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High-performance computing for computational modelling in built environment-related studies – a scientometric review

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Abstract

Purpose – This paper aims to present the result of a scientometric analysis conducted using studies on high-performance computing in computational modelling. This was done with a view to showcasing the need for high-performance computers (HPC) within the architecture, engineering and construction (AEC) industry in developing countries, particularly in Africa, where the use of HPC in developing computational models (CMs) for effective problem solving is still low.

Design/methodology/approach – An interpretivism philosophical stance was adopted for the study which informed a scientometric review of existing studies gathered from the Scopus database. Keywords such as high-performance computing, and computational modelling were used to extract papers from the database. Visualisation of Similarities viewer (VOSviewer) was used to prepare co-occurrence maps based on the bibliographic data gathered.

Findings – Findings revealed the scarcity of research emanating from Africa in this area of study. Furthermore, past studies had placed focus on high-performance computing in the development of computational modelling and theory, parallel computing and improved visualisation, large-scale application software, computer simulations and computational mathematical modelling. Future studies can also explore areas such as cloud computing, optimisation, high-level programming language, natural science computing, computer graphics equipment and Graphics Processing Units as they relate to the AEC industry.

Research limitations/implications – The study assessed a single database for the search of related studies.

Originality/value – The findings of this study serve as an excellent theoretical background for AEC researchers seeking to explore the use of HPC for CMs development in the quest for solving complex problems in the industry.

Keywords High performance computing, Computational modelling techniques, Computational models, Scientific models

Paper type Literature review

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Introduction

With the increase in the need to define, analyse and communicate basic concept with ease, the need for representations in the form of models has become highly relevant. These models are the objective method of representing an object, phenomena and physical processes (Friedenthal *et al.*, 2012). The United Kingdom Government Office for Science (2018) pointed out that modelling is as old as human civilisations and has been used to depict, represent and understand the world. Scientific models are often mathematical models that describes a system using mathematical concepts. These mathematical concepts are quite easy to initiate at early stages, but when the system becomes complex, a computational model might become an option. Computational modelling involves using computer programs to represent a process (UK Government Office for Science, 2018). Computational models (CMs) are used to translate observations into anticipation of future events. The development of this type of model has been made possible by technological advancement and the advent of modern computers (Imbert, 2017). In the view of Hwang and Martins (2018), these types of models are pervasive in the science and engineering domain because they provide easier alternatives to physical experiments. They are considered valuable in most applications that involve design, decision-making, research or forecasting as evident in the architecture, engineering and construction (AEC) industry.

With the evolution of the modern computer from the mid-20th century into the high-performance computer (HPC), the ease of executing computational tasks has become tremendous (Ezell and Atkinson, 2016). These HPCs have given room for a wide range of applications for computational modelling in diverse fields such as science and engineering, finance and economics, business management, among others (Calder *et al.*, 2018). It has also given the advantage of the reduction in cost implications for experiments and resource management, and allows for fast project delivery, and the simulation of real conditions (Hwang and Martins, 2018). The AEC industry is not left out of this development as several models have been developed to help solve the numerous problems that have characterised the industry. Many AEC researchers now use different CMs to shed light on some of the "wicked" problems that have bedevilled the industry and have attempted to unearth solutions to these problems (Maqsood *et al.*, 2003). Most significant is the use of structural equation modelling (SEM), computer simulations and machine learning (ML) which has gained considerable embrace among AEC researchers (Akanmu *et al.*, 2020; Alizadeh and Yitmen, 2018; Baker *et al.*, 2020; Cheng *et al.*, 2020; Zhao *et al.*, 2019) in most developed and some developing countries.

Unfortunately, in most developing countries, particularly in Africa, technological advancement and inadequate research and development have been described as principal culprits of the slow growth of the AEC industry (Aghimien *et al.*, 2019b; Dulaimi and Hwa, 2001). Most built environment-related researches emanating from these African countries have focused on peripheral issues which in most cases assessed the cause and effect of diverse problems and subsequent solutions to such problems. In many cases, these researches are conducted through exploring existing theories and developing conceptual models through descriptive and inferential statistics along with some first or second-generation multivariate analysis. The use of computational approaches such as ML and simulations is hard to come by within these African studies, and the resultant effect is the lack of a well-represented and animated process of solving complex issues facing the AEC industries of these countries. This lack of computational modelling is not unrelated to poor technological advancement. The absence of HPCs and the lack of technicality to operate these digital systems especially within AEC organisations, and even institutes of higher learning, is one of the numerous challenges leading to this problem (Oke *et al.*, 2018).

As there is an increasing desire to resolve complex problems using CMs, the influence of HPC in the development of these models cannot be overlooked (Almeida, 2013). Hence, this study explored the body of knowledge to unearth the role of high-performance computing in computational modelling by assessing the area of focus and trends in past studies as well as revealing areas for future studies. This was done with a view to further emphasis the need for HPC within AEC organisations, higher education institutes and other research organisations in developing countries particularly in Africa where the use of HPC in developing CMs for effective problem solving is still low. Theoretically, the study gives guidance for future knowledge areas relating to high-performance computing and computational modelling that future researches within the industry can explore in the quest for solving complex problems facing the industry.

Overview of high-performance computing and computational modelling

Developing a research model is a scientific activity which is done to make a particular phenomenon easy to comprehend, define, quantify, visualise or simulate. The process of generating a model is termed "modelling", and this is achieved by referencing the model to existing accepted knowledge for verification, and validation (Wilbur *et al.*, 2005). Modelling is an essential and integral part of many scientific disciplines, and each of these disciplines has specific ideas that translate into the modelling types used to resolve issues. Some of the commonly used models are conceptual model, computational model, operationalise model, mathematical model and graphical model (Kwakkel and Pruyt, 2013; Wood, 2017).

