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Atmospheric cloud modeling methods in computer graphics: A review, trends, taxonomy, and future directions

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ABSTRACT

The modeling of atmospheric clouds is one of the crucial elements in the natural phenomena visualization system. Over the years, a wide range of approaches has been proposed on this topic to deal with the challenging issues associated with visual realism and performance. However, the lack of recent review papers on the atmospheric cloud modeling methods available in computer graphics makes it difficult for researchers and practitioners to understand and choose the well-suited solutions for developing the atmospheric cloud visualization system. Hence, we conducted a comprehensive review to identify, analyze, classify, and summarize the existing atmospheric cloud modeling solutions. We selected 113 research studies from recognizable data sources and analyzed the research trends on this topic. We defined a taxonomy by categorizing the atmospheric cloud modeling methods based on the methods' similar characteristics and summarized each of the particular methods. Finally, we underlined several research issues and directions for potential future work. The review results provide an overview and general picture of the atmospheric cloud modeling methods that would be beneficial for researchers and practitioners.

Contents

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1. Introduction

Clouds are fraction components of the sky in the atmospheric environment. The existence of atmospheric clouds could be observed almost every day with attractive shapes and numerous formations. They are vital in contributing to the richness of the natural phenomena in the sky. These components are challenging and complicated due to their characteristics that require the scientific body of knowledge about the large-scale atmospheric environment and the physical processes accounting for the cloud particles' visibility and formation (Lohmann et al., 2016). Therefore, understanding the atmospheric clouds' presence and appearance is essential (Cohn, 2017; Odugo, 2018). In the computer graphics field, the atmospheric clouds are commonly used in a wide range of applications such as movie productions (e.g., Hasegawa et al., 2010; Miller et al., 2012; Webb et al., 2016; Murphy et al., 2018), meteorological studies (e.g., Yang et al., 2013; Xu et al., 2015; Rimensberger et al., 2019; Xie et al., 2019), video games (e.g., Nowak et al., 2018; Schneider, 2018), flight simulations (e.g., Hu et al., 2009b; Zhang et al., 2014; Kang et al., 2015), virtual reality (e.g., Penney, 2016; Wright et al., 2019; Li et al., 2020), and art visualization (e.g., Álvarez et al., 2007; Shen et al., 2019).

There is an exceptional demand for modeling the atmospheric clouds in the area of computer graphics. The cloud modeling plays a significant role in generating the virtual clouds and as a feeder for rendering and visualizing clouds' final appearance. It is challenging to develop a realistic nature of atmospheric clouds without a proper understanding and a practical design. Several modeling methods have been proposed to solve problems associated with atmospheric clouds in the last four decades. Mainly on image quality (e.g., Qiu et al., 2013; Suzuki et al., 2015; Goswami, 2019), performance (e.g., Yuan and Guo, 2015; Goswami and Neyret, 2016; Murphy et al., 2018), or both of them (e.g., Wang, 2003; Xu et al., 2009; Nowak et al., 2018). However, researchers and practitioners, especially the novices and inexperienced, find it difficult to understand and choose well-suited solutions for their research work. A contributing factor can be the lack of available review papers on the atmospheric cloud modeling methods in computer graphics. There are no comprehensive or systematic literature review papers covering this topic to the best of our knowledge. In the previous literature, the published manuscripts only focused on reviewing a subset of the modeling methods (e.g., Ebert, 1996; Ebert et al., 2003; Tan and Yang, 2009; Lagae et al., 2010; Limtrakul et al., 2010), but not covering the complete solutions related to the atmospheric cloud modeling methods.

This paper aims to deliver a broad and up-to-date review of the atmospheric cloud modeling methods proposed previously in the computer graphics field, including classical and modern solutions. This paper is inspired and motivated by the inherent significance and widespread use of atmospheric cloud modeling methods in various graphical-based applications and the need for the latest review on this topic. In brief, our review process was conducted based on consecutive phases and steps. These involve designing, conducting, analyzing, and documenting the review. This study's results are expected to help the researchers and practitioners understand the characteristics and behaviors of every method proposed in the existing literature, and it could also be a quick reference to get an overview of useful methods. This paper would also be an extension of the survey on atmospheric cloud-related research work in computer graphics (Ebert, 1996; Ebert et al., 2003; Cerezo et al., 2005; Tan and Yang, 2009; Lagae et al., 2010; Limtrakul et al., 2010; Hufnagel and Held, 2012; Zamri and Sunar, 2019).

The contributions of this review paper include:

- portraying the publication trend analysis of the research studies by providing a recent update on the distribution of the publication per manuscript type, year, and venue,
- proposing the up-to-date taxonomy of the existing atmospheric cloud modeling methods based on six crucial driven methods (physics, heuristic, data, hybrid, control, and hardware) that have different nature of work,
- elucidating every method involved in the proposed taxonomy by identifying the core characteristics of the relevant methods deeply, and
- underlining the future research directions and their challenging tasks by highlighting several research opportunities that could help the researchers participate in the future based on the analysis of the existing pattern of solutions that has not been updated for a long time.

The remaining of this paper is structured as follows: Section 2 presents the methodology used for the review process, Section 3 presents the results obtained to answer the pre-determined research questions, Section 4 discusses the advantages and disadvantages of existing atmospheric cloud modeling methods, and Section 5 concludes the paper.

