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ORIGINAL RESEARCH

An integrated taxonomy of standard indicators for ranking and selecting supercomputers

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Abstract

Due to the ever-increasing computing requirements of modern applications, supercomputers are at the centre of attraction as a platform for high-performance computing. Although various features and indicators for testing and evaluating supercomputers are proposed in the literature, a comprehensive feature set to guide designers in comparing supercomputers and selecting an appropriate choice is not provided. Here, an integrated feature-based taxonomy comprised of seven indicator groups including passive infrastructure, hardware, software, support and maintenance, service, business, and security features is proposed. Also, a case study using our proposed framework is provided and a comparison between some commercial and research supercomputers including Fugaku's ideal supercomputer, Sharif supercomputer, Aramco supercomputer, and ITU supercomputer is presented. Moreover, here, the authors' proposed method is compared with the Top500 method, which shows that the authors' proposed method facilitates the ranking, comparison, and selection of the appropriate supercomputer in various fields by considering various aspects of design and implementation. The ranking results show that Aramco supercomputer, ITU supercomputer, and Sharif supercomputer have 65.9%, 57.6%, and 48.2% of ideal supercomputer points, respectively.

KEYWORDS

mathematics computing, computer architecture, performance evaluation, computer testing

1 | INTRODUCTION

Supercomputers, or high-performance computing (HPC) systems, are the most powerful computers in the world that can solve complex scientific and industrial problems by performing thousands of billions of operations per second [1]. Supercomputers include several high-performance servers, all in the form of a cluster with high-speed connections, multiple storage levels, and a set of applications used to run HPC applications [2]. Many big players in the computer industry, such as Google, Microsoft, Amazon, VMware, and Intel have joined the development of HPC cloud services [3]. High-performance computing cloud refers to the use of supercomputer resources using a cloud model to run HPC applications which is widespread as an option for indoor clusters and On-promise HPC systems. Cloud computing brings some advantages to consumers in terms of accessibility and elasticity [4]. In general, the cloud model is composed of five essential characteristics: on-demand self-service, broad network access, resource pooling, rapid elasticity, measured service, three service models including Software as a Service, Platform as a Service, Infrastructure as a Service (IaaS) [5–7]. Often developers, designers, and users face obstacles to find the best HPC equipment and product for their service development. In this direction, adoption of an integrated taxonomy and comparison method based on the characteristics of supercomputers is an important and challenging task. Taxonomy is the science of categorisation and classification of things based on the components of an ideal supercomputer system. [8].

In this paper, we examine the available HPC systems and present Hierarchical Supercomputer KPI[1] Taxonomy (HSKT) as a novel taxonomy associated with the main characteristics of

[1] Key Performance Indicator

supercomputers. HSKT is a new multi-level and hierarchical circular based taxonomy that is presented to describe the key concepts of HPC systems. More specifically, we present a new multi-level hierarchical taxonomy whose characteristics are extracted from a thorough research of conventional technologies for creating HPC infrastructures including the strong supercomputer of Summit [9] developed by IBM and Titan [10] in America, Fugaku [11] supercomputer in Japan and Tianhe-I [12] supercomputer in China. The first level of our hierarchical taxonomy is related to the main characteristics of HPC components. These features include passive infrastructure features, hardware technical features, software features, support and maintenance features, service features, business features, and security features. In the second and third levels, each feature of the previous level is expanded with more details, which will be fully described in the next sections of this paper.

The rest of this paper is organised as follows: Section 2 presents related works. Section 3 describes our proposed taxonomy Model: HSKT. Section 4 offers the elements of HSKT model, including the major characteristics of HPC systems. Section 5 presents our proposed comparison and selection process. Section 6 explains the evaluations of our proposed solutions. Finally, section 7 concludes the paper and presents future works.

2 | RELATED WORKS

Many supercomputers have been built in the world, and the three countries, the United States, China, and Japan are the superpower producers of HPC systems in the world. Summit [9], Titan [10], Fugaku [11], Tianhe-I [12], Sunway [13], and Sierra [14] are among the most powerful supercomputers in the world in the Top500 supercomputer list[2]. In this regard, the articles related to the present study as well as the Top500 method as the closest work done in the field of supercomputer ranking and comparison are categorised and reviewed as follows.

2.1 | Works related to supercomputers in the field of cloud computing

Today, the parameters of cloud computing technology are important indicators in the design and implementation of supercomputers [15]. Authors in [16], have examined the available cloud computing technologies and presented a taxonomy associated with their main characteristics. Moreover, they have presented a new multi-level and hierarchical circular based taxonomy to describe the key concepts of cloud computing, which help to easily and quickly compare cloud computing products. Also, they have presented a new taxonomy, and its characteristics are extracted from a thorough research of conventional technologies for creating cloud computing infrastructures such as VMware, Microsoft private cloud, and Openstack. However, this study focuses only on cloud computing and does not focus on the HPC domain.

NIST[3] has developed a standard containing a taxonomy of the reference architecture of cloud computing [8]; however, this taxonomy does not provide a comprehensive category that applies all the features of HPC products. Moreover, it does not provide any comparison and selection process for HPC systems. Authors in [3, 17] have explored a taxonomy and comparison for cloud computing services via a tree-structured taxonomy. They have organised the characteristics of cloud computing services and proposed a tree-structured taxonomy. Authors in [18] have executed a prospective study on cloud computing and have proposed the related ontology. In their model, each of the cloud providers has its own set of pricing, billing, flexibility, support, and other important characteristics for their service model. Authors in [19] have proposed a table-based taxonomy for choosing a suitable cloud provider. Furthermore, they have offered a comparison method for significant features. Authors in [20] have provided discussions about cloud products and have explained their dimensions for comparison. They have also analysed some listed products. Fifteen dimensions considered in this study for comparison are as follows: resource offered, level of virtualisation, flexibility, ease of solution, legacy support, scaling, integration, standards, lock-in, interoperability, SLAs[4], redundancy, security, resource billing, and other issues such as software. Their analysis explains the differences between HPC in cloud products and does not focus on component technologies in a vacuum. They only emphasise the theoretical part of classification and do not propose any tool or solution for providers or users.

2.2 | Works related to supercomputers in the field of high-performance computing

Authors in [21] have presented a comprehensive overview and classification of task-based technologies for HPC systems. They have provided an initial task-focused taxonomy for HPC technologies, which covers both programming interfaces and runtime mechanisms. Also, they have demonstrated the usefulness of their taxonomy by classifying state-of-the-art task-based environments in use today.

Authors in [22] have developed a taxonomy of HPC cloud for scientific and business applications, vision, and research challenges. They have discussed plenty of questions in HPC cloud, which range from how to extract the best performance of an unknown underlying platform to what services are essential to make its usage easier. Moreover, they have discussed the right pricing and contractual models to fit small and large users which are required for the sustainability of HPC clouds.

