measures [9]. However, centrality-based measures are unable to capture the specific role of each node in terms of the intermediate relationships between nodes. As a remedial measure, brokerage analysis has been used in many areas providing valuable information for understanding the structure of the citation network [24] and studying the effects of brokerage roles on innovation performance based on a network of firms [10,25]. There are three actors, and two of them are connected through the third actor, a broker. Assuming that a network is partitioned into mutually exclusive groups, brokers can be categorized into several types depending on the affiliations of the three actors. Brokerage analysis analyzes every triad, and the role of each node in that triad is given a partition vector. For each node, there are five types of brokerage relationships, as shown in Fig. 1: (1) coordinator, (2) consultant, (3) gatekeeper, (4) representative, and (5) liaison [10,24].

The first two types of brokerage relations are within-group brokerages. If all three nodes belong to the same group, the broker can be considered a coordinator. In this study, if an HSE research paper mediates between two other papers, and all three are in the same research cluster, it is called a coordinator. The role of a consultant is like that of a coordinator, however, the broker is affiliated with a different group. A sub-research cluster of an HSE paper that links two other papers belonging to the same research cluster can be considered a consultant. The last three types of brokers are between-group brokerages, and they can be differentiated by the group to which the broker belongs. When the broker belongs to the same group as the recipient paper, it is labeled a gatekeeper. If an HSE paper from one research cluster delivers knowledge obtained from a paper in a different research cluster to yet another paper

Table 1
Centrality measures.

Measure	Descriptions	References
Degree Centrality (DC)	DC equals the number of ties that a node has with other nodes. The more ties the node has, the more active, or more central, the node. As the citation network is a directed network, in-degree centrality (in-DC) measures the number of papers that cite this focal paper, whereas out-degree centrality (out-DC) measures the number of papers that this focal paper cites. Thus, in-DC is used to show a paper's importance because it reflects how the paper is recognized by other authors. Because the size of the network influences DC, it is often standardized by dividing DC by the maximum number of nodes that a node can be connected to, n - 1, where n is the number of nodes in a network.	[6,7,9–11,22,23]
Betweenness Centrality (BC)	BC is concerned with the extent to which one node exists on the shortest path (the geodesic distance) between other nodes. Nodes with high BC scores can control the flow of information and, thus, might be able to take on the role of gatekeeper or broker. BC values can also indicate which nodes are viewed most often as leaders. Further, BC can be standardized by dividing it by (n - 1)(n - 2)	[6,7,10,11,21,22]
Closeness Centrality (CC)	CC emphasizes the distance of a node to all others in the network by focusing on the geodesic distance from each node to all others. A node that can reach other nodes through short distance paths is more central. In a directed network, this can be differentiated in terms of in-closeness (in-CC) and out-closeness (out-CC). In addition, standardized CC is calculated by multiplying n - 1 to it.	[6,10,23]
Eigenvector Centrality (EC)	EC captures the influence or power of nodes in a network, which is calculated as a weighted sum of direct and indirect connections of every length in the network. A paper with a large EC score indicates that the paper is more influential than other papers.	[6,22]
Bonacich Power Cenrality (BP)	BP is a measure extending DC. A node is weighted more if it connects to other nodes that have high centrality measures. Intuitively, a researcher would be at an advantaged position if they are connected to many other highly connected researchers.	[11]
PageRank Centrality (PR)	In addition to the popularity of a paper measured by the number of citations, prestige is another important indicator, which is the number of times a paper is cited by highly cited papers. PR is used as a measure for both popularity and prestige. The formula calculates PR using an iterative algorithm and corresponds to the principal eigenvector of the normalized citation matrix of the papers.	[9]
Structural Holes (SH)	The SH measure can be used to reflect boundary-spanning positions in a network. If an individual researcher is associated with a high SH measure, this indicates that the researcher is serving as a broker or gatekeeper across different groups in the network. There are two different approaches to the calculation of structural holes: a constraint-based approach and an efficiency-based approach. Efficiency-based SH measures identify researchers whose ego networks were rich in SHs.	[11]

in another research cluster, the paper acts as a gatekeeper. On the other hand, the paper is considered a representative when the broker is aflfiiated with the same cluster as the source paper. An HSE research paper HSE research paper cited by the other paper from different research cluster cites a paper that belongs to the same research cluster again is considered a representative. In the case of a liaison, all three papers belong to different groups. When an HSE research paper links two other papers from different research clusters, it plays the role of a liaison.

2.1.2. Co-word analysis

"Co-word analysis" [26] is the study of the relation between words used in various parts of a document. This technique is a well-established and effective approach that can reveal the intellectual structure of a research field to discern research patterns and trends in specific research fields by establishing a subject similarity between two documents [12,27]. Co-word analysis presumes that a group of aggregated keywords could indicate underlying themes, and co-occurrences of keywords could show the associations with underlying themes [27,28]. The number of co-occurrences of two keywords is the number of publications in which both keywords occur together in the title, abstract, or keyword list [29]. The more often two terms co-occur in the same line of text, the smaller the distance between the two terms [12]. Thus, a higher co-occurrence frequency of two keywords implies greater correlation [30].

2.2. Analysis procedure

By combining various bibliometric approaches, this study is conducted according to the procedures shown in Fig. 2. The first step is collecting data related to HSE research. HSE papers were retrieved from the ISI Web of Science (WOS) database based on the subjects shown in Table 2. A total of 2064 papers related to HSE were retrieved based on the following subjects: "space human explorat,*" "human space explora,*" "human space,*" "human space mission,*" "human space flight,*" "human spaceflight,*" "manned space,*" "manned mission,*" "human mission,*" "human explor,*" "space human,*" "space habit,*" "planetary habit,*" human planetary,*" "space human habit,*" "human habit,*" "habitation mission*." The search was run in early November 2016.

The oldest paper found was dated 1990, and the search yielded 2064 documents from the year 1990 to August 2016. Document information included the author(s), title, source (journal title), country, document type, number of times cited, author keywords and keywords plus, addresses, and subject categories. All the journals were published in English. After the pre-processing, 1921 papers were selected by removing the documents without keywords or an abstract. Table 2 shows the characteristics of publication outputs.

The second step is the construction of the bibliometric matrix. First, a paper-citation network is compiled to analyze the knowledge structure among critical HSE publications. VOSviewer and Netminer [31] were used to build the network matrix and to visualize the network, respectively. To visualize a citation network, a direction of arrows is defined. The citation relationship is represented as an arrow from A to B if paper A cites paper B. This representation is in accordance with the direction of the citation. On the other hand, the reverse direction indicates the influence or knowledge flow because if A cites B, B exerts an influence on A, and the knowledge flows from B to A. From 1067 papers with 1871 links, critical papers are mapped in a citation network, which consists of 336 papers with 900 links. In a citation network, the importance of each citation is considered the same along with the knowledge flows from a cited article to the article that cites; hence, a citation network is a non-weighted and directed network [8,16].

After compiling two bibliometric matrices, the main research areas are identified by two clustering indicators. The first indicator is the clustering method based on edge-betweenness clustering [13] in association with the optimal modularity concept [14,16,32] to find the research themes by grouping similar articles in the citation network. To generate edge-betweenness clustering and the key-route main path

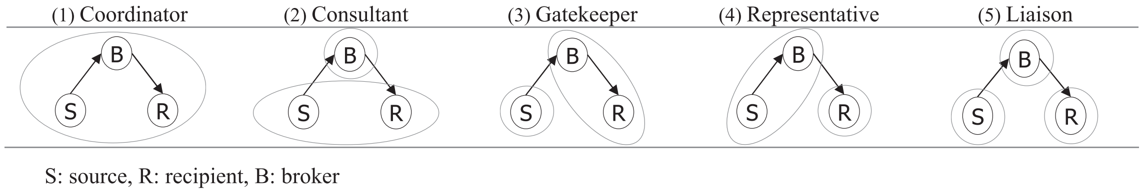


Fig. 1. Five types of brokerage relations.