Scientific models are often mathematical models, which describes a system and explain a phenomenon using mathematical concepts and language (Ningthoujam *et al.*, 2018). At the initial stage, such models are usually easy to handle by humans, but when it becomes complex, such models become rather challenging to initiate (Wood, 2017). At this juncture, a computational model is usually used. This type of modelling includes formulating and modelling real-world problems, then using a computer program, to develop solutions (Dayan, 1994). Computational models comprise key mathematical, logical or causal relationships, which can help translate observations into anticipation of future events, used to test ideas, extract value from data and ask questions about specific behaviours (Bölöni *et al.*, 2018). Also, these models contain several variables that make up the system under study, and computational analysis is carried out by adjusting these variables and observing how the changes affect the outcomes predicted by the model. These results are used to make predictions about what will happen in the real systems under study in response to the changing conditions (Terletskyi and Provotar, 2015).

High-performance computing plays a pivotal role in the development of CMs. High-performance computing has been described as the application of supercomputers to solve computational problems that are either too large for standard computers or would take too long to execute (Ezell and Atkinson, 2016). It involves the use of supercomputers and some massive parallel processing techniques to solve complex computational issues using computer modelling, simulation and data analysis (Techopedia, 2016). As opposed to a desktop computer which generally has a single processing chip in the form of a central processing unit, the HPC system, is made up of a network of nodes, which contains one or more processing chips, as well as its memory (Almeida, 2013). Thus, HPC is a machine that combines many processors and makes their combined computing power available to use. The introduction of supercomputers has been the bedrock of high-performance computing, and this has led to the ease in the development of CMs (Tulasi *et al.*, 2015).

Research methodology

The study was viewed from an interpretivism philosophical stance on the premise that reviewing existing studies and interpreting the trends will help in bringing to light the usefulness of high-performance computing in computing complex models in the AEC industry. Oshodi *et al.* (2020) have earlier mentioned that this method of reviewing literature has gained significant recognition among built environment-related studies in recent times. In doing this, the study used a scientometric review of existing literature using the steps in Figure 1. The scientometric approach gives a visual perspective of the structural and dynamic aspects of existing scientific researches, and also help in the identification of authors, countries, funding bodies, journals and types of collaborations that exist within a particular area of research (Blažun *et al.*, 2015; Cobo *et al.*, 2011). Based on its ability to give clear view of past happenings within a subject area, the scientometric review has continued to gain recognition in built-environment studies (Aghimien *et al.*, 2019a; Darko *et al.*, 2020; Nazir *et al.*, 2020; Yin *et al.*, 2019). The literature search was done using Scopus database on the premise that the database covers a considerably large number of published articles than its counterparts (Chadegani *et al.*, 2013; Guz and Rushchitsky, 2009). This database gives a broad spectrum of scientific studies and has been used as a source of literature mining for most bibliometric and scientometric studies conducted in recent times (Aghimien *et al.*, 2019a). Also, as there is a significant overlap between Scopus and some database such as Web of Science (Olawumi *et al.*, 2017), using one accessible database helps eliminate this issue of article duplication.

Past studies have considered journal articles to be more reliable sources of knowledge due to their concise information and rigorous review processes (Jin *et al.*, 2018; Ramos-Rodríguez and Ruíz-Navarro, 2004; Zheng *et al.*, 2016). Based on this assumption, some researchers have advocated the use of only journal articles for literature review (Butler and Visser, 2006; Jin *et al.*, 2018; Zhao, 2017). However, others have found the inclusion of proceedings from conferences to be equally useful (Vuksic *et al.*, 2018; Webster and Watson, 2002). Therefore, to broaden the extraction of relevant literature, the use of journals and conference proceedings was considered for this study. The keyword search was done using TITLE-ABS-KEY "high-performance computing", AND "computational modelling". To accommodate as many publications as possible, no restriction was placed on the year of publication. The initial search gave a total of 122 publications. This extraction was then refined by selecting only articles published in the field of computer science, engineering,

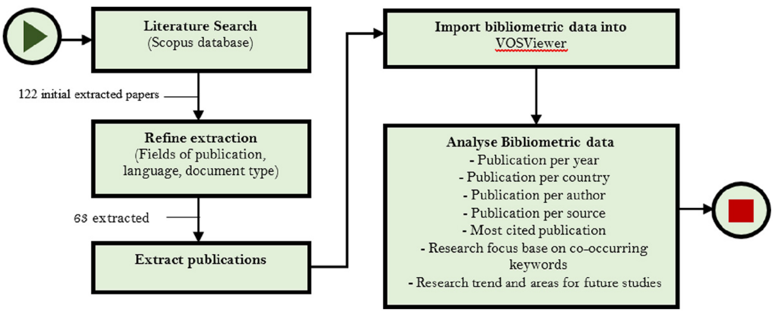

Figure 1.
Research framework

environmental science, energy and mathematics. These fields were selected based on their relations to the issue under investigation and the built environment wherein the use of high-performance computing is being proposed. The language was set at English only, and at the end of refining the extracted literature, 63 articles were retained for further evaluation. The results were presented based on the number of publications per year, publications per country, publications per authors, publication per sources and most cited publications. Additionally, the co-occurrence network of co-authorship and keywords was also assessed using VOSviewer version 1.6.15.0.