[2] https://www.top500.org/lists/top500/

[3] National Institute of Standards and Technology

[4] Service Level Agreements

2.3 | Ranking of supercomputers in the Top500 method

The best and closest work done in the field of supercomputer ranking and comparison, and in the same framework as the work proposed by HSKT, is the Top500 method, which introduces and ranks the Top500 supercomputers in the world every year in terms of processing power. The Top500 method is a basis for analysing supercomputers and identifying the trend of supercomputers in the world in terms of market, architecture, and technology. The first and most important feature for evaluating supercomputers in the Top500 method is the Rmax parameter, which indicates the maximum performance obtained by the LINPACK benchmark. The LINPACK benchmark is used to calculate the processing power of floating point systems. In other words, the speed of computers to solve linear equations in mass systems is measured and these systems are ranked based on their ability to solve these equations. The main information and characteristics of supercomputers that are important and published in the TOP500 method include those listed with descriptions in Table 1.

Very few parameters are considered for the ranking of supercomputers in the Top500 list. Therefore, due to the presence of various HPC components and services in their design and implementation, the ranking and comparison of supercomputers have not been fully considered in the existing literature, and the various components and HPC features are not considered in this list. Furthermore, the ranking and comparison of supercomputers using the fully integrated features proposed in this study have not been considered in the existing literature.

2.4 | Motivation and contribution

Although many studies have been reported in the field of supercomputing, an overall study on the related standards, their focus area, and pros and cons have not been paid attention to enough. Having such a comprehensive guide motivated us to provide a taxonomy model in companion with related indices. This taxonomy model could help to plan, design, and procure supercomputers from their viewpoints.

The existing literature suffers from some viewpoints. Some studies [19, 20] provide a list of characteristics for HPC but do not provide a comprehensive list, or at the deep levels, the differences between the characteristics are blurred. However, some studies [21] have focused on the software aspects of supercomputers and have not covered some other important features considered in our study.

Various parameters are examined to rank supercomputers, such as the Top500 list focusing on evaluating the products (supercomputers). However, some HPC components and features, mainly related to design, planning, and procurement, have not been covered enough.

The main contributions of this study are as follows:

- Survey all the features important in comparing supercomputers and presenting an integrated feature set for supercomputers.
- Proposing a novel hierarchical taxonomy containing a holistic integrated view of all features of supercomputers.
- Proposing a novel ranking procedure to score supercomputers and select the best one.
- Proposing a comprehensive feature set for comparing supercomputers and selecting an appropriate choice.

This study is a step towards achieving comprehensive indicators to compare the supercomputers. Our study provides a classification of supercomputer characteristics and proposes a new taxonomy that considers all features of HPC products in seven categories: (1) passive infrastructure features, (2) technical hardware features, (3) software features, (4) support and maintenance features, (5) service features, (6) business features, and (7) security features. Moreover, this study helps supercomputer designers and developers to select their appropriate products according to their needs regarding the capabilities of available supercomputers' components and tools. Also, this classification is easily extensible and can be used for evaluation in other areas of ultra-fast processing such as providing high-performance artificial intelligence services.

TABLE 1 Features offered in Top500 list.

Features	Description
Location and installation	The place and country where the supercomputer is located.
Power and electricity consumption	Power and electricity consumption of the supercomputer in KW[a]
Manufacturer	Platform and hardware manufacturer or vendor
Type of computer	The type of computer specified by the manufacturer
Year	Year of installation/last major update
#Processor	The amount and number of processor cores
Rmax	Maximum performance achieved by LINPACK
Field of application	Industry, academia, research, government and…

[a]Kilowatt

3 | PROPOSED TAXONOMY MODEL: HSKT

This section introduces our proposed taxonomy model, Hierarchical Supercomputer KPI Taxonomy (HSKT). The HSKT is a useful tool for comparing supercomputer components and can classify various HPC solutions from different aspects. Figure 1 shows the HSKT in terms of the seven feature groups, for some feature groups decomposed up to four layers. More details of the proposed taxonomy are described in the next section. In this section, we introduce the elements of the HSKT model. The proposed HSKT method for identifying and distinguishing the features of supercomputer products,

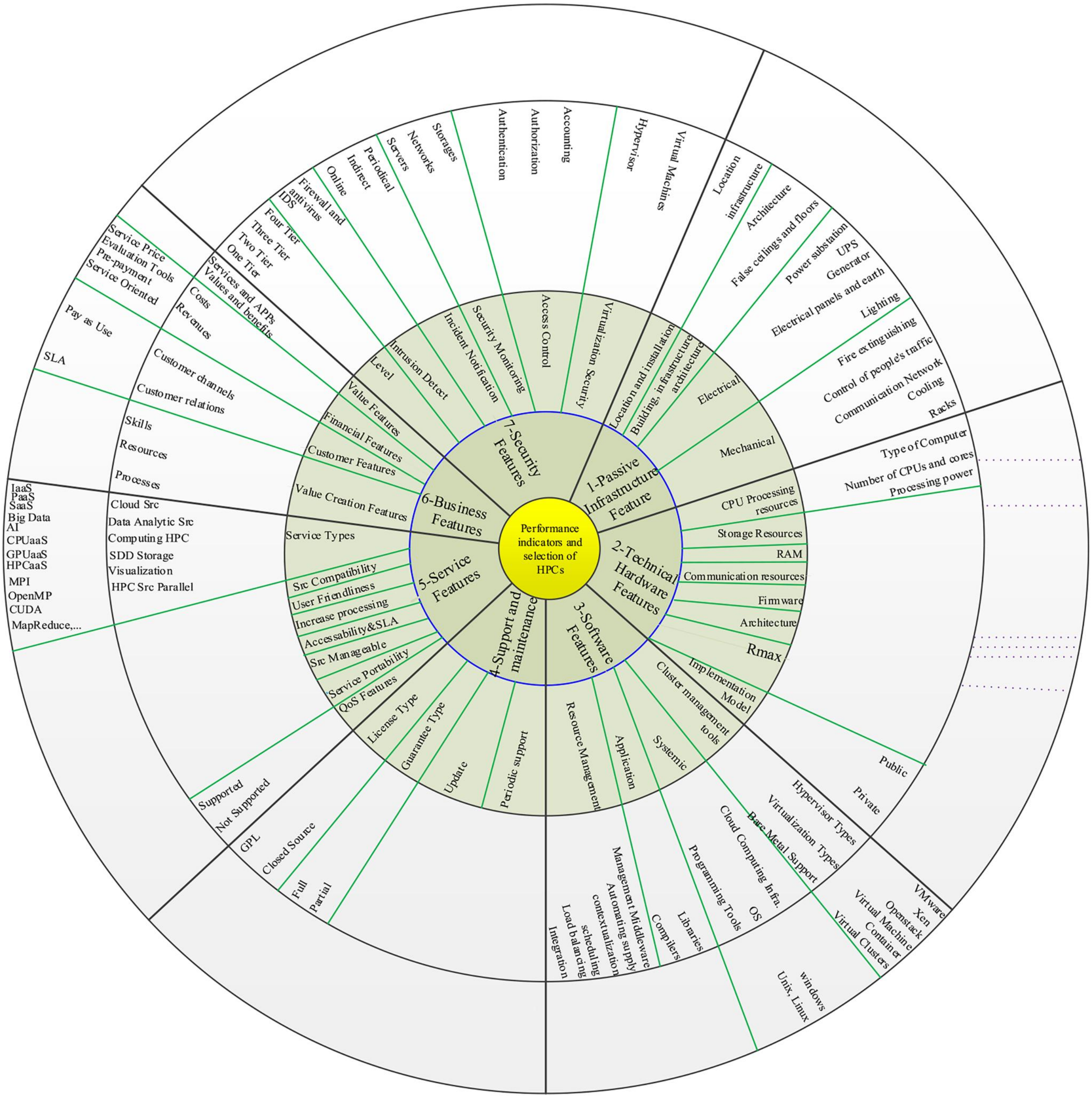

FIGURE 1 HSKT taxonomy model.

categorises the features into seven main groups. These main feature groups are (1) passive infrastructure features, (2) technical hardware features, (3) software features, (4) support and maintenance features, (5) service features, (6) business features, and (7) security features.