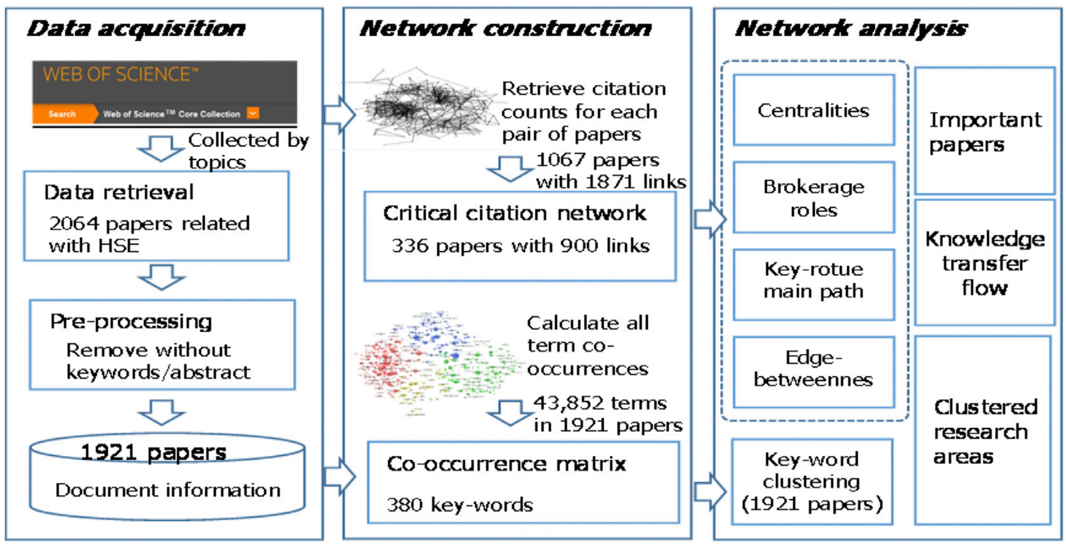


Fig. 2. Research procedure and methods.

Table 2
Characteristics by year of publication outputs.

Year	TP			AU	CR	NR	TC	PG	Year	TP			AU	CR	NR	TC	PG
	A	P	R							A	P	R					
1990	5	1		14	1	16	8	65	2004	35	49	4	346	83	2004	1158	815
1991	18	9	2	73	12	327	189	260	2005	35	43	3	230	74	2464	1029	690
1992	19	18	2	86	15	404	376	344	2006	48	28	5	270	74	2317	1139	867
1993	20	13	1	88	14	326	131	325	2007	75	35	10	465	111	3817	1493	1178
1994	28	22	2	133	35	1079	401	484	2008	68	19	13	345	98	3574	1065	1004
1995	17	14	4	117	23	629	166	369	2009	82	9	10	441	95	3567	1106	1006
1996	19	8	1	89	25	1068	362	368	2010	106	7	15	637	124	4323	1138	1397
1997	16	5	5	108	25	1009	509	282	2011	73	14	6	406	91	3496	704	1059
1998	29	9	1	115	35	887	509	334	2012	90	13	9	614	112	5055	711	1384
1999	29	17		154	43	907	642	398	2013	109	11	7	635	126	4290	620	1401
2000	21	21	1	215	38	1027	523	378	2014	120	5	9	731	134	5199	383	1381
2001	28	30	2	210	60	1593	982	626	2015	105	5	9	655	116	4956	158	1397
2002	28	17	2	190	46	1309	1360	547	2016(Nov.)	75	3	15	514	93	5859	34	1272
2003	23	32	5	230	57	1794	1691	632	Total	1321	457	143	8111	1760	63296	18587	20263

*A: Article; P: Proceeding paper; R: Review; TP: Number of publications; AU: Number of authors; CR: Cited references; NR: Cited reference count; TC: Times cited; PG: Page count.

applied an in-house program, Pajek is utilized [8,12,33]. The key research areas are also identified by clustering with the keyword co-occurrence matrix. A keyword co-occurrence matrix is also compiled to identify important subjects of published research by measuring all co-occurrences of any possible pair of concepts. After uploading the set of 1921 HSE publication records, extraction, performed using the VOS-viewer program, is conducted using a natural language processing algorithm [29,34]. After the major research groups are identified, this study then conducted key-route main path analysis to trace and visualize the most critical trajectories of HSE research [8,16,18]. Finally, centrality indexes and brokerage analysis are measured to investigate highly influential papers in the HSE research.

3. Results

3.1. Major research themes

3.1.1. Edge-betweenness-based clustering

There are six review articles that address various research areas. These articles are complex to cluster and the modularity without these six review articles provides a superior clustering result indicated by its higher network modularity [16]. Thus, without these six papers, the largest modularity of the HSE network is 0.726 divided into 15 clusters. Three clusters with very few articles are excluded from the analysis.

Table 3 shows the important papers, which are explained in Section 3.3.

Table 3
Important papers.

Papers	TC	CI	C
Brenner 2003 [35]	745	6	–
Cucinotta 2006 [36]	266	46	–
Durante 2008 [37]	221	31	1
Pieters 2009 [38]	221	8	4
Benton 2001 [39]	205	14	2
Adams 2003 [40]	195	2	5
White 2001 [41]	106	18	–
Smith 2005 [42]	103	8	5
Nicholson 2005 [43]	92	14	10
Joseph 1992 [44]	87	8	1
Zeitlin 2013 [45]	83	16	2
Gueguinou 2009 [46]	77	5	7
Testard 1996 [47]	74	7	8
O'neill 2006 [48]	64	9	2
Reitz 2009 [49]	58	11	2
Hellweg 2007 [50]	48	7	8
Durante 2003 [51]	45	7	8
Simonsen 2000 [52]	43	9	1
Nicholson 2009 [53]	40	4	10
Kanas 2009 [54]	38	10	3
Durante 2005 [55]	35	6	1
Cucinotta 2013 [56]	29	3	1
Basner 2013 [57]	28	6	3
Crawford 2012 [58]	27	4	–
Tucker 2004 [59]	27	2	1
Manzey 2004 [60]	26	9	3
Crawford 2004 [61]	26	12	4
Testard 1999 [62]	24	5	8
Fajardo-cavazos 2007 [63]	21	10	10
Horneck 2003a [64]	19	10	6
Lobascio 2008 [65]	18	3	1
Spudis 2001 [66]	18	13	4
Stein 2001 [67]	18	5	5
Chang 2001 [68]	17	2	1
Obe 1999 [69]	16	5	8
Horneck 2006 [70]	15	6	6
Crawford 2006 [71]	13	5	4
Horneck 2003b [72]	12	2	8
Salotti 2011 [73]	11	7	9
Kim 2011 [74]	10	4	2
Mckenna-lawlor 2012 [75]	10	5	2
Czupalla 2004 [76]	10	6	6
Fajardo-cavazos 2010 [77]	10	3	10
Carpenter 2010 [78]	8	4	–
Carpenter 2012 [79]	8	2	–
Crawford 2015 [80]	8	0	4
Salotti 2012 [81]	8	5	9
Flynn 2005 [82]	7	3	3
Gronstal 2007 [83]	7	4	4
Perkins 2008 [84]	7	3	10
Cockell 2010 [85]	6	4	4
Lebel 2011 [86]	5	3	1
Narici 2012 [87]	5	3	2
Cockell 2004 [88]	5	5	4
Crawford 2014 [89]	5	1	4
Green 2010 [90]	5	2	5
Harrison 2005 [91]	4	2	3
Crawford 2001 [92]	4	4	4
Crawford 2010 [93]	4	2	4
Goswami 2012 [94]	4	2	5
Neal 2014 [95]	1	1	4
Turci 2015 [96]	1	1	12
Moissl-eichinger 2016 [97]	0	0	7
Kaur 2016 [98]	0	0	12

*TC: Total citations; CI: Citations included, C: Cluster.