Results and discussions

Publication per year

Out of the 63 extracted documents, 48 were from conference proceedings while the remaining 15 were journal publications. This is understandable as it has been observed that the field of computer science wherein most high-performance computing studies domicile, recognises conferences as a venue for article publication more than journal outlets (Van Hemert, 2009; Vardi, 2009). The result in Figure 2 reveals that prior to the year 2000, only one paper was published. However, the year 2000 and 2001 saw the publication of two articles, while a significant increase was witnessed in 2002 and 2003 with seven publications each. Since then, there has been considerable rise and fall in the number of articles with only 2015 and 2019 experiencing a significant number of six publications each. Despite conducting the literature search for this study in July 2020, no publication was evident for the year. The implication of this is that there is the possibility of a drop in the publications by the end of the year.

Publication per country

The extracted publications emanated from 31 countries, and Figure 3 shows the countries with at least five citations. The map reveals that more American and European countries have been publishing in this area. Only one Asian country is represented on the map (South Korea). Furthermore, the result affirms the need for this current study in African countries as no study can be found on the map from the continent. Out of the 31 countries where these publications were extracted from, only Kenya and South Africa appeared with one publication each with no citation at all; hence, their exclusion from the map. The USA topped the list with 25 publications and 216 citations. This is followed by Germany and Brazil with four publications each and 48 and 13 citations, respectively. While Canada, Spain, the UK and South Korea all have three publications each, France ranked the least with just one publication and 13 citations.

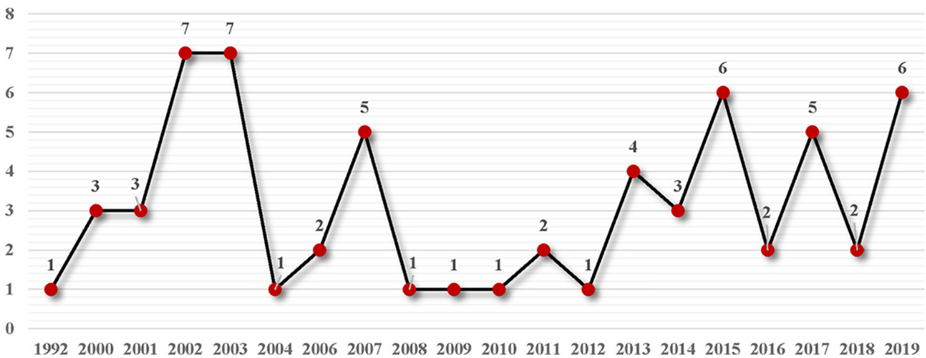

Figure 2.
Publication per year

Publication per author

The extracted publications were published by 225 authors. This includes the lead authors and their co-authors. Table 1 shows the most published authors with at least two publications and one citation. From the result, it is evident that the highest number of publications for any given author in this area is two as all the eight revealed authors have two publications each. These eight authors were further grouped into four distinct clusters base on their co-authorship relations, as seen in Figure 4. Furthermore, these authors are affiliated with institutions and organisations in the USA, Romania and Brazil. Johnson W.R. has the highest number of citations of 27, followed by Holmes and Miller with nine citations each. Further probe on the co-authorship relations revealed that Holmes and Miller are co-authors with Johnson on an article published in 2003. Similarly, Dogaru I. and Dogaru R.

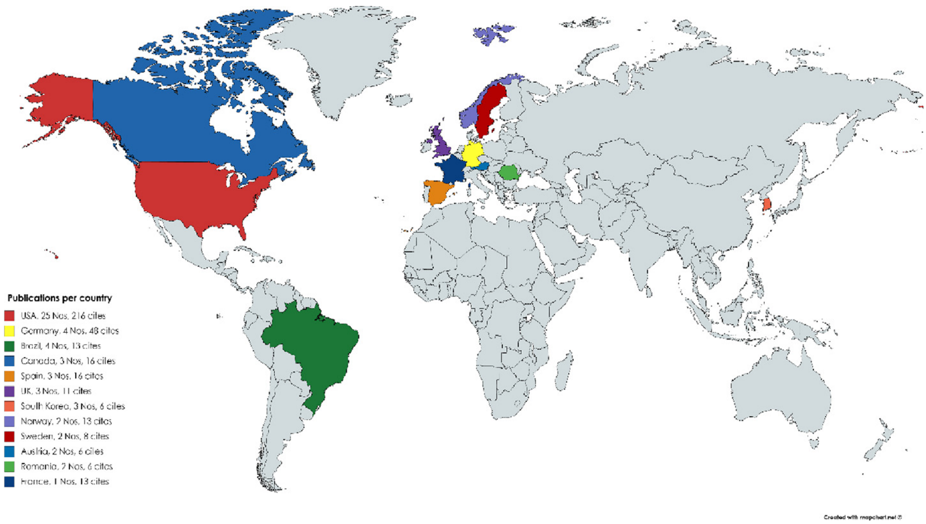

Figure 3. Publications per country

Table 1. Number of publications per author

Authors	Affiliation	Nos	Citation
Johnson, W.R.	Sandia National Laboratories, PO. Box 5800, Albuquerque, NM 87185, USA	2	27
Holmes V.P.	Sandia National Laboratories, PO. Box 5800, Albuquerque, NM 87185, USA	2	9
Miller, D.J.	Sandia National Laboratories, PO. Box 5800, Albuquerque, NM 87185, USA	2	9
Dogaru I.	University Politehnica of Bucharest, Natural Computing Laboratory, Applied Electronics and Information Engineering, Bucharest, Romania	2	6
Dogaru, R.	University Politehnica of Bucharest, Natural Computing Laboratory, Applied Electronics and Information Engineering, Bucharest, Romania	2	6
Dos Santos, R.W.	Department of Computer Science, Universidade Federal de Juiz de Fora, Juiz de Fora, MG, Brazil	2	4
Demmel, J.	Ohio Supercomputer Center, USA	2	1
Gordon, S.I.	University of California, Berkeley, USA	2	1

both co-authored two papers in the year 2015 that has gained six citations so far. Dos Santos, R.W. has two publications that have gained four citations. The least citation came from Demmel J. and Gordon S.I who alongside other authors, published two articles in 2013 and 2016. In terms of the most recent top publishing authors, while other recent authors might exist in the bibliographic data gathered, Figure 4 which shows that Dogaru I., Dogaru R., Demmel J., and Gordon S.I are the most recent with at least two documents and one citation. These authors can be seen in the yellow nodes on the map.