In the HSKT model, the characteristics of a supercomputer are classified into seven major groups. Each of these major characteristics groups consists of some different specific minor characteristics subgroups. HSKT model is hierarchical; in other words, the specification of supercomputer products is presented in a layered model. These indicators and sub-indices have been selected in such a way that all areas related to the design and implementation of the supercomputer are considered in an integrated and complete manner. The indicators and sub-indices presented in HSKT cover all stages of the life cycle of supercomputers, from the analysis and design step to the final step of operation and support, taking into account business aspects. The most important indicators provided for comparing supercomputers in the Top500 are explained in section 2. However, it is notable that the Top500 method only focuses on performance indicators such as processing speed.

In the next section, the characteristics of HSKT classification model and characteristics are presented and explained.

4 | ELEMENTS OF HSKT TAXONOMY MODEL

The HSKT model was introduced in the previous section, which provides a comparative method and tool for making decisions based on the characteristics of supercomputers. Table 2 summarises more details of feature groups. These feature groups and their ingredient features in sub-layers are overviewed in this section.

4.1 | Group 1: Passive infrastructure features

The passive infrastructure section of supercomputers includes a set of physical infrastructure equipment including a physical deployment plan, a network connection map, a network communication map, a power supply map, power cables etc. in accordance with TIA 942 standard. Indicators of passive infrastructure include location and installation indicators according to TIA 942, building, architecture and infrastructure indicators, electrical, and mechanical indicators.

4.2 | Group 2: Technical hardware features

The technical part of supercomputer hardware includes a set of architecture and hardware infrastructure resources. Hardware infrastructure is the computing nodes, high-speed network and storage space. High-performance computing products may be compatible with only some specific hardware. Therefore, the network, server, and database compatibility of cloud products should be explored before using them. Concerning network facilities, high speed connection types between modules should be considered. In servers, characteristics of processing resources and server models should be considered. In data storage, the technology used to store data at local and a remote location should be considered [23]. Details of these indicators of technical hardware are shown in Table 2 and include the following:

- CPU Processing Resources
- Storage Resources
- RAM
- Communication network resources
- Firmware
- Hardware Architecture
- Rmax
- Implementation Model

4.3 | Group 3: Software features

The supercomputer software component is a set of system software and firmware that manages the overall supercomputer architecture seamlessly. Important features which are expected from HPC software are supporting a programmable user interface, real time websites, and elastic service creation. Programmable user interface includes HPC software support from programmable control panels, attributes, environments, and programming languages. The software features include the following:

- Cluster Management Tools
- Systemic
- Application
- Resource Management

4.4 | Group 4: Support and maintenance features

The supercomputer support and maintenance department is responsible for the continuity of services and is subject to performance reviews, service work, repair or replacement of equipment, tools, cleaning, and regulation and support services. The technical support process of HPC includes software support and supercomputer hardware. Support policy shows how the HPC provider supports its product. Class of support and level of service defines the support policy. Support and maintenance features include the following:

- Licence Type and Time
- Guarantee Type
- Update
- Learning
- Performance Monitoring
- SLA Monitoring
- Periodic Support

4.5 | Group 5: Service features

The supercomputer services section includes all the capabilities and management and executive features that are provided to the customer of supercomputer services in the form of Bare Metal or on a virtual platform. In addition to processing services, service domains such as Big data and artificial intelligence can also be virtualised in supercomputers. High-performance computing Service features include the following:

- Service Types
- Service Compatibility
- User Friendliness
- Increase the processing power
- Access ability & SLA
- Service Automation and Manageability
- Portability
- QoS (Supported, Not Supported)

4.6 | Group 6: Business features

The supercomputer business section can be defined as the process of identifying problems and opportunities, setting

TABLE 2 Features and sub-features.

No.	Feature group	Sub-feature 1	Sub-feature 2	Sub-feature 3 (ideal state values)	Sub-feature variable type	Range
1	Passive infrastructure features (according to TIA[a] 942 standard)	Location and installation	Location	Distance from flood zone, distance from coastlines or floods, distance from busy highways, distance from airport	Linguistic (very low-very high)	VLH*
			Infrastructure	Development capabilities, communications, mechanical and electrical parts and building access tools	Linguistic	VLH*
		Building, infrastructure architecture	Building architecture	The width of the corridors, rooms, arrangement of racks, etc.	Linguistic	VLH*
			False ceilings and floors	Height, type and quality of false ceiling and floor	Linguistic	VLH*
		Electrical	Adequacy of power substation for load	Power substation power, load consumption	Linguistic	VLH*
			UPS[b]	Power substation power, load consumption	Linguistic	VLH*
			Generator	Its enclosure, security, capacity, fuel compartment, filters	Linguistic	VLH*
			Electrical panels and earth	Type and structure of panels, security, ground connection racks and electrical appliances, lightning protection	Linguistic	VLH*
			Lighting	Type of lights, intensity, number of sockets and sensors	Linguistic	VLH*
		Mechanical	Fire extinguishing	Fire detection and alarm system, gas type, plumbing, alarm, smoke detection, NFPA[c] standard	Linguistic	VLH*
			Control of people's traffic	Security, CCTV[d], access control to all rooms, image capture	Linguistic	VLH*
			Communication network	Type of racks, cabling, fibre optics, labels	Linguistic	VLH*
			Cooling	Location, quality of air conditioners and sensors, plumbing, heat dissipation, HVAC (Heating, Ventilation, and Air Conditioning control	Linguistic	VLH*
			Racks	Type of racks, cabling, security, order	Linguistic	VLH*
2	Technical hardware features	CPU processing resources	Type of computer	Intel Xeon, Fujitsu, AMD, ARM[e]	Linguistic	VLH*
			Number of CPUs and cores	Number of nodes, number of processing cores	Linguistic	VLH*

(Continues)

TABLE 2 (Continued)