To identify the key terms of each cluster, the word cloud technique is applied to the title and abstract of all papers using freeware http://www.wordclouds.com/.

Table 4 shows the published paper trends and key terms by each cluster. Based on the similarity of the keyword in each cluster, the clusters are classified into four research themes, "biological risks from space radiation," "health and performance during long-duration spaceflight," "program and in-situ resources for HSE missions," and "habitat and life support systems in the space environment".

Fig. 3 shows each clusters grouped by four themes.

The first theme is composed of Clusters 1, 2, and 8, and the subjects are related to observation, assessment, and mitigation of space radiation to protect humans from the harsh environment. Exposure to a complex space radiation is a major hazard to astronauts exploring the solar system [36].

In Cluster 1, Cucinotta, Durant, and their co-workers are key researchers, and they describe how research in cancer radiobiology can support human missions to Mars and other planets [37]. In space, astronauts are exposed to galactic cosmic ray (GCR)s composed of high-energy protons and high charge (Z), energy (E) (HZE), and nuclei and solar particle events (SPE). HZE ions belong to high linear-energy-transfer (LET) radiation leading to increased health risks including fatal cancer risks, circulatory diseases, and damage to the central nervous systems (CNS) [56]. Animals have behavioral deficits reflecting accelerated brain aging [44,68]. High-quality accelerator-based research with heavy ions will continue to be the main source of knowledge for space radiation health effects and will lead to reductions in uncertainties in human health risk predictions [55]. The development of biological countermeasures (BCM) can minimize or prevent physical, cognitive, and behavioral disorders due to space radiation [37]. Shielding is a practical countermeasure for exposure to GCRs with varying degrees dependent on shield thickness and material. These works have been developed by co-citing with other researchers, suggesting new materials [65], and investing in shielding materials using both particle accelerators and computer simulation [52]. However, regardless of the shielding material used, its interaction with highly energized particles produces nuclear fragmentation or "secondary particles" which have been reported as a radiation threat to astronauts such as chromosomal aberration and DNA damage assays [86].

Cluster 2 focuses on the measure for space radiation. So far, many studies on risk assessment of space radiation have been conducted, and additional efforts have been made to address crews' risks using models that incorporate biological effects [74]. Commonly used GCR models, such as Badhwar–O'Neill [48], are used to investigate absorbed doses and dose equivalent rates. The depth-dose distributions executed by Reitz and co-workers serve as benchmarks for space radiation models and radiation transport calculations that are required for mission planning [49]. Many radiation measurements have been conducted in the recent past on the International Space Station (ISS) using instruments such as detector systems [39,87]. The Radiation Assessment Detector (RAD) is an energetic particle detector and conducts radiation measurements [45]. From a comprehensive study by McKenna-Lawlor and colleagues, Monte Carlo simulations were performed to estimate radiation exposure [75].

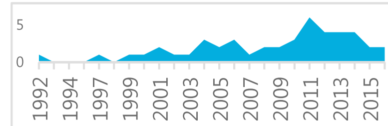
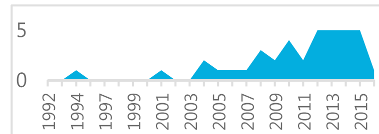
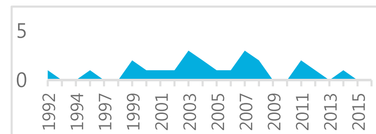
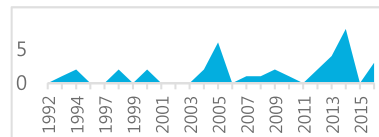
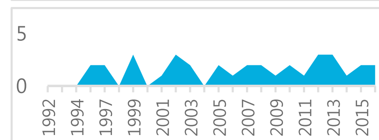
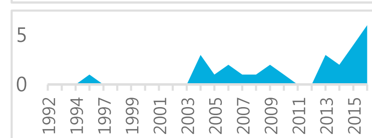
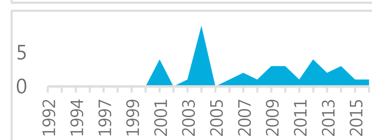
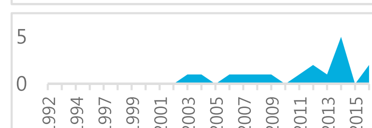
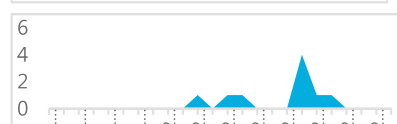
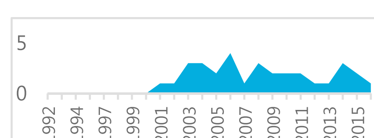
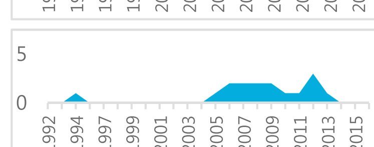
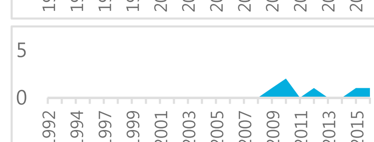
The subjects in Cluster 8 are similar to those in Cluster 1 and address the biological effects of space radiation focusing on the estimates of equivalent doses from GCR and solar cosmic radiation behind various shields and the radiation risks for astronauts on a mission to Mars [50]. Several measurements of chromosomal aberrations have been performed in blood lymphocytes from astronauts' space missions in low earth orbit (LEO) [62]. Physical measurements should be complemented by biological dosimetry procedures, the application of intrinsic biomarkers (e.g., chromosomal aberrations in lymphocytes) [51,69,72].

The second theme is composed of Clusters 3, 5, and 7, for which the subjects are related to human health and performance factors during long-duration spaceflight.

Cluster 3 focuses on behavior health and performance [54,82], which require an interdisciplinary understanding of human physical and cognitive abilities [60,91]. Understanding how neurocognition is affected by long-duration spaceflight will be essential for ensuring the success of exploration-class missions and the safety of the crew [57].

Cluster 5 is related to nutritional, medical, and exercise countermeasures. Maintaining adequate nutrient intake during spaceflight is important to meet the nutritional needs of astronauts and to counteract

Table 4
Keyword and trends in HSE main research areas.