Publications per source

In terms of the source of publications, all the extracted publications came from 54 different sources. Looking at sources with at least ten citations, it was observed that most of the sources with the highest citations are from conference proceedings. The only journal on the list is "ACM Transactions on Mathematical Software" which is a top-rated journal in the field of computer science, mathematics and applied mathematics. The journal is rated Q1 (i.e. the best quartile range) with an H-index of 78 (Scimago Journal Rank, 2020). The Proceedings of the 12th Institute of Electrical and Electronics Engineers (IEEE) International Symposium on High-Performance Distributed Computing in 2003 and the Proceedings of the 36th annual Simulation Symposium in 2003 organised by the IEEE computer society has the highest number of publications of three each. The six articles from these two proceedings have garnered a total of 161 citations so far (Table 2).

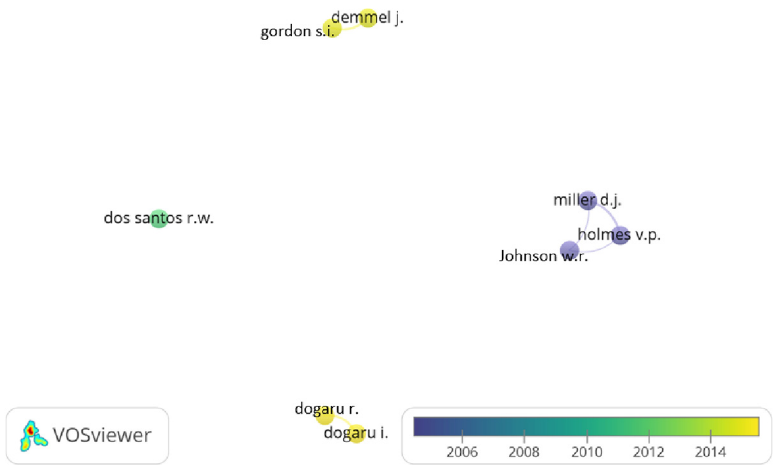

Figure 4.
Co-authorship map

Table 2.
Number of publications per source

Source	Nos	Citation
Proceedings of the IEEE International Symposium on High-Performance Distributed Computing	3	139
Proceedings – Simulation Symposium	3	22
Lecture notes in Computer Science	2	39
ACM transactions on Mathematical Software	1	19
Proceedings – 17th Workshop on Parallel and Distributed Simulation, PADS 2003	1	20
Proceedings of the International Conference on Parallel and Distributed Systems – ICPADS	1	10

Most cited publications

In recent time, citation counts have been used to determine the bibliometric performance of scholarly publications and the impact of academics on their academic community (Hirsch, 2005; Wang *et al.*, 2019; Zhang, 2013). To this end, the most cited publications were assessed with the minimum number of citations set at ten. Only seven publications met this threshold, as seen in Table 3. Out of the seven extracted papers, only one was published recently in the year 2018. This was a journal article published by Hwang and Martins in ACM transactions on mathematical software. The work used computational mathematical modelling to develop a computational architecture for coupling heterogeneous numerical models and computing coupled derivatives. This article has been cited 19 times. However, the most cited document in this area of research is the work of Hwang and Kesselman in 2003 on a flexible failure handling framework for the grid. The paper was presented at the IEEE international symposium on high performance distributed computing and has been cited 116 times. Next to this is the work of Oeser, Bunge and Mohr in 2006, which used geophysical modelling cluster to develop a cluster design in the earth sciences Tethys and has been cited 39 times.

Research focus base on co-occurring keywords

To understand the area of focus of past studies, a co-occurrence map based on the data gathered was done using the VOSviewer software. According to van Eck and Waltman (2014), VOSviewer is a software that enables the easy visualisation of bibliometric networks by displaying nodes and providing distance-based visualisations. The software is mostly suitable for picturing more extensive networks. For extraction, while the software has a default of five minimum number of co-occurrence for the keywords to be extracted, several studies have adopted different thresholds based on the number of documents under review. For example, Aghimien *et al.* (2019a) adopted four as the minimum for the review of 91 articles, while Yin *et al.* (2019) adopted 20 co-occurrences for 4,395 articles on BIM for off-site

Authors	Title	Source	Citations
Hwang and Kesselman (2003)	Grid workflow: a flexible failure handling framework for the grid	Proceedings of the IEEE International Symposium on High-Performance Distributed Computing	116
Oeser *et al.* (2006)	Cluster design in the earth sciences Tethys	Lecture notes in Computer Science	39
Perumalla *et al.* (2003)	Scalable RTI-based parallel simulation of networks	Proceedings – 17th Workshop on Parallel and Distributed Simulation, PADS 2003	20
Hwang and Martins (2018)	A computational architecture for coupling heterogeneous numerical models and computing coupled derivatives	ACM transactions on Mathematical Software	19
Beiriger *et al.* (2000)	Constructing the ASCI computational grid	Proceedings of the IEEE International Symposium on High-Performance Distributed Computing	18
Muzy *et al.* (2003)	Optimisation of cell spaces simulation for the modelling of fire spreading	Proceedings – Simulation Symposium	13
Abawajy (2002)	Job scheduling policy for high throughput computing environments	Proceedings of the International Conference on Parallel and Distributed Systems – ICPADS	10