No.	Feature group	Sub-feature 1	Sub-feature 2	Sub-feature 3 (ideal state values)	Sub-feature variable type	Range
			Processing power	In the range of tera, one hundred tera, peta, one hundred peta, hexa	Linguistic	VLH*
		Storage resources	Storage in the range of peta bytes, one hundred petas and more	Linguistic	VLH*	
		RAM	The amount of node memory is 20 GB, 50, 100 and more	Linguistic	VLH*	
		Communication resources	Infiniband, DDR4 up and faster than 20Gbps	Linguistic	VLH*	
		Firmware	Type of IPMI (Intelligent Platform Management Interface)/ ILO (Integrated Lights-Out) and its communications	Linguistic	VLH*	
		Hardware architecture	Cluster, converging with artificial intelligence, parallel processing architecture MPP[f]	Linguistic	VLH*	
		Rmax	Several TFlops	Linguistic	VLH*	
		Implementation model	Private, public, centralised, distributed	One for general or distributive	Deterministic	1–2
3	Software features	Cluster management tools	Hypervisor types	Type 1 or type 2 hypervisor or combination, closed or open source	Deterministic	VLH*
			Virtualisation types	Virtual machine, virtual cluster, container	Deterministic	1–3
			Bare metal support	Bare metal type, cloudy or real	Deterministic	Y/N
		Systemic	Cloud computing infrastructure	IaaS, PaaS, SaaS	Deterministic	1–3
			Operating system	Windows, Linux, Unix and so on	Deterministic	1–4
			Programming tools	Creating programming platforms like Python and so on	Linguistic	VLH*
		Application	Libraries	Create a library for user programming	Linguistic	VLH*
			Compilers	Instal compilers for translating programming languages	Linguistic	VLH*
		Resource management	Management middleware	Server interfaces and management tools	Linguistic	VLH*
			Automating supply	Automatic supply of physical and virtual resources	Linguistic	VLH*
			Contextualisation	Filtering and identifying physical and virtual resources	Linguistic	VLH*
			Scheduling	Use proper scheduling algorithms in nodes	Linguistic	VLH*
			Load balancing	Network load balance	Linguistic	VLH*
			Integration	Software compatibility and integration	Linguistic	VLH*
4	Support and maintenance	Licence type	Limited and unlimited GPL[g] licences, closed source	Unlimited GPL licences, closed source	Linguistic	VLH*

TABLE 2 (Continued)

No.	Feature group	Sub-feature 1	Sub-feature 2	Sub-feature 3 (ideal state values)	Sub-feature variable type	Range
		Guarantee type (full, partial)	Full	Deterministic	Y/N	
		Update	Update time less than 6 months	Deterministic	Y/N	
		Teaching and learning	Train and teach employees to use, maintain and discipline	Deterministic	Y/N	
		Performance monitoring	Performance monitoring and warning	Deterministic	Y/N	
		SLA monitoring	Monitoring availability according to SLA	Deterministic	Y/N	
		Periodic support	For all management, system and application equipment and software	Deterministic	Y/N	
5	Service features	Service types	Cloud service	IaaS, PaaS, SaaS	Deterministic	1–3
			Bare metal service	Ability to provide any service as bare metal	Deterministic	Y/N
			Data analytic service (big data, AI, …)	Big data, artificial intelligence, machine learning	Deterministic	1–3
			Computing HPC (CPU, GPU,…)	CPU, GPU, HPC	Deterministic	1–3
			SSD storage[h]	SSD, NVMe (Nonvolatile Memory Express), RDMA (Remote Direct Memory Accesss)	Deterministic	Y/N
			Visualisation	Full	Deterministic	Y/N
			HPC service parallel (MPI, …)	MPI, OpenMP, CUDA (Compute Unified Device Architecture), mapreduce	Deterministic	1–4
		Service compatibility	Integration and compatibility between services and software	Deterministic	Y/N	
		User friendliness	In terms of beauty and ease	Deterministic	Y/N	
		Increase processing	Full	Linguistic	VLH*	
		Access ability & SLA	SLA compliance	Deterministic	Y/N	
		Service automation and manageable	Being a monitoring and management tool and programming	Deterministic	Y/N	
		Service portability	Exchange of services between different platforms	Deterministic	Y/N	
		QoS features	Supported			
Not supported	Supported	Deterministic	Y/N			
6	Business features	Value features	Services and APPs	Advantages of services for the customer	Linguistic	VLH*
			Values and benefits	Benefits for the customer	Linguistic	VLH*

(Continues)

TABLE 2 (Continued)

No.	Feature group	Sub-feature 1	Sub-feature 2	Sub-feature 3 (ideal state values)	Sub-feature variable type	Range
		Financial features	Costs (use price evaluation tools, …)	Use of price evaluation tools, based on service and …	Linguistic	VLH*
			Revenues (pre-payment, service oriented, pay as use)	Prepaid model, service-based, payment based on usage	Linguistic	VLH*
		Customer features	Customer channels	Full	Linguistic	VLH*
			Customer relations (SLA, etc)	SLA and so on	Linguistic	VLH*
		Value creation features	Skills	Full	Linguistic	VLH*
			Resources	Full	Linguistic	VLH*
			Processes	Full	Linguistic	VLH*
7	Security features	Level	Level 1,2,3 and 4	According to TIA 942 standard	Deterministic	1–4
		Intrusion detect	IDS[i] software	Full	Deterministic	Y/N
			Firewall and antivirus	Full	Deterministic	Y/N
		Incident notification	Scan servers	Full	Deterministic	Y/N
			Scan network	Full	Deterministic	Y/N
			Scan storage	Full	Deterministic	Y/N
		Security monitoring	Servers	Full	Deterministic	Y/N
			Networks	Full	Deterministic	Y/N
			Storages	Full	Deterministic	Y/N
		Access control	Authentication	Full	Deterministic	Y/N
			Authorisation	Full	Deterministic	Y/N
			Accounting	Full	Deterministic	Y/N
		Virtualisation security	Virtual machines	Full	Deterministic	Y/N
			Hypervisor	Full	Deterministic	Y/N

[a]Telecommunications Industry Association
[b]Uninterruptible Power Supply
[c]National Fire Protection Association
[d]Closed-Circuit Television
[e]Advanced RISC (Reduced Instruction Set) Machine
[f]Massively Parallel Processing
[g]General Public License
[h]Solid-State Drive
[i]https://hpc.sharif.edu/
VLH*: Very Low-Very High.

goals, describing situations, and evaluating the costs and benefits associated with it.

High-performance computing Business features include the following:

- Value Features
- Financial Features
- Customer Features
- Value Creation

4.7 | Group 7: Security features

The field of supercomputer security is very important because stability and prevention of errors and damage in supercomputer is more important than usual data centres. The rate of breakdowns and security breaches in HPC systems is increasing day by day. Developers of these systems must make the best use of security and fault tolerance techniques to prevent their loss of data in order to be able to defend themselves against security risks. High-performance computing Security Features include the following:

- Level
- Intrusion Detection
- Incident Notification
- Security Monitoring
- Access Control
- Security in Virtual Layer

5 | PROPOSED METHOD FOR COMPARISON AND SELECTION

This section introduces a comparison process based on the introduced characteristics and HSKT taxonomy. This comparison process is an effective method suitable for supercomputer providers and developers to select the best matching products in accordance with their preferences and policies. In this method, a score of each HPC is calculated based on both supercomputer features and user requirements. Then, different HPCs are compared and ranked based on the calculated scores. The matching percentage of each HPC to user requirements is calculated in the next step. Finally, the best supercomputer is suggested to the user based on the computed score and matching percentage, which has an emphasis on the compatibility ratio of supercomputers to the user's demands and priorities. Table 2 shows the types and value ranges for features and sub-features introduced in HSKT. Moreover, in this table, the range of variables is depicted in front of them as well as their variable types. More precisely, a numerical min-max range for deterministic features and a linguistic min-max range for linguistic features are defined. We divide deterministic variable types into two categories, which are Y/N (yes or no) features with a specified numeric value. In the former category, the deterministic values of one and zero types are considered for Yes and No types, respectively, such that score one is added to the sub-feature grade if the HPC product has the intended characteristics and zero otherwise. In the latter category, the number of supported target characteristics is counted and considered as their value. Furthermore, the value of linguistic variables is computed in a five-level Likert-type [24] rating scale from 1 for "Very Low Acceptance" to 5 for "Very High Acceptance". In order to have numerical values of linguistic features in calculations, the translation map shown in Table 3 is used to map linguistic variables to corresponding deterministic values.