Themes	Clusters			5 key terms	Trends by year
Biological risks from space radiation (108 papers)	1	HZE ions effects & countermeasure (46 papers)	particle cell ion dose shielding		
	2	Measurement & space radiation model (39 papers)	model transport detector neutron assessment		
	8	chromosomal aberration (23 papers)	astronaut protection damage chromosomal aberration		
Health & perfor-mance during long duration spaceflight (99 papers)	3	Behavioral health (37 papers)	health cognitive behavioral psychological sleep		
	5	Physical performance (35 papers)	microgravity exercise muscle countermeasure gravity		
	7	Microbial monitoring (27 papers)	microbial habitability life iss immune		
In-situ resource & mission program of HSE (62 papers)	4	Resource potential & use (36 papers)	scientific surface resource water robotic		
	9	Mission scenario & architecture (17 papers)	scenario mass edl vehicle architecture		
	11	Public engagement (9 papers)	public mission program science/ scientific analogue/ analogue		
Habitat and life support system (54 papers)	6	Life support requirements (32 papers)	resource plant water bioregenerative waste		
	10	Simulated survival experiment (16 papers)	spore bacillus subtilis dna radiation survival		
	12	Lunar dust toxicity (6 papers)	dust simulant/soil toxicity chemical ros		

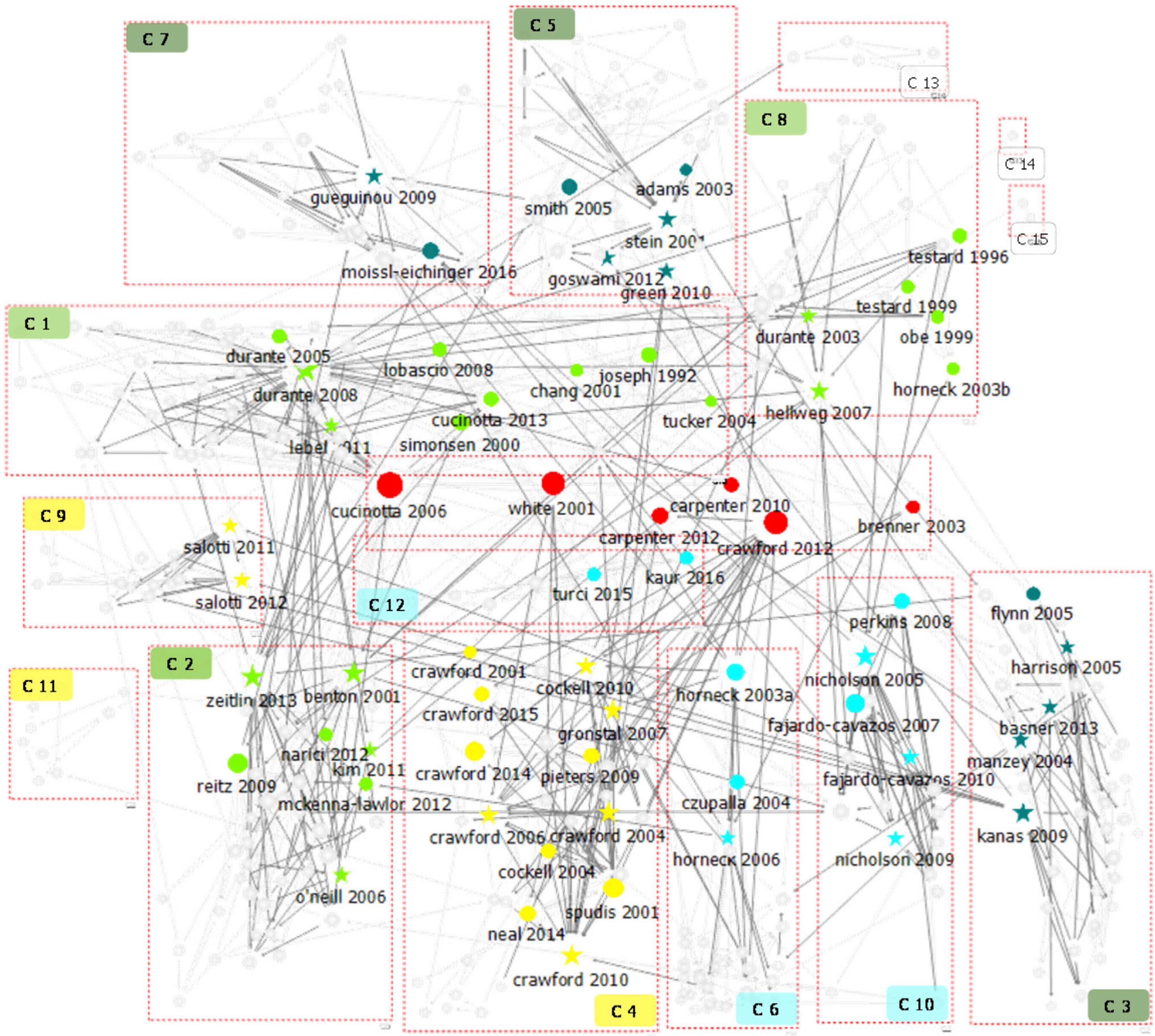


Fig. 3. Results of clustering.

the negative effects of spaceflight on the human body [42,67]. Comparisons of changes in muscle strength and size may be useful for the investigation of certain aspects of the skeletal muscle unweighting that occurs in microgravity [90]. A Moon base could also be important for developing and testing monitoring technologies, medical treatments, and behavioral health countermeasures in a genuine surface operations space environment [94].

The subjects in Cluster 7 address the effects of spaceflight on the human immune system, microbial communities, and acceptable resolutions to ensure safe and efficient space habitation. The human immune system can be negatively affected in the spaceflight environment. Astronaut immune function becomes dysregulated during long-term spaceflight [46]. Information on the microbial monitoring conducted in the ISS will have an impact on the planning and implementation of long-term human spaceflights [97].

The third theme is composed of Clusters 4, 9, and 11. These clusters group together papers associated with technologies that enable successful human activities in space from missions' operations for entry, descend, and landing (EDL) and in-situ resource utilization (ISRU) processing to provide critical and low-cost programs for optimizing exploration requirements and strategies for future HSE missions.

Cluster 4 is related to space life science to understand and utilize space resources and related HSE missions and programs for EDL. Crawford, Cockell, and their co-workers are key researchers who summarize space life science research including the whole spectrum of studies [61], the astrobiological aspects of lunar exploration [71,83,85,93], and the scientific rationale for resuming lunar surface exploration [58] using the Moon to test robotic sample return technologies and human-robotic interactions [95]. HSE exploration has scientific advantages over robotic missions [58,61,66,88,92]. Understanding the distribution of lunar water ice [38] is important for both science and exploration. Detailed studies of the lunar dust and plasma environment could be investigated by appropriate instruments on robotic landers [79,95].

Cluster 9 addresses mission scenarios and mission architectures for EDL technologies, structures, and resources to determine the size, mass, and shape of the main landing vehicle, which is simple and efficient [73,81].

Finally, cluster 11 is composed of only a few papers that focus on a participatory approach designed to engage the public as a major stakeholder and provide lessons learned for optimizing exploration requirements and program strategies focusing on field science training programs and terrestrial analogue environments.

The last theme is composed of Clusters 6, 10, and 12, and the subjects are related to life support and habitat on the surface of the Moon or Mars and the transportation of organisms to the lunar surface for in-situ investigations using surface laboratories [78]. These experiments could yield new insights into the evolution of organisms in the space environment, the possibility of microbial, plant, and cultivated crop production, and the potential for healthy human and animal reproduction in space [58].