Table 3. Most cited publications

construction. For this current study, the 63 extracted documents have a total of 767 keywords. Using the default minimum co-occurrence of the software revealed only 18 keywords which make it practically impossible to draw any logical conclusion. Thus, following Yin *et al.* (2019) suggestion of conducting multiple experiments that will yield the optimal graphic for the extracted clusters, this study adopted three minimum number of co-occurrence. This threshold gave 56 keywords that have co-occurred three times. The network visualisation map is shown in Figure 5 with five different clusters representing each area of focus of research. High-performance computing and computational modelling/model are seen at the centre of the map as they were the main search keywords to which other keywords are linked. While computational model and computational modelling both have a total link strength (TLS) of 221 each, high-performance computing has a TLS of 183. The 56 co-occurring keywords discovered are grouped into five different clusters with a TLS of 2248. These keywords and their number of occurrences together with their TLS are highlighted in Table 4.

Cluster 1 – *Computational modelling and theory*, is the red nodes on the map, which has 20 co-occurring keywords. This includes high-performance computing, computational model, computational theory, computational modelling, high-level language, high-performance liquid chroma, high-performance computers, parallel processing systems, natural science computing, problem-solving. Based on the latent similarity of these keywords, this cluster shows the application of high-performance computing in the aspect of developing and understanding of computational models and theories. A theory has been described as a coherent group of tested propositions, popularly regarded as accurate, used as principles for explaining and predicting a class of phenomenon (Pfeiffer, 2017). In some cases, these theories are complex in nature. For complex theories, logical exploration of the system to be studied is required using mathematical models before a hypothesis is generated. In more recent times, such mathematical models have either been replaced by

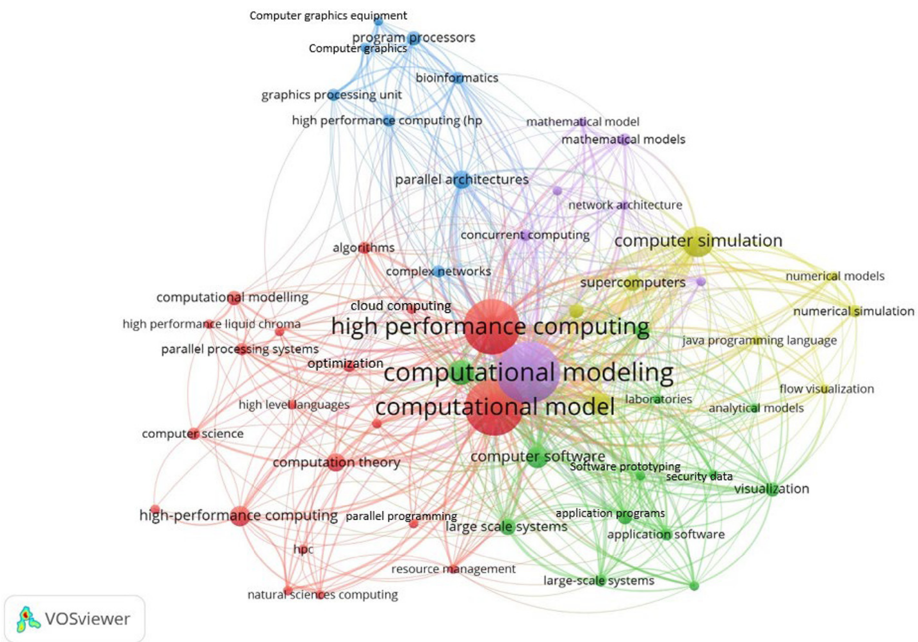

Figure 5.
A network visualisation map

Keyword	Occ.	TLS	Keyword	Occ.	TLS
Computational modelling	39	221	Numerical simulation	4	24
Computational model	35	221	Optimisation	4	17
High-performance computing	33	183	Parallel processing systems	4	24
Computer simulation	15	90	Analytical models	3	24
Computer architecture	11	77	Cloud computing	3	12
Computer software	9	69	Computational science	3	5
Distributed computer systems	9	71	Computer graphics	3	19
High-performance computing	8	29	Computer graphics equipment	3	19
Computation theory	7	34	Flow visualisation	3	25
Parallel architectures	7	53	High level languages	3	17
Large scale systems	6	47	High-performance computing systems	3	19
Supercomputers	6	35	High-performance liquid chromatography	3	10
Application programs	5	50	High-performance computing clusters	3	30
Cluster computing	5	37	HPC	3	9
Computational modelling	5	18	Internet	3	24
Grid computing	5	36	Java programming language	3	27
Program processors	5	28	Laboratories	3	36
Visualisation	5	49	Mathematical model	3	23
Algorithms	4	27	Natural sciences computing	3	18
Application software	4	45	Network architecture	3	28
Bioinformatics	4	29	Numerical models	3	23
Complex networks	4	31	Parallel computing	3	19
Computer science	4	17	Parallel programming	3	19
Concurrent computing	4	32	Problem solving	3	23
Graphics processing unit	4	24	Resource management	3	25
High performance computing	4	23	Scientific computing	3	18
Large-scale systems	4	36	Security of data	3	34
Mathematical models	4	28	Software prototyping	3	37

Notes: Occ. = Number of occurrence; TLS = Total link strength

Table 4. Extracted keywords and total link strength

complex CMs or validated by them, and these are achieved by running computer codes (UK Government Office for Science, 2018). The rise of HPC has helped in the development of such codes and testing the validity of these mathematical models (Tulasi *et al.*, 2015). These have been made possible through the series of programming languages embedded into the HPC which makes execution of tasks possible. Earlier languages are FORTRAN and COBOL, while more recently Python, R program, MATLAB among others have been found as useful programming languages useful for computational science. Furthermore, these computational codes take a lot of time to execute, but with the advent of HPC with a processing speed of 3.5 GH_z, a lot of computational time is saved (Tulasi *et al.*, 2015).