Equation (1) defines each feature based on its type. In this regard, all characteristics introduced in previous sections for HPC products can be categorised as deterministic or linguistic variables. While variables in mathematics usually take numerical values for deterministic types, non-numeric linguistic variables are often used to facilitate the expression of rules and facts [25]. A linguistic variable such as age may have a value such as young or old. However, the great utility of linguistic variables is that they can be modified via linguistic hedges applied to primary terms [25]. Two levels of the HSKT taxonomy hierarchy are considered to calculate the HPC score: main feature groups and sub-features. Every feature score j from group i of seven feature groups is denoted by $f_{ij}(h)$ for HPC h, where i ranges in $[1\ldots7]$, and j for f_{ij} varies according to the number of features in feature group i. Each $f_{ij}(h)$ is calculated as follows:

$$f_{ij}(h) = \begin{cases} 1 \; or \; 0 & \text{for Y/N binary features,} \\ d & \text{for deterministic features,} \\ l & \text{for linguistic features} \end{cases} \tag{1}$$

where for Y/N features the value of $f_{ij}(h)$ equals either 1 (representing Yes) or 0 (representing No), for deterministic features, the value of $f_{ij}(h)$, d, ranges from 0 to the ideal value, m, and for linguistic features, the value of $f_{ij}(h)$,l, ranges from 1 to 5, according to the linguistic to deterministic mapping of Table 3. Since some of the features could be neglected by the user, we define the binary parameter c_{ij} which show whether the feature f_{ij} is important from the user's viewpoint to be considered in calculations ($c_{ij} = 1$) or not ($c_{ij} = 0$). Therefore, the feature group score, $F_i(h)$, for feature group i is calculated using Equation (2):

$$F_i(h) = \sum_j c_{ij} f_{ij}(h), \tag{2}$$

TABLE 3 Mapping linguistic to deterministic values.

Linguistic value	Deterministic value
Very low acceptance	1
Low acceptance	2
Medium acceptance	3
High acceptance	4
Very high acceptance	5

where c_{ij} equals 1 for those features that the user determines to consider them; otherwise it is set to zero. Now, the score of HPC h, denoted by $S(h)$ is calculated using Equation (3):

$$S(h) = \sum_{i=1}^{7} C_i W_i F_i(h), \tag{3}$$

where the binary parameter C_i, similar to c_{ij}, denotes whether feature group i (from seven feature groups) is to be considered in score calculation ($C_i = 1$), or not ($C_i = 0$), and W_i is the weight of feature group i, which is normalised to 1, Thus

$$\sum_{i=1}^{7} W_i = 1 \tag{4}$$

The weights of each feature group are proposed in Table 5 and explained in the next section. In order to normalise the HPC compliance scores, we use min-max normalisation, considering the ideal HPC as the maximum possible score. Equation (5) normalises any HPC score derived from Equation (3) in percentage to the range 0%–100% in which maximum score of the ideal HPC, I, in each of the seven feature groups is $F_1(I)$ through $F_7(I)$ and also score of total of all features is $S(I)$.

$$NormS(h) = \frac{S(h)}{S(I)} \times 100 \tag{5}$$

Very similar to Equation (5), Equation (6) calculates $NormF_i(h)$, the normalised score for each feature group i of HPC h. In this equation, the score of feature group i of the ideal HPC I, denoted by $F_i(I)$, is the maximum possible score for that feature group.

$$NormF_i(h) = \frac{F_i(h)}{F_i(I)} \times 100 \tag{6}$$

Therefore, the results of Equation (5) and Equation (6) for the HPCs reveal their overall ranking and in terms of the feature groups separately.

Then, we calculate the percentage of coverage of each HPC with the features requirements of the user. Apart from comparing and ranking HPCs, we can overall estimate how much each HPC covers a user requirement set, r_{ij}, using the HSKT and the relevant scoring. For this purpose, we define g_{ij}, in Equation (7) denoting the score achieved by HPC h out of f_{ij}. In order to simplify the calculations and uniform handling of the feature values, g_{ij} ranges from 1 to 5, not only for lingual features, which range in the [1–5] naturally but also for other types of features. Therefore deterministic feature values are scaled from $g_{ij} = 1$ (for minimum requirement meeting) to $g_{ij} = 5$ (for maximum requirement meeting). For binary feature values of 0, $g_{ij} = 1$ (not requirement meeting), and of 1, $g_{ij} = 5$ (requirement meeting).

$$g_{ij}(h) = l, \tag{7}$$

where g_{ij} is substituting f_{ij} in equation 2. We define Equation (8) and Equation (9), similar to Equation (2) and Equation (3), respectively, for calculating $G_i(h)$ and $T(h)$ as follows:

$$G_i(h) = \sum_{j} c_{ij} g_{ij}(h), \tag{8}$$

$$T(h) = \sum_{i=1}^{7} C_i W_i G_i(h), \tag{9}$$

Then, for the specified requirement feature values, the overall coverage percent of each alternative HPC h, $Cov(h)$, features with user require is calculated by Equation (10):

$$Cov(h) = \frac{\mathrm{T}(h)}{N \times 5} \times 100, \tag{10}$$

where N denotes the number of features considered in the calculations. The coverage percent of each feature group i is also calculated using equation (11):

$$CovF_i(h) = \frac{G_i(h)}{N \times 5} \times 100. \tag{11}$$

6 | EXPERIMENTAL AND EVALUATION RESULTS

In this section, we present a practical HPC comparison procedure to evaluate the capability of our proposed HSKT representation model as well as our proposed comparison process. In this section, the maximum value for the best supercomputers (like the Japanese Fugaku supercomputer) is used as the normalised maximum points for an ideal supercomputer. Along with this ideal supercomputer, three other supercomputers are considered for evaluation. Specifications of these supercomputers are as follows:

- **Ideal supercomputer:** It has all the features and capabilities and is superior in terms of all functional and non-functional indicators so that it covers the capabilities of the world's top supercomputers. In the scenario of this article, Japan's Fugaku supercomputer was considered an ideal supercomputer as an example. Fugaku is a petascale supercomputer at the Riken Center for Computational Science in Japan. It started development in 2014 as the successor to the K computer and started operating in 2021. Fugaku made its debut in 2020 and became the fastest supercomputer in the world in the June 2020 TOP500 list, as well as becoming the first ARM architecture-based computer to achieve this. It achieved 1.42 exaFLOPS in HPL-AI benchmark, making it the first ever supercomputer that achieved 1 exaFLOPS. As of

TABLE 4 Characteristics of supercomputers evaluated in Top500.