The subjects in Cluster 6 are related to the space life support system (LSS) for generating oxygen, treating waste, and producing food using in-situ resources efficiently to sustain humans for long periods in deep space. For future HSE missions to the Moon [64] or Mars [70], the LSS requires greater plants and physicochemical processes to recycle the atmosphere, process water and waste, and for on-site food production [76]. Bioregenerative systems are indispensable in this recycling process [70].

The subjects in Cluster 10 address simulated survival experiments to explore the space environment and its effects on human life. Fajardo-Cavazos, Nicholson, and their co-workers are key researchers in this field. Bacillus ubtilis spores have long been used as a reliable proxy for the hardiest types of microbes that contaminate spacecraft and their assembly facilities [53,63]. The Mars simulation chamber used for environmental simulations is described [43,84]. On Mars, DNA that is subjected to a wide range of environmental challenges such as high UV radiation, desiccation, low temperatures, low pressure, and oxidants in Martian soil can exist for considerable periods of time on the Martian surface [77].

The subjects in Cluster 12 are composed of only a few papers. However, they are recently published and focus on research efforts to evaluate possible health risks. This research will enable humans to work and live on the lunar surface despite increased levels of reactive oxygen species (ROS) due to inhalation exposure to lunar dust and provide chemical reactivity values as an important property of lunar soils [96]. Many of these studies have made use of lunar simulants as a proxy for lunar dust [98].

3.1.2. Keyword-based clustering

In this study, the titles and abstracts from 1921 publications are used as term sources, and 43,852 unique terms are extracted from the sample. A minimum number of occurrences of 20 is set, and 633 terms meet the threshold. Among the 633 terms, relevance scores are calculated by VOSviewer, and the 60% most relevant terms are selected. Finally, 380 terms are obtained, from which terms not germane to the goals of the analysis are excluded such as specific place names, general statistical terms, and units of measurement for time, quantity, and rate. Fig. 4 shows the term co-occurrence map, which consists of four clusters.

The first cluster ("G1") groups together terms connected with radiation technologies to meet an integrated, optimized approach to assess astronaut risk due to space radiation exposure, develop radiation mitigation and BCM, utilize integrated radiation protection shielding technologies, improve understanding of the GCR and SPE and the ability to better predict and monitor the radiation environment.

The second cluster ("G2") represents the terms related to the long-term physical and mental health of the crew members during and after flight. The terms cover the design and maintenance of operational environments for work behaviors such as sleep, stress, a safe and efficient environment, and medical technologies.

The third cluster ("G3") groups together terms associated with sustaining human presence in space, which will require existing systems and vehicles to become more independent, incorporate intelligent autonomous operations, and take advantage of the knowledge of local resources. These terms are associated with enabling successful human activities in space from missions' operations to finding, extracting, and processing ISRU.

The last cluster ("G4"), addresses terms related to environmental control and life support systems and habitation systems to sustain humans for long periods of time in deep space with minimal reliance on earth-supplied consumables, expendables, replacement equipment, and crew intervention and maintenance coupled with capabilities to efficiently use in-situ resources and recycle, reuse, and repurpose consumable and expendables.

3.2. Main paths

This study applies key-route main path analysis to find and visualize the core paths, namely, the key knowledge diffusion paths in HSE. This study uses Pajek software to determine SPC values for each citation link and then to search for the key-route paths. Among 64 most often-cited publications connected by 134 links, 19 form the backbone of the HSE network. This is the same as the results using the CPM algorithm. The creation of main paths and the start, intermediate, and final publications of each path are presented in Fig. 5. Fig. 5 shows that all the influential articles on the overall development trajectories related to HSE are divided into three main themes.

The first theme deals with identifying and mitigating space environmental risks. The papers in the upper part investigated the issues of space radiation, which is considered one of the major hazards for personnel in space and has emerged as the most critical issue to be resolved for long-term missions both orbital and interplanetary. Exposure to the types of ionizing radiation encountered during space travel can cause damage to DNA resulting in potential detrimental health consequences. Testard 1996 [47] and Testard 1999 [62] discussed that long-term spaceflights lead to significant elevation of the frequencies of chromosomal aberrations in lymphocytes through bio dosimetric measurements on space crews who have experience in near-Earth orbits. Chang 2001 [68] observed mutations in brain tissue using animal models. Tucker 2004 [59] discussed complex chromosomal rearrangements that will ultimately lead to cell death. Cucinotta 2006 [36] argued that the energy of some GCR particles is so high that it is difficult to shield from them at all using conventional materials. Lobascio 2008 [65] suggested new materials for shielding. Durante 2008 [37] argued the significant biological effects of secondary particles. Carpenter 2010 [78], Carpenter 2012 [79] and Crawford 2012 [58] focused on the potential value of the Moon as a platform for astronomical and other scientific investigations and discussed in-situ surface measurements such as the robotic Lunar Lander on the biological effects of the lunar environment. Focusing on the risk of lunar dust, Turci 2015 [96] evaluated the possible health risk to future astronauts because of inhalation exposure to lunar dust. and Kaur 2016 [98] talked about the reactivity of dusts.

The second theme is related to space resources. The research on the ISRU by Carpenter 2010 [78], Carpenter 2012 [79], and Crawford 2012 [58] also followed by Crawford 2014 [89] discussed t new scientific instruments and the return of additional samples from the lunar surface. Crawford 2015 [80] discussed the implementation of a global exploration roadmap [99] and outlined possible international contributions to human and robotic missions from the Moon to Mars that would provide opportunities for the detailed scientific investigation of the Moon which, in addition to numerous scientific benefits, would also provide a much clearer picture of lunar resource potential.

Another path consists of previous papers which address the potential of astrobiology on the Moon in detail. Spudis 2001 [66] and Crawford 2004 [88] argued the scientific advantages of HSE over robotic missions. Crawford 2006 [71] and Gronstal 2007 [83] discussed the Moon as a potentially valuable site to address the arrangement of life science and astrobiology questions. Cockell 2010 [85] discussed the Moon as a testing ground for technological principles and approaches to the major environmental parameters that affect life in outer space.

3.3. Important papers

3.3.1. Centralities

In this study, 64 important papers were derived in consideration of the centrality indicators shown in Table 1. As shown in Table 5, all six