Cluster 2 – *Parallel computing and improved visualisation* is seen in the blue nodes of the map and has eight co-occurring keywords. These are complex networks, parallel architectures, high-performance computing, graphics processing unit, bioinformatics, program processors, computer graphics and computer graphics equipment. The keywords in this cluster reveal the focus of studies on high-performance computing in parallel computing and improvement of computer graphics for better visualisation. It has been noted that when it becomes necessary to communicate ideas about complex systems, visualisation is a good alternative in achieving this. This is because a well-developed model can help simplify complex interactions at work by mere pictorial illustrations (UK Government Office for Science, 2018). Most engineering problems require proper data visualisation to present data in such a manner that scientist can understand (Imbert, 2017). The general feature of highly powerful Graphics Processing Units (GPU) of HPC has made ease of data visualisation a reality. HPC is made up of GPUs such as NVIDIA GTX 480 Spec series, which are designed to speed up graphics-oriented tasks like image rendering (Tulasi *et al.*, 2015). With the aid of such data visualisation techniques, theories represented as a model can also be simplified for further deductions. Thus, the use of HPC for data visualisation has helped improved the method of data visualisation and save time and resource that could have been used if traditional approaches were considered. Furthermore, the analogy, which is a cognitive process involving the transfer of information from one subject (the source) to another (the target), is made easier through HPC. The use of analogic model plays a vital role in problem-solving tasks such as prediction, cognition, perception, emotion, among several others (Coelho, 2010). In more recent times, it has found relevance in activities like face recognition and facial perception. ML algorithms such as the artificial neural network (ANN) is a useful tool for such activity (Seyedzadeh *et al.*, 2018). This requires a large amount of data, computing system of large storage capacity and GPU and high-speed processor. All these requirements fit into the properties of HPC, and these have played a crucial role in getting such tasks executed with ease.

Cluster 3 – *Large scale application software* is in the green region of the map and accounts for thirteen keywords. Significant among them are computer software, software prototyping, large scale systems, analytical models, application software, application programmes, the security of data, cluster computing and visualisations. These keywords give pointers to study conducted in the area of high-performance computing in the development of large-scale application software. Today, several application softwares are designed to make daily living easier. The complexity of tasks involved in built environment-related researches has informed the use of large-scale application software. A study by Adah *et al.* (2018) highlights some important large-scale application software used in the built environment. These software's solve issues related to flow visualisation, 3D modelling and rendering, numerical analysis, prediction and estimation of data among several others. The importance of these softwares for sustainable development has been explicitly discussed – improved job delivery by handling the complex task with complex softwares, faster delivery due to faster process time and enhancement on precision and accuracy of the job done. Although the complexity of this large-scale application software may seem like a barrier to users with less familiarity and skills, the development of this software is no less different. This is a factor which might impede the development and use of large-scale application software. In a study conducted by Wang *et al.* (2018), intent on the enhancement of performance and productivity of large-scale application software, information and common features of scientific codes were collated to enhance the knowledge of the scientific functions and dependency of these large-scale application softwares. For high-performance computing, these software were subjected to a reliability test to confirm their level of reliability and to check if the reliability requirements are met (Zhang *et al.*, 2017). Based on the discovered reliability, it is evident that the utilisation of large-scale application software for high-performance computing in built environment researches will enhance productivity and accuracy (Clarke and Larmour, 2016).

Cluster 4 – *Computer simulations* can be seen in the yellow region of the map. This cluster also has eight keywords in it, and these are computer simulation, numerical models, numerical simulation, flow visualisation, java programming language, supercomputers, grid computing and distributed computer system. These keywords point to the use of high-performance computing in computer simulations. The use of computer simulations has gained significant attention in most studies that have used high-performance computing.

Bringing simulation into construction, AbouRazik (2010) describe simulation as the process of using computer-based representations of construction systems to give an insight into the behaviour of these systems. Computer simulation has been noted to be a useful tool in aiding better design and construction decisions, and it has been notably exploited in process planning and resource allocation (Zhang *et al.*, 2005). In a study related to microclimate, ENVI-met was used to simulate the microclimate of an environment, thereby generating results which would have been delayed due to periodic situation (Misni *et al.*, 2019). With simulation, it is possible to properly view and analyse research details, while investigating future occurrences as is the case in the study of the futuristic year 2050 projection (Mata, 2020). Computational fluid dynamics, a simulation method which has been used prominently in urban physics and building energy studies for flow visualisation has transformed from being a mere emerging tool to an accepted field due to its reliability and accuracy (Blocken, 2015). It was used to generate a 3D model in the determination of the velocity of gas and liquid magnitude and distribution at a monolith module entrance in a chemical engineering-related study (Lei *et al.*, 2020). It can also be used in conjunction with experimental fluid dynamics to make a hybrid for faster results, and improved time and cost spent on research (Meroney, 2016). Computer simulation using high-performance computing has been used in other areas such as the minimisation of detriment to the built environment due to solar water heating system, using energy plus software (Santos and Giglio, 2020), and in the prediction of thermal sensation in the built environment to provide comfort for building occupants while considering energy saving, using a human simulator (Koelblen *et al.*, 2018). Notwithstanding the numerous benefits accrued from computer simulation, Wan and Ng (2018), in a study conducted based on rural areas of China, reasoned against the idea of simulations for measurement compared to locally acquired indicators in the determination of the sustainability of the built environment in these local areas. Simulations such as computational fluid dynamics require a massive level of computation and as such parallel programming should be considered for such computations to achieve high-performance computing (Ashraf *et al.*, 2016). Although extra precaution should be taken when performing computer simulation, to avoid error and maintain accuracy, proper utilisation of computer simulations results in reliable results.