Indicators	Fugaku	Sharif	DAMMAM	ITU
Rmax (petaflops)	415	0.45	22.4	0.7
Architecture	MPP	Cluster	Cluster	Cluster
Rank in Top500	1	-	10	484
Year	2020	2020	2020	2007
Manufacturer	Fujistu	Intel/HPE	HPE	HPE
CPU type	A64FX - Fujistu ARM	Intel	Xeon-gold	Intel xeon
The number of cores	1,000,000	800	70,000	1032
Power (KW)	28,335	2000	18,000	3000
Field of application	Research	University	Industrial aramco	University

TABLE 5 The Weights of feature categories.

Feature group	Relative weight (W_i)
Passive infrastructure	0.14
Hardware	0.29
Software	0.07
Support and maintenance	0.07
Service	0.29
Business	0.07
Security	0.07

November 2021, Fugaku is the fastest supercomputer in the world [11].

- Sharif supercomputer[6] (HPC 1): The processing power of this supercomputer is less than 100 teraflops. The corresponding features and processing power of the Sharif supercomputer are listed in Table 4.
- DAMMAM Supercomputer[7] (HPC 2): The specifications of this supercomputer are in accordance with the supercomputer indicators of the Saudi Aramco company called DAMMAM, which has a processing power of about 22 Petaflops.
- ITU[8] Supercomputer[9] (HPC 3): The specifications of this supercomputer are in accordance with the indicators of the ITU supercomputer in Turkey. Its processing power is about one Petaflops.

The features and processing power of the studied supercomputers are listed in Table 4.

As a case study, HPC 1, HPC 2, and HPC 3 are considered as well as customer requirements that need an HPC with features depicted in Table 2 and matching with the HSKT model. In order to compare and rank the supercomputers, we need to weigh each feature group. Although the relative weights of feature groups may vary according to the user's opinion, we propose the relative normalised weights in Table 5. The weights assigned to the category of seven indicators estimate the importance of each indicator category. These weights are mainly based on the relative costs expensed on the seven feature groups in some domestic HPC implementation projects we engaged in and seemed rational in our mind and based on some field experts' opinions gathered in this study. The hardware and service are more important than the other indicators; therefore, their weights are more than the others. Table 6 shows the details of evaluation procedure to compute the score of HPC. For the ideal supercomputer, all values have the maximum possible score, while the other three supercomputers are assigned the relative values for each feature according to its evaluation. The details of the calculation and evaluation process are shown in Table 6. In the first step, we compute the score of each HPC regardless of the customer's requirements by considering value 1 for all C_i parameters defined in Equations 1 and 2. In each of the seven indicators, the weights of the sub-features are considered equal. Therefore, the value of 1 is considered for all parameters C_i in Equations 1 and 2.

The results of these calculations are depicted in a bar chart (Figure 2) for overall comparison and a radar chart (Figure 3) to compare the scores of feature groups. In the second stage, we suppose a customer wants to select an HPC among three available options, HPC 1, HPC 2, and HPC 3, whose features are mentioned in Table 6, regarding his requirements. In the stage, we compute the score of HPCs based on the equations defined in section 5 and estimate the matching percentage between the HPCs and the user requirements. The result for the example is depicted as the bar chart of Figure 4 for an overall view of the matching percentage and as the radar chart of Figure 5 showing more details on the matching scores of feature groups separately. The calculated matching percentages reveal that for the expressed example, HPC 2 better matches the user requirements.

[6] https://hpc.sharif.edu/
[7] https://www.top500.org/system/179885/
[8] International Telecommunication Union
[9] https://be.itu.edu.tr/en/newsdetail/2022/01/14/the-usage-of-uhem-resources

TABLE 6 Value and computed scores for high-performance computing (HPC) indicators.

Feature group	Sub-features 1	Sub-features 2	Ideal f_{ij} values (Fugaku)	HPC 1 f_{ij} values (sharif)	HPC 2 f_{ij} values (DAMMAM)	HPC 3 f_{ij} values (ITU)	Requirement values of HPC- r_{ij}	Ci	Coverage ideal g_{ij}	Coverage HPC 1 g_{ij}	Coverage HPC 2 g_{ij}	Coverage HPC 3 g_{ij}
1. Passive infrastructure	Location and installation	Location	5	3	4	5	-	0	-	-	-	-
		Infrastructure	5	4	3	4	3	1	5	1	3	U*
	Building, infrastructure architecture	Building architecture	5	3	3	3	4	1	5	3	2	U*
		Ceilings and false floors	5	4	4	3	-	0	-	-	-	-
	Electrical	Adequacy of power substation for load	5	4	5	2	4	1	5	5	3	U*
		UPS	5	3	3	2	3	1	5	3	3	U*
		Generator	5	4	2	3	3	1	5	5	3	U*
		Electrical panels and earth	5	3	2	3	3	1	5	4	2	U*
		Lighting	5	4	4	2	3	1	5	5	3	U*
	Mechanical	Fire extinguishing	5	3	3	2	4	1	5	2	3	U*
		Control of people's traffic	5	3	4	2	-	0	-	-	-	-
		Communication network	5	3	4	3	4	1	5	-	2	U*
		Cooling	5	4	3	4	3	1	5	4	3	U*
		Racks	5	3	4	2	5	1	5	3	3	3
2. Hardware	CPU processing resources	Type of computer	5	3	4	3	3	1	5	3	4	4
		Number of CPUs and cores	5	2	4	3	5	1	5	3	4	4
		Processing power	5	3	4	3	4	1	5	2	4	4
	Storage resources		5	3	1	1	2	1	5	4	3	4
	RAM		5	3	3	3	3	1	5	3	3	4
	Communication resources		5	3	3	3	2	1	5	3	3	4
	Firmware		5	3	2	2	2	1	5	3	4	4
	Hardware architecture		5	3	3	3	3	1	5	4	5	4
	Rmax		5	2	4	4	2	1	5	4	5	4
	Implementation model	Private, public, centralised, distributed	2	2	1	2	2	1	5	-	3	4

TABLE 6 (Continued)