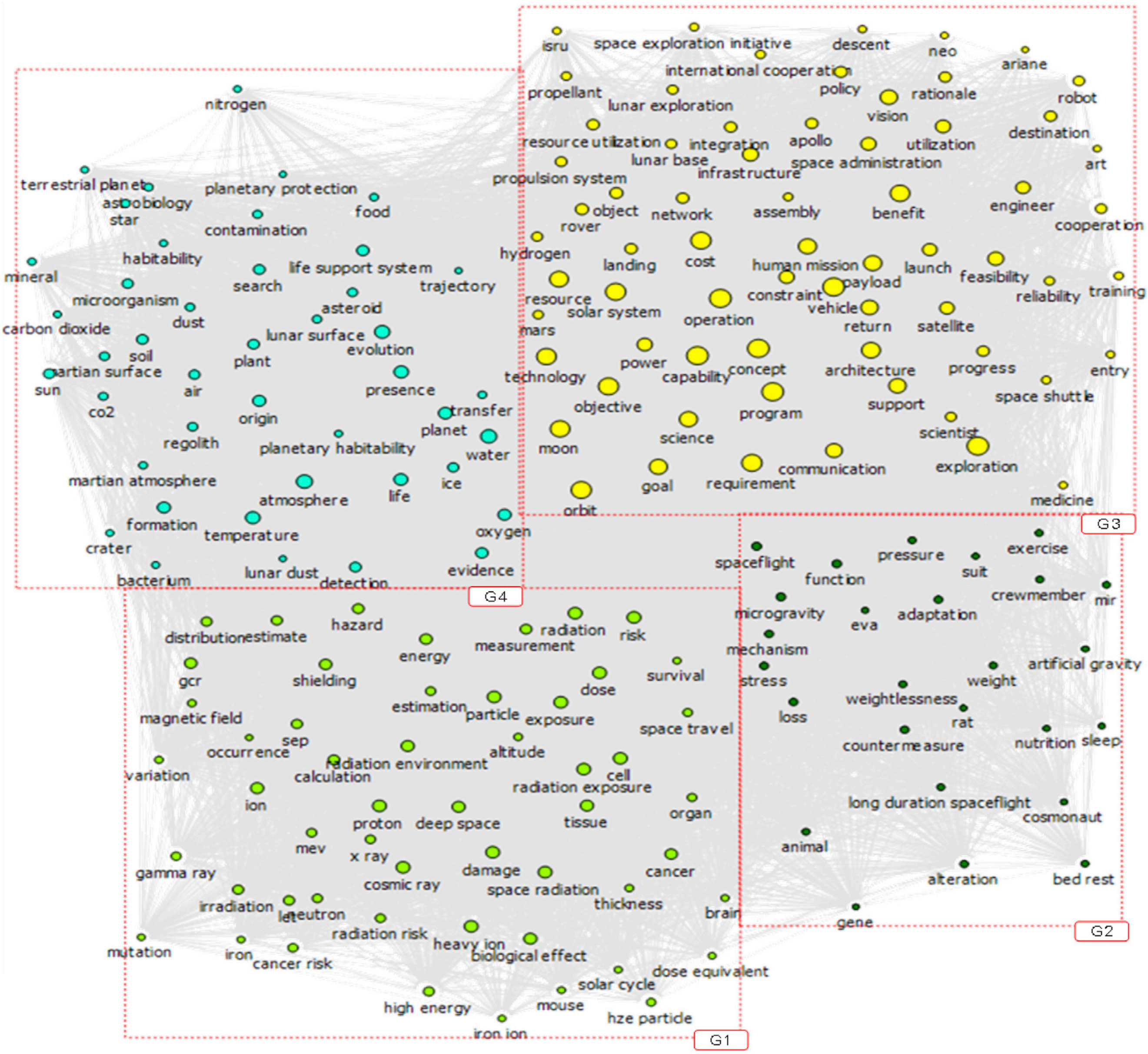


Fig. 4. Keyword co-occurrence map.

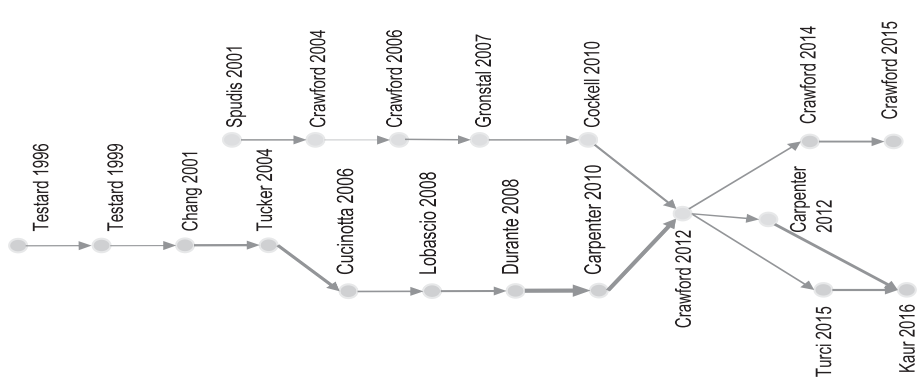


Fig. 5. Key-route main path of HSE researches.

non-clustered papers, including main path papers that contribute to knowledge diffusion in HSE, appear important. The clusters associated with "space radiation" include the most important papers: C1 (nine papers), C2 (seven papers), and C8 (six papers). The clusters, however, related to "human health and performance" include a few important papers compared to size. C3 (five papers), C5 (five papers), and C7 (two

Table 5
Centrality scores.