Cluster 5 – *Computational mathematical modelling* is in the purple region of the map and has seven keywords. These are computational modelling, concurrent computing, network architecture, high-performance computing systems, mathematical models and internet. Computational mathematical modelling and computational modelling are interwoven. Mathematical modelling can be used in the prediction of future occurrences based on analysis with computational tools (Khoshnaw, 2019). It can be used in the computation as well as efficiency evaluation of modelled systems. A mathematical model implemented as a Delphi software program used in the operation of combined heat and power (CHP) plants is used for calculations, optimisations, simulation of operating modes and the analysis of changes in efficiency (Tatarinova *et al.*, 2017). With the use of high-performance computing, running such software program in a parallel mode leads to less runtime, and increases computational efficiency. To keep up with the growing complexity of built energy systems, mathematical modelling systems such as model predictive control (MPC) can yield optimal solutions based on given objectives and constraints in anticipation of future energy generation (Stadler *et al.*, 2018). This MPC is usually best performed using parallel computer architecture feature of HPC (Gaska *et al.*, 2017). The complexity of urban planning also informed the use of computational mathematical modelling such as multiparametric mixed-integer linear programming in consideration of appropriate decision-making in ensuring the preconceived goals of a project is attained (Schüler *et al.*, 2018). Furthermore, for engineering research which involves structural analysis, heat transfer and fluid flow, a numerical technique called finite element method (FEM) is mostly used. With the growing complexity of engineering problems, FEM has become computational, and this is aided by softwares such as MATLAB, Abaqus, Autodesk Simulation, SimScale, among others. With the use of computational mathematical modelling, several factors and parameters can easily be considered and scaled to achieve optimal performance.

Trends in high-performance computing research and areas for future studies

In terms of the trend of publication, Figure 6 shows the overlay visualisation of the 56 extracted co-occurring keywords. The figure revealed that the area of concentration for these studies between the year 2000 to 2005 was more on network architecture, mathematical models, java programming language, application software, concurrent computing, internet, flow visualisation, distributed computer systems. However, studies evolved from the year 2005 to 2010 into more of computational modelling rather than mathematical. Areas such as high-performance computing, computer software, complex networks, computer simulations, parallel architectures, program processors, algorithms and computational theory continued to enjoy significant attention. These keywords are seen in the green areas of the map. In more recent times, areas such as high-level languages, high-performance computing, natural science computing, optimisation, parallel processing systems, cloud computing, graphics processing units and computer graphics equipment are gaining prominence. These keywords are found in the yellow areas of the map. This implies that there is a continuous improvement in research on high-performance computing as high-level programming is now being considered with a view to give better and more quality outputs.

Table 4 shows that some keywords have low TLS, e.g. computational science, and high-performance liquid chromatography, but, a look at the overlay visualisation map on Figure 5 reveal that these keywords exist in old publications (before the year 2010); hence,