Feature group	Sub-features 1	Sub-features 2	Ideal f_{ij} values (Fugaku)	HPC 1 f_{ij} values (sharif)	HPC 2 f_{ij} values (DAMMAM)	HPC 3 f_{ij} values (ITU)	Requirement values of HPC- r_{ij}	Ci	Coverage ideal g_{ij}	Coverage HPC 1 g_{ij}	Coverage HPC 2 g_{ij}	Coverage HPC 3 g_{ij}
3. Software	Cluster management tools	Hypervisor types	5	2	3	4	3	1	5	4	2	4
		Virtualisation types	3	2	5	4	-	0	-	-	-	-
		Bare metal support	1	0	1	0	1	1	5	3	2	4
	Systemic	Cloud computing infrastructure	3	2	1	3	2	1	5	3	3	4
		Operating system	4	2	2	3	3	1	5	3	3	4
		Programming tools	5	0	4	4	3	1	5	4	3	4
	Application	Libraries	5	0	3	2	3	1	5	1	3	4
		Compilers	5	2	4	4	-	0	-	-	-	-
	Resource management	Management middleware	5	2	3	4	4	1	5	4	3	4
		Automating supply	5	2	4	3	4	1	5	3	3	4
		Contextualisation	5	2	2	4	5	1	5	4	3	4
		Scheduling	5	3	4	5	3	1	5	3	3	4
		Load balancing	5	3	4	5	4	1	5	3	4	4
		Integration	5	2	4	3	3	1	5	2	4	4
4. Support and maintenance	Licence type	Limited and unlimited GPL licences	5	1	4	3	4	1	5	U*	U*	2
	Guarantee type		1	0	1	1	0	1	5	3	U*	2
	Update		1	1	1	1	0	1	5	2	U*	2
	Teaching and learning		1	1	1	1	0	1	U*	U*	U*	U*
	Performance monitoring		1	0	1	1	0	1	5	1	2	2
	SLA monitoring		1	0	0	0	1	1	5	U*	1	2
	Periodic support		1	1	1	1	0	0	5	2	U*	2
5. Service	Service types	Cloud service	3	2	2	1	3	1	5	4	4	3
		Bare metal service	1	0	1	0	1	1	5	3	4	3
		Data analytic service (big data, AI, …)	3	1	2	1	1	1	5	4	4	3
		Computing HPC (CPU, GPU,…)	3	2	2	3	2	1	5	2	3	3
		SSD storage	1	1	1	0	1	1	5	3	4	3

(Continues)

TABLE 6 (Continued)

Feature group	Sub-features 1	Sub-features 2	Ideal f_{ij} values (Fugaku)	HPC 1 f_{ij} values (sharif)	HPC 2 f_{ij} values (DAMMAM)	HPC 3 f_{ij} values (ITU)	Requirement values of HPC- r_{ij}	Ci	Coverage ideal g_{ij}	Coverage HPC 1 g_{ij}	Coverage HPC 2 g_{ij}	Coverage HPC 3 g_{ij}
		Visualisation	1	0	1	0	1	1	5	3	4	3
		HPC service parallel (MPI, …)	4	0	2	3	3	1	5	3	4	3
	Service compatibility		1	0	1	1	1	1	5	3	4	3
	User friendliness		5	2	3	4	4	1	5	3	4	3
	Increase processing		5	2	3	2	4	1	5	3	4	3
	Access ability & SLA		1	0	0	1	1	1	5	3	3	3
	Service manageable		5	3	3	3	4	1	5	4	3	3
	Service portability		1	0	1	0	1	1	5	4	3	3
	QoS features	Supported/Not supported	1	0	1	0	1	1	5	3	3	3
6. Business	Value features	Services and APPs	5	3	2	3	4	1	5	2	U*	3
		Values and benefits	5	3	3	4	4	1	5	3	U*	3
	Financial features	Costs (use price evaluation tools, …)	3	1	3	2	3	1	5	3	U*	3
		Revenues (pre-payment, service oriented, pay as use)	5	3	3	4	3	1	5	3	U*	3
	Customer features	Customer channels	5	3	3	4	2	1	5	3	1	3
		Customer relations (SLA, etc)	5	3	3	3	4	1	5	3	U*	3
	Value creation features	Skills	5	2	4	3	-	0	-	-	-	-
		Resources	5	2	3	4	-	0	-	--	-	-
		Processes	5	3	3	4	-	0	-	-	-	-
7. Security	Level	Level 1,2,3 and 4	4	2	2	3	3	1	5	3	5	2
	Intrusion detect	IDS software	1	1	1	0	1	1	5	3	5	2
		Firewall and antivirus	1	1	1	1	1	1	5	4	5	2
	Incident notification	Periodic	1	1	1	0	1	1	5	3	5	2
		Indirect	1	0	1	0	0	1	5	U*	U*	U*
		Online	1	1	1	0	1	1	5	1	5	2
	Security monitoring	Scan servers	5	3	3	4	4	1	5	1	5	3

TABLE 6 (Continued)

Feature group	Sub-features 1	Sub-features 2	Ideal f_{ij} values (Fugaku)	HPC 1 f_{ij} values (sharif)	HPC 2 f_{ij} values (DAMMAM)	HPC 3 f_{ij} values (ITU)	Requirement values of HPC- r_{ij}	Ci	Coverage ideal g_{ij}	Coverage HPC 1 g_{ij}	Coverage HPC 2 g_{ij}	Coverage HPC 3 g_{ij}
		Scan network	5	3	4	3	3	1	5	1	4	2
		Scan storage	5	3	3	2	2	1	5	1	3	4
	Access control	Authentication	5	2	3	4	3	1	5	1	5	2
		Authorisation	5	1	3	2	3	1	5	1	3	4
		Accounting	5	3	3	4	2	1	5	1	5	2
	Virtualisation security	Virtual machines	5	1	3	4	4	1	5	1	3	2
		Hypervisor	1	0	1	0	1	1	5	1	4	2
Sum of feature scores -*S(h)*			313	150	210	193						
Matching percent with ideal HPC-*NormS(h)*			100	48.2	65.9	57.6						
Coverage score of requirements-*T(h)*									365	193	216	194
Coverage percent of requirements –*Cov(h)*									100	56.8	68.6	62.6

U*: Unknown.

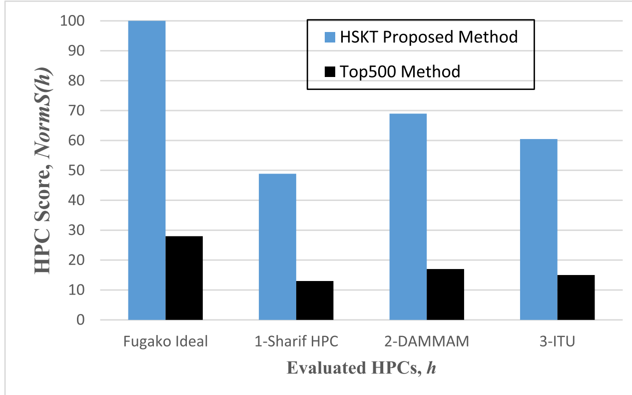

FIGURE 2 Sum of feature scores of studied HPCs: Fugaku (ideal high-performance computing (HPC)), sharif (HPC 1), DAMMAM (HPC 2), and ITU (HPC 3).

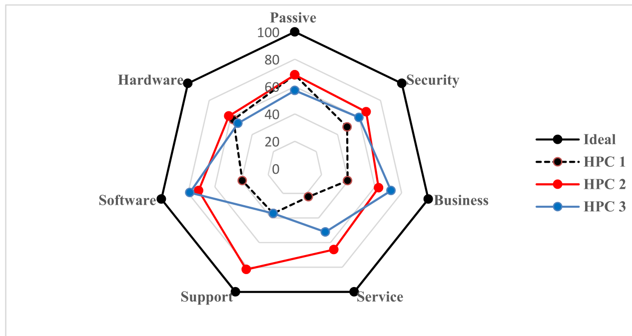

FIGURE 3 Comparison of feature scores ($NormF_i(h)$) in seven feature groups for the studied HPCs: Fugaku (ideal high-performance computing (HPC)), sharif (HPC 1), DAMMAM (HPC 2), and ITU (HPC 3).