Cluster	Papers	In-D	Out-D	In-DC	Out-DC	In-CC	Out-CC	BC	EC	In-PC	Out-PC	PG	Efficiency
–	[35]	6	0	0.02	0.00	0.12	0.00	0.00	0.07	1.26	0.00	0.00	0.83
–	[36]	46	6	0.14	0.02	0.17	10.00	0.01	0.47	9.63	1.57	0.02	0.95
–	[41]	19	0	0.06	0.00	0.16	0.00	0.00	0.17	3.98	0.00	0.01	0.93
–	[58]	5	23	0.02	0.07	0.02	0.10	0.00	0.07	1.05	6.03	0.00	0.86
–	[78]	4	3	0.01	0.01	0.02	0.03	0.00	0.11	0.84	0.79	0.00	0.71
–	[79]	1	9	0.00	0.03	0.00	0.08	0.00	0.03	0.21	2.36	0.00	0.76
1	[37]	31	11	0.09	0.03	0.10	0.04	0.01	0.41	6.49	2.88	0.01	0.93
1	[44]	8	0	0.02	0.00	0.11	0.00	0.00	0.08	1.68	0.00	0.01	0.91
1	[52]	9	0	0.03	0.00	0.12	0.00	0.00	0.07	1.88	0.00	0.01	0.98
1	[55]	6	1	0.02	0.00	0.07	0.00	0.00	0.10	1.26	0.26	0.00	0.67
1	[56]	3	4	0.01	0.01	0.01	0.04	0.00	0.13	0.63	1.05	0.00	0.59
1	[59]	2	2	0.01	0.01	0.11	0.01	0.00	0.09	0.42	0.52	0.00	0.63
1	[65]	3	4	0.01	0.01	0.06	0.03	0.00	0.11	0.63	1.05	0.00	0.80
1	[68]	2	3	0.01	0.01	0.08	0.01	0.00	0.03	0.42	0.79	0.00	0.92
1	[86]	3	6	0.01	0.02	0.01	0.04	0.00	0.14	0.63	1.57	0.00	0.78
2	[39]	14	2	0.04	0.01	0.04	0.01	0.00	0.07	2.93	0.52	0.01	0.95
2	[45]	16	3	0.05	0.01	0.05	0.03	0.00	0.13	3.35	0.79	0.00	0.90
2	[48]	9	1	0.03	0.00	0.03	0.00	0.00	0.06	1.88	0.26	0.00	0.90
2	[49]	11	2	0.03	0.01	0.04	0.01	0.00	0.12	2.30	0.52	0.00	0.85
2	[74]	4	4	0.01	0.01	0.01	0.03	0.00	0.12	0.84	1.05	0.00	0.78
2	[75]	5	1	0.02	0.00	0.03	0.01	0.00	0.03	1.05	0.26	0.00	0.67
2	[87]	3	3	0.01	0.01	0.01	0.03	0.00	0.10	0.63	0.79	0.00	0.83
3	[54]	10	4	0.03	0.01	0.05	0.01	0.00	0.01	2.09	1.05	0.01	0.89
3	[57]	6	2	0.02	0.01	0.02	0.01	0.00	0.01	1.26	0.52	0.00	0.97
3	[60]	9	2	0.03	0.01	0.03	0.01	0.00	0.00	1.88	0.52	0.00	0.95
3	[82]	3	3	0.01	0.01	0.02	0.01	0.00	0.00	0.63	0.79	0.00	0.94
3	[91]	2	6	0.01	0.02	0.01	0.02	0.00	0.00	0.42	1.57	0.00	0.88
4	[38]	8	0	0.02	0.00	0.03	0.00	0.00	0.02	1.68	0.00	0.00	0.59
4	[61]	12	3	0.04	0.01	0.05	0.01	0.00	0.05	2.51	0.79	0.01	0.78
4	[66]	13	0	0.04	0.00	0.05	0.00	0.00	0.04	2.72	0.00	0.00	0.72
4	[71]	5	7	0.02	0.02	0.03	0.02	0.00	0.05	1.05	1.84	0.00	0.64
4	[80]	0	7	0.00	0.02	0.00	0.08	0.00	0.02	0.00	1.84	0.00	0.59
4	[83]	4	10	0.01	0.03	0.02	0.04	0.00	0.04	0.84	2.62	0.00	0.78
4	[85]	4	8	0.01	0.02	0.02	0.04	0.00	0.05	0.84	2.10	0.00	0.69
4	[88]	5	2	0.02	0.01	0.05	0.01	0.00	0.02	1.05	0.52	0.00	0.76
4	[89]	1	11	0.00	0.03	0.00	0.08	0.00	0.03	0.21	2.88	0.00	0.75
4	[92]	3	1	0.01	0.00	0.02	0.00	0.00	0.02	0.63	0.26	0.00	1.00
4	[93]	2	13	0.01	0.04	0.01	0.05	0.00	0.05	0.42	3.41	0.00	0.85
4	[95]	1	7	0.00	0.02	0.00	0.10	0.00	0.03	0.21	1.84	0.00	0.91
5	[40]	2	1	0.01	0.00	0.02	0.01	0.00	0.00	0.42	0.26	0.00	1.00
5	[42]	8	0	0.02	0.00	0.09	0.00	0.00	0.05	1.68	0.00	0.00	0.91
5	[67]	5	6	0.02	0.02	0.02	0.02	0.00	0.02	1.05	1.57	0.00	0.90
5	[90]	2	8	0.01	0.02	0.01	0.03	0.00	0.02	0.42	2.10	0.00	0.84
5	[94]	2	6	0.01	0.02	0.01	0.04	0.00	0.06	0.42	1.57	0.00	0.97
6	[64]	10	0	0.03	0.00	0.05	0.00	0.00	0.03	2.09	0.00	0.00	0.84
6	[70]	6	3	0.02	0.01	0.04	0.02	0.00	0.01	1.26	0.79	0.01	0.93
6	[76]	6	1	0.02	0.00	0.05	0.01	0.00	0.00	1.26	0.26	0.01	0.96
7	[46]	5	5	0.02	0.02	0.02	0.02	0.00	0.01	1.05	1.31	0.00	0.80
7	[97]	0	9	0.00	0.03	0.00	0.06	0.00	0.02	0.00	2.36	0.00	0.93
8	[47]	7	0	0.02	0.00	0.10	0.00	0.00	0.03	1.47	0.00	0.01	0.63
8	[50]	7	5	0.02	0.02	0.02	0.02	0.00	0.05	1.47	1.31	0.00	0.97
8	[51]	7	2	0.02	0.01	0.08	0.01	0.00	0.08	1.47	0.52	0.00	0.78
8	[62]	5	1	0.02	0.00	0.07	0.00	0.00	0.03	1.05	0.26	0.00	0.72
8	[69]	5	1	0.02	0.00	0.09	0.00	0.00	0.02	1.05	0.26	0.00	0.61
8	[72]	2	3	0.01	0.01	0.03	0.01	0.00	0.00	0.42	0.79	0.00	0.84
9	[73]	7	2	0.02	0.01	0.02	0.01	0.00	0.01	1.47	0.52	0.00	0.78
9	[81]	5	5	0.02	0.02	0.02	0.02	0.00	0.00	1.05	1.31	0.00	0.70
10	[43]	14	2	0.04	0.01	0.04	0.01	0.00	0.02	2.93	0.52	0.01	0.72
10	[53]	4	5	0.01	0.02	0.02	0.02	0.00	0.01	0.84	1.31	0.00	0.53
10	[63]	10	2	0.03	0.01	0.03	0.01	0.00	0.02	2.09	0.52	0.00	0.60
10	[77]	3	7	0.01	0.02	0.01	0.02	0.00	0.01	0.63	1.84	0.00	0.56
10	[84]	3	5	0.01	0.02	0.01	0.02	0.00	0.01	0.63	1.31	0.00	0.50
12	[96]	1	5	0.00	0.02	0.00	0.08	0.00	0.02	0.21	1.31	0.00	0.56
12	[98]	0	6	0.00	0.02	0.00	0.07	0.00	0.02	0.00	1.57	0.00	0.50

papers). The clusters related to "program and in-situ resources" appear to be driven by C4 (12 papers). C9 has only two important papers, and C11 includes no important papers. Finally, the cluster related to "habitat and space life support" subjects include a small number of important papers: C6 (three papers), C10 (five papers), and C12 (two papers). The key results of each paper are explained in Section 3.1.1. Edge-betweenness based clustering. As shown in Table 3, highly total cited papers are not necessarily highly-cited in the HSE paper network. The papers with high total citations such as Smith 2005 [42], Pieters 2009 [38], and Adams 2003 [40], appear to have low in-DC. The papers with high values of in-DC, BC, EC, in-PC, PG, and efficiency are Cucinotta 2006 [36], Durante 2008 [37], Zeitlin 2013 [45], White 2001 [41], and Reitz 2009 [49]. This implies that these papers are major knowledge sources for the HSE field with both popularity and prestige. In general, the papers with high in-DC appear high in BC, EC, and PG. However, although the old papers that have high in-DC such as Benton 2001 [39], Pieters 2009 [38], Crawford

2004 [61], Spudis 2001 [66], Nicholson 2005 [43], and Fajardo-Cavazos 2007 [63] show low BC and efficiency. This implies that there are redundant relations among those papers' connections. Some papers with high out-DC and BC, such as Crawford 2012 [58] and Crawford 2010 [93], are also important knowledge sources playing hub roles.

3.3.2. Brokers

Brokerage analysis was conducted to identify the roles in exchanging knowledge. Main research areas driven from edge-betweenness clustering are designated as partition value, and the intermediate relationships between HSE research areas are analyzed. Regarding the five brokerage types, the partial scores of each paper in the weighted version were obtained. Only 160 papers among 330 papers except for six non-clustered articles have at least one brokerage score. Among them, the brokerage scores of 24 papers in total were high compared to the other papers as shown in Table 6 and Fig. 3.

Durante 2008 [37] in C1, which has the highest scores in all the five brokerage roles, plays a significant role as a knowledge broker both within its research area (C1) and outside (C2, C5, and C8). It acts as a key coordinator in C1's papers and a consultant by linking two papers to outside research areas. Durante 2008 [37] also plays a gatekeeper and representor role by delivering knowledge from outside research papers to C1 and transferring C1's knowledge externally. Thirteen papers play a role of key coordinator, which mediates between the other two papers that belong to the same group. In the research subjects related to space radiation, Lebel 2011 [86] (C1), O'Neill 2006 [48] (C2), and Durante 2003 [51] (C8) play a key coordinator role in each sub-research area. In the sub-research area related to “space life science and technologies” (C4), Crawford 2004 [51], Crawford 2010 [93], Crawford 2006 [71], and Cockell 2010 [85] play a key coordinator role. Salotti 2011 [73] also plays a key coordinator role in subjects related to “mission scenario and architecture” (C9). In the research area of “behavioral health” (C3), Harrison 2005 [91] and Basner 2013 [57] play a key coordinator role. Stein 2001 [67] plays a key coordinator role in the research area of “physical performance” (C5). In the researches of “habitat and life support system”, Fajardo-Cavazos 2010 [77] and Nicholson 2009 [53] in C10 are key coordinators. Horneck 2006 [70] is a key coordinator in C6. No paper in C7 and C12 plays a broker role.