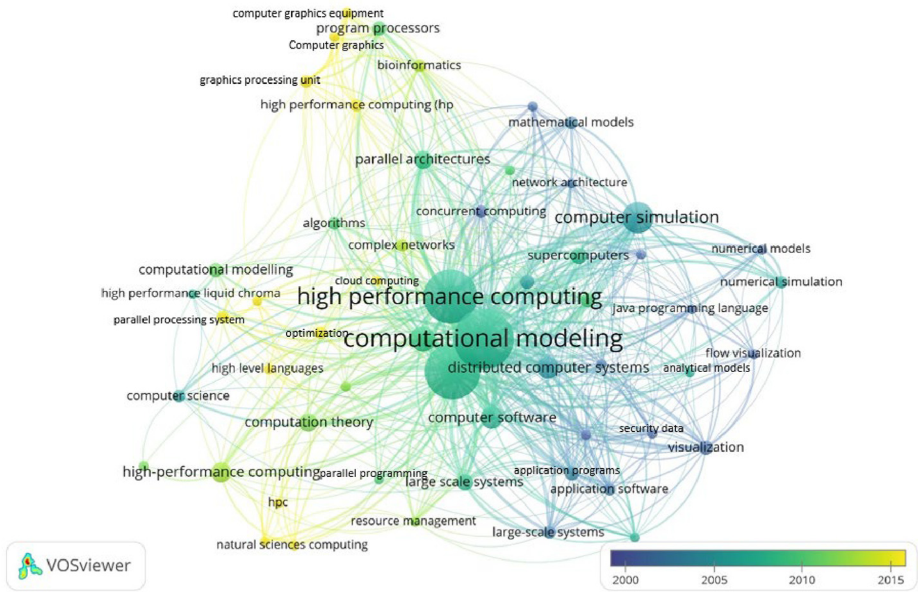

Figure 6.
An overlay visualisation map

they might not be an ideal area for future studies. However, future studies in the built environment can place focus on HPC in the development of CMs, along with other trending areas such as cloud computing which have a TLS of 12. This low TLS is a pointer to the fact that the number of publications in this area might still be very few. Andriole (2016) has earlier described cloud computing as one of the significant technological areas were organisations need to grow their capabilities to survive the new digital era. Furthermore, Kagermann (2014) noted that the fourth industrial revolution is mostly IT with features such as cyber-physical systems, Internet of Things and cloud computing. Researchers in the AEC would do well by taking advantage of the limited research on HPC in cloud computing to make significant advancement in the industry. Also, optimisation, high-level programming language and natural science computing as they relate to the AEC industry can be explored, since these keywords are evident in more recent researches and they revealed a TLS of 17 and 18 – refer to Table 4. Horsman *et al.* (2017) has earlier noted that computing is linked with natural science through technology. With the clamour for a sustainable environment and the mimicking of nature in construction development (Welles, 2019), *vis-à-vis* the availability of a wide range of digital technologies, researchers can explore the possible use of HPC in developing designs relating to the natural environment. Furthermore, for better visualisations, AEC research focus can be placed on computer graphics equipment and GPUs as they appear to be recent areas of focus but have a TLS of 19 and 24 respective (Figures 6 and 7).

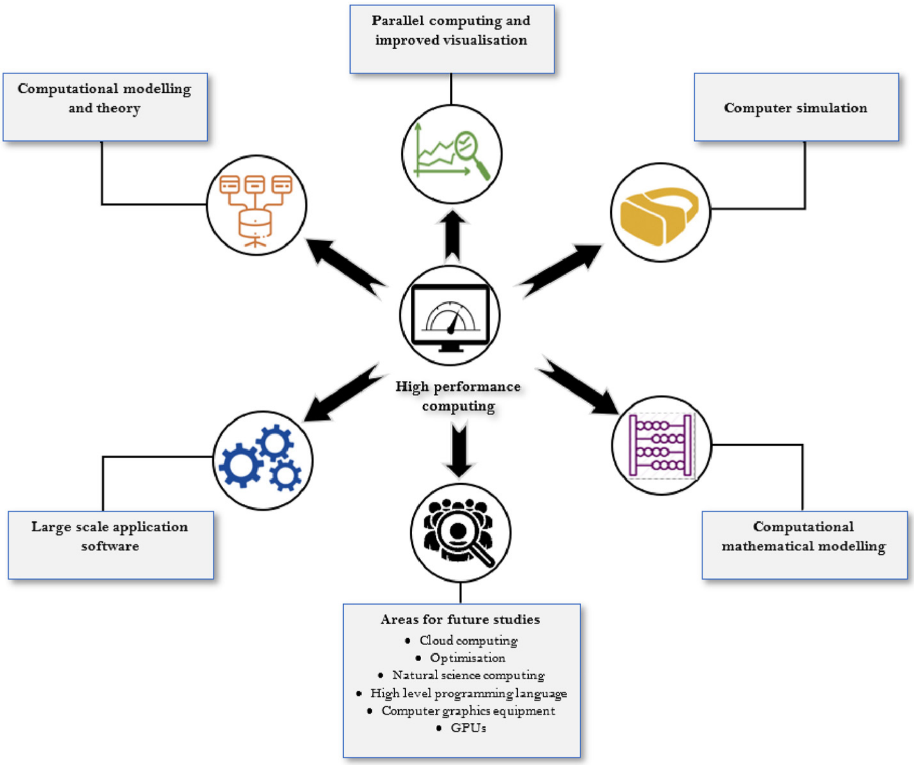

Figure 7.
Area of focus of HPC in computational modelling and area for future studies

Implication of findings

Practically, this study also shows that the AEC industry stands a chance to benefit from impactful researches conducted using HPC. This is because HPC offers the possibility of developing complex computational models and theories needed for solving complex problems in the industry. Furthermore, the use of large-scale application software provides solutions to issues surrounding flow visualisation, 3D modelling and rendering, numerical analysis, prediction and estimation (Adah *et al.*, 2018) as well as offering design and project productivity and accuracy (Clarke and Larmour, 2016). Parallel computing and improved visualisation, computer simulations and computational mathematical modelling all bears considerable benefits for project designs and delivery using HPC. Theoretically, considering the absence of studies that have explored the use of high-performance computing in computational modelling within the AEC, this study provides an excellent theoretical backdrop for researchers seeking to explore the usefulness and application of HPC in the development of CMs, particularly within the AEC industry. The study also reveals areas for possible research in HPC in relation to cloud computing, optimisation, natural science computing, high-level programming language, computer graphics equipment and GPUs.

Conclusion

The development of CMs is generally dependent on high-performance computing. Unfortunately, the scientometric review conducted revealed a knowledge gap in the use of high-performance computing for CMs development in the AEC industry of developing countries particularly in Africa where substantial complex problems are affecting the industry's ability to deliver projects successfully. Base on the review conducted, the study has been able to showcase the area of focus of past studies. Furthermore, the study was able to unearth the possible areas for future studies which can prove beneficial to AEC industry researchers and research organisations who stands to gain meaning and impactful researches by beaming their searchlights in these areas of studies.

While the study contributes significantly to the body of knowledge, the findings are limited to the use of a single database (Scopus) for the search of the literature. Future studies can, therefore, be conducted using other databases or the combination of two or more databases to extract more articles for review. Also, this study area can benefit from empirical studies exploring the potential impact of HPC in solving complex problems within the AEC industry.

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