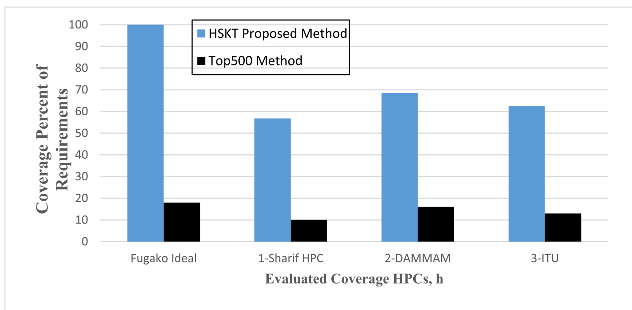

FIGURE 4 Coverage Percent of the Requirement Feature values for the Studied HPCs: Fugaku (Ideal high-performance computing (HPC)), Sharif (HPC 1), DAMMAM (HPC 2), and ITU (HPC 3).

6.1 | Results of the Top500 method

In this part, in order to compare the proposed HSKT framework with the Top500 framework, we have evaluated and ranked 4 introduced supercomputers using the Top500 framework, the results of which are shown in Table 7.

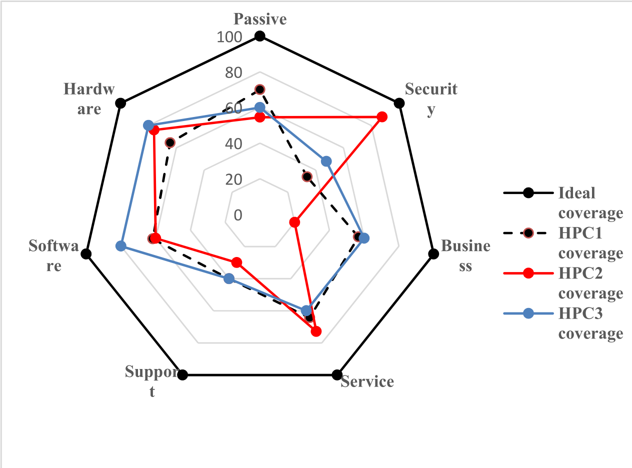

FIGURE 5 Coverage percent of the requirement feature values in seven feature groups for the studied HPCs ($CovF_i(h)$): Fugaku (ideal high-performance computing (HPC)), sharif (HPC 1), DAMMAM (HPC 2), and ITU (HPC 3).

TABLE 7 Values and scores related to the indicators of the Top500 method.

ITU	DAMMAM	Sharif	Fugaku	Indicators
4	4	3	5	Location
2	5	4	5	Power (KW)
3	4	3	5	Computer type
3	4	2	5	# Process cores
3	3	3	5	Hardware architecture
2	4	2	5	Rmax
3	4	1	5	Application fields
3	3	2	5	Variety of services

Figure 2 shows the normalised matching scores (in relative to the ideal HPC) of the HPCs in the proposed HSKT method and Top500 method, whose feature values mentioned in Tables 6 and 7. As the figure shows, after the ideal HPC, the ranking sequence is as follows: HPC 2 (65.9), HPC 3 (57.6), and HPC 1 (48.2). The radar chart of Figure 3 shows the more details of feature scores in seven feature groups for the studied HPCs.

Figure 4 shows the coverage percent of the example customer requirement feature values of Tables 6 and 7 in the proposed HSKT method and Top500 method. As the figure shows, the HPC 2 with 68.6% coverage meets the requirements of the customer better than the other two alternatives (HPC 1 and HPC 3). The radar chart of Figure 5 shows the coverage percent values separately for seven feature groups. According to the obtained results, the main advantage of HSKT compared to similar items such as Top500 is considering all important dimensions and indicators for choosing a supercomputer, which has a significant impact on the final choice of the user.

The main limitation of the evaluations provided in this section can be the lack of exact data on some features of supercomputers under study. In this case, the features that their value is not provided exactly can be estimated according to some relevant and indirect data. Accessing accurate data can tune the computations to the reliable results.

7 | CONCLUSION AND FUTURE WORK

In this paper, we introduced an integrated hierarchical supercomputer KPI taxonomy (HSKT) and an associated method for comparing and ranking supercomputers to fulfil the specific requirements of designers and developers. Using these evaluation indicators, the designers and developers can evaluate and rank different supercomputers. The HSKT was comprised of seven main feature groups, including passive infrastructure, hardware, software, support and maintenance, service, business, and security features, as well as the sub-features in each feature group. Our proposed method for comparison and ranking supercomputers was based on a weighted average scoring of the HSKT features. In addition to comparing and ranking supercomputers, our proposed method could be used to select the most appropriate supercomputer among a list of supercomputers in which the matching percentage of each supercomputer and the user specified requirements were calculated. Our proposed comparison and ranking process was flexible so that some features could be ignored according to the user's preferences. Therefore, users could focus on their desired specific aspects of the alternatives to compare supercomputers. HSKT compares mandatory features for different supercomputer designs. The empirical HPC features presented in this study provide a new integrated understanding of all important aspects of characteristics related to HPC systems. Our proposed HSKT taxonomy and evaluation method can be applied to other sections, such as spatial computing, artificial intelligence, and geographical information systems. The main limitation of this study was the lack of complete data on the supercomputers we studied. Therefore, we had to estimate some of the measures according to some relevant and indirect data. Accessing the more accurate data could better tune the proposed model to generate more reliable results.

Regarding emerging trends such as machine learning, artificial intelligence, and internet of things, which cause heavy processing of massive data, future work could focus on next generation computing using fog and edge computing [26, 27]. In this regard, an extension of the proposed model could be used to devise a plan to compare novel emerging computing technologies including nano computing, quantum computing, bio computing, optical computing, memory computing, and current silicon-based supercomputing [28, 29]. Furthermore, quantum, biological, and optical technologies have the potential to provide a new computing model to replace John van Neumann's computing model. Therefore, these technologies can solve problems that current computers cannot solve, but in nano and memory technology, the main goal is to improve the speed and performance of computers that work based on the Turing machine computing model

[30]. In this direction, it is important to note that we are approaching the end of Moore's law, and thus the quantum computing technology has the greatest potential to provide an emerging computing method compared to the other mentioned technologies and will replace the current silicon-based computing methods [31].

AUTHOR CONTRIBUTION

Davood Maleki: Conceptualisation, Investigation, Methodology, Project administration. **Alireza Mansouri:** Formal analysis, Investigation, Methodology, Visualisation, Writing – original draft. **Ehsan Arianyan:** Formal analysis, Writing – original draft.

CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

None.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study. However, some data for supercomputer indicators comparison are mentioned in Table 6 in the article.

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