Kanas 2009 [45], Zeitlin 2013 [45], and Manzey 2004 [60] act as coordinators in each research area and as representers transferring their own research to other research areas. Kanas 2009 [45] transfers C3's knowledge to C5 and C9. Zeitlin 2013 [45] transfers C2's knowledge to C1 and C7, and Manzey 2004 [60] transfers C3's knowledge to C5 and C6. Hellweg 2007 [50] plays significant brokerage roles, such as representor and consultant, within and outside its research areas by linking two papers of C2 and C10 and transferring C8's knowledge to both. Gueguinou 2009 [46] acts as a coordinator and a gatekeeper and delivers knowledge from C5 to C7. Nicholson 2005 [43] delivers knowledge obtained from papers in C8 to papers in C10. Benton 2001 [39] plays a consultant and gatekeeper role between C1 and C2 by linking two papers in C2 and delivering knowledge from C1 to C2. Gronstal 2007 [83] plays both a gatekeeper and representor role by delivering knowledge from C6 to C4 and transferring C4's knowledge to C1. There are few papers that play a significant liaison role transferring knowledge between two different sub-areas as a third actor from the other sub-area. Durante 2008 [37] (C1) delivers knowledge as a liaison which enables “health performance” (C5) and “space radiation” (C2, C8) to communicate with each other. Green 2010 [90] (C5) also delivers knowledge on “health performance” (C3, C7) to “space life science and technologies” (C4).

4. Discussion and conclusions

Apollo 11 was the first spaceflight to land humans on the Moon, and the next step in space exploration is to explore the solar system with the final objective of a human mission to Mars. Multiple deep space destinations and intermediate human missions, such as Near Earth Asteroids [100], are conceivable. Numerous activities are being conducted by major space agencies, public and private industries, and academia. Recently, worldwide national space agencies have exerted substantial effort to make an HSE mission to the Moon and Mars a reality. As the HSE field has obtained huge investments from governments as well as interests from researchers, understanding the research trends and issues associated with the HSE field is important to both governments and researchers. Strategic knowledge gaps (SKGs) (ISECG, 2016, https://www.nasa.gov/exploration/library/skg.html) have been used by global space agencies to help formulate research and investment strategies and

Table 6
Brokerage scores.

Papers	Cluster	Coordinator	Representor	Gatekeeper	Liaison	Consultant	Total
[37]	1	137	62	40	3	14	256
[54]	3	18	20	0	0	0	38
[50]	8	5	15	4	1	8	33
[43]	10	0	0	26	0	2	28
[67]	5	28	0	0	0	0	28
[39]	2	0	0	19	0	8	27
[45]	2	11	14	0	0	0	25
[61]	4	19	2	0	0	0	21
[93]	4	19	0	2	0	0	21
[46]	7	13	0	5	0	0	18
[83]	4	3	5	6	0	3	17
[60]	3	8	8	0	0	0	16
[70]	6	7	3	4	0	2	16
[71]	4	15	0	0	0	0	15
[77]	10	15	0	0	0	0	15
[81]	9	7	4	2	0	1	14
[85]	4	9	0	4	0	0	13
[86]	1	9	0	3	0	0	12
[57]	3	11	0	0	0	0	11
[91]	3	11	0	0	0	0	11
[51]	8	6	4	0	0	0	10
[74]	2	1	2	4	0	3	10
[73]	9	6	0	4	0	0	10
[53]	10	10	0	0	0	0	10
[94]	5	3	4	1	0	1	9
[90]	5	0	3	0	2	3	8
[48]	2	7	1	0	0	0	8

prioritize technology development.

The main aim of this paper is to consolidate the academic research areas on HSE using a bibliometric study of HSE literature. This study provides an overall view of intellectual structure by identifying research trends and areas of the HSE field based on the bibliometric indicators using citations and co-occurrence analysis on keywords. This study (1) investigated the growth patterns in HSE literature retrieved from the WOS database; (2) delineated the themes that classify HSE research and mapped the relationships among the themes using an edge-betweenness clustering technique and co-word analysis; (3) explored the development trajectories in HSE research with key-route main path analysis, and (4) identified influential papers with centrality and brokerage measures.

Fifteen research clusters, identified using an edge-betweenness clustering method on critical citations of 336 papers with 900 links, are grouped into four research themes by applying the word cloud technique to the title and abstract of all articles: The first theme is related to the biological risks of protecting humans from the harsh environment. The studies on human health and performance during long-duration spaceflight have been growing steadily. Recent studies on enabling successful human activities in space from mission operations and in-situ resource utilization has increased to design critical and low-cost programs for optimizing exploration requirements and strategies for future missions. Finally, the studies and experiments on habitat and life support on the surface of the Moon or Mars have also been increasing among the key research themes. These research themes are also the same as the classification of the key-word analysis based on all 1921 papers. The global key-route main path based on critical citations of 336 papers reveals the trajectories of three major themes: "the effects of the space environment such as radiation and dust on human health and performance," "potential and use of space resources," and the "benefits of HSE missions". Papers with high centrality scores were identified as important papers in the citation network, which shows the overall structure of the HSE field, in terms of knowledge flow. Additionally, the specific role of each paper in exchanging knowledge was identified using brokerage analysis.

Compared with traditional literature reviews that are entirely based on researchers' subjective interpretations, the bibliometrics approach suggested in this research reflects the actual state of the HSE field by precisely assessing the major research themes and trajectories based on the citation relationships among papers. These findings contribute to an understanding of the current trends and new research opportunities for researchers who become interested in HSE but do not have much of a theoretical background on domain and technology knowledge. As in all human missions, the human factors must receive the required attention addressing the effects of space conditions (such as microgravity and radiation) on physical and biological systems. Social issues, however, such as public involvement, which attracts enormous public interest, have not yet been studied. Only a few studies in "C11" have been conducted, and their influence was weak.

When analyzing the 336 representative papers, this study focused on their citation links and research topics, but it did not investigate the technical aspects of HSE research and the mission activities of the national space agencies of important countries. HSE research areas are interdisciplinary in nature, covering various subject categories of social science and medicine as well as science and technology. Here, the interdisciplinary study of research areas was not conducted because the subject categories of WOS are classified uniformly based on the published journal level without considering the detailed subject of each paper. The technical aspects of HSE, like Mars landing of heavy spaceships, nuclear electric propulsion, and thermal resistance during atmospheric reentry may be identified and classified by refining the technical subject categories like Astronomy & Astrophysics, Engineering, Aerospace, and Multidisciplinary Sciences. The network-based bibliometric analysis approach suggested in this study can provide practitioners and decision-makers with the underlying knowledge diffusion flow from multifaceted aspects of the recent worldwide efforts in permanent human habitation on a planetary body other than Earth, thus expanding lunar or Mars surface exploration.

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