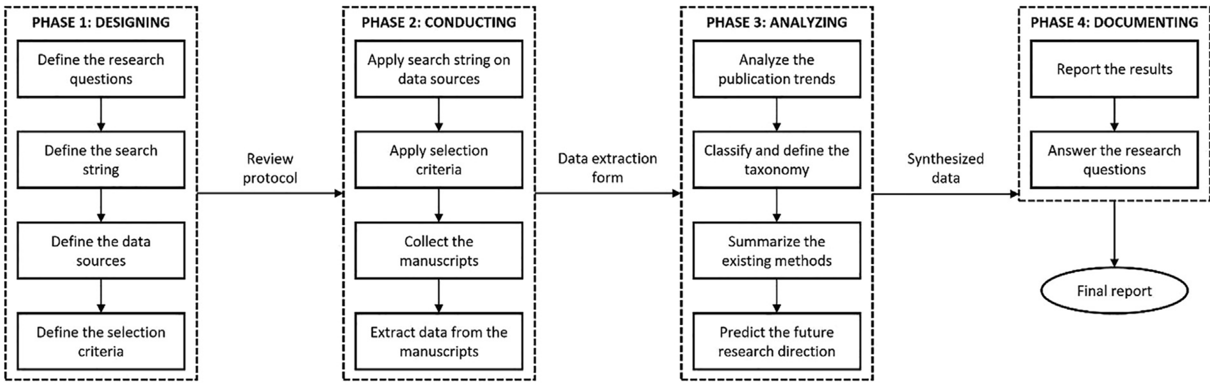


Fig. 1. Review process.

Table 1
Selection criteria.

Type of Criterion	Requirements
Inclusion	Studies in the form of journal papers, conference papers, books, book chapters, technical reports, theses, course notes. Studies subject to be applied in the computer graphics field. Studies are written in the English language. No restriction on year of publication.
Exclusion	Studies focusing on cloud computing that are not referring to the atmospheric clouds. Studies focusing on point clouds that are not referring to the atmospheric clouds.

2. Method

This section explains the process involved in reviewing the atmospheric cloud modeling methods in computer graphics. We adopted the guidelines recommended by Snyder (2019) in which four phases are to be executed in the review process: (i) designing, (ii) conducting, (iii) analyzing, and (iv) documenting. Fig. 1 illustrates the entire processes involved and the output produced for each phase.

2.1. Designing the review

The first phase is intended to design and plan the strategy for producing the review protocol. Four steps are to be considered by defining the (i) research questions (RQ), (ii) search terms, (iii) data sources, and (iv) selection criteria. To achieve our research goal, we are required to answer the following research questions:

- RQ1. What are the publication trends of research studies in modeling the atmospheric clouds in computer graphics? Objective: to classify primary studies in assessing distributions of publication types, year, and venues depending on the number of primary studies.
- RQ2. What is the up-to-date taxonomy of representing the atmospheric cloud modeling methods in computer graphics? Objective: to categorize existing atmospheric cloud modeling methods into specific groups organized systematically and hierarchically to give a general picture of the focused topic.
- RQ3. What are the existing atmospheric cloud modeling methods that have been adopted in computer graphics? Objective: to identify the trends of methods used from the primary studies and summarize the existing atmospheric cloud modeling methods' main characteristics, giving an overview of the topic's current state of understanding.
- RQ4. What are the future research directions regarding the modeling of atmospheric clouds in computer graphics? Objective: to identify research issues and gaps concerning the state-of-the-art of the atmospheric cloud modeling.

This review's results are meant to be valuable answers for researchers to further contribute to this area of research work and practitioners to understand the existing methods better and thus be able to apply the one that better suits their desired goals.

To define the search terms, we used a search string based on a set of important keywords. These include "clouds", "atmospheric clouds", "cloud modeling", "modeling clouds", "cloud shape", "cloud generation", "cloud construction", "cloud creation", and "cloud formation".

Regarding the data sources, we identified several online digital databases and search engines that can be used to search and collect the manuscripts as the primary studies in the literature review process. These include ACM Digital Library, IEEE Xplore Digital Library, ScienceDirect, Scopus, Springer Link, Taylor & Francis Online, Web of Science, Wiley Online Library, CiteSeerX, Google Scholar, ResearchGate, and Semantic Scholar.

We consider the inclusion and exclusion criteria to define the selection criteria, as indicated in Table 1. In general, the manuscripts must be written in the English language, and the proposed methods in the manuscripts should be applied in solving computer graphics problems. The manuscripts that focus on cloud computing and point clouds are excluded because the keywords are irrelevant and out of our scope because they are not referring to the atmospheric clouds.

2.2. Conducting the review

The second phase is executed to perform the strategies for literature search, selection, collection, and data extraction based on several definitions in the previous phase. It is a straightforward process where the search activity begins by applying the defined search keywords on the online digital databases and search engines. The literature search results are called "candidate studies". Inclusion and exclusion selection criteria are then applied to the candidate studies to filter and determine the relevant studies. After removing the duplication of relevant studies from different data sources, the manuscripts are collected. Based on our final selection process, we successfully compiled 113 manuscripts. These results are called "primary studies" as our main dataset for the review process. In particular, we first sorted the primary studies in ascending order based on the year of publication and the first author's name. We then assigned a unique paper ID for each sorted primary study (see Table 3). The extraction of essential characteristics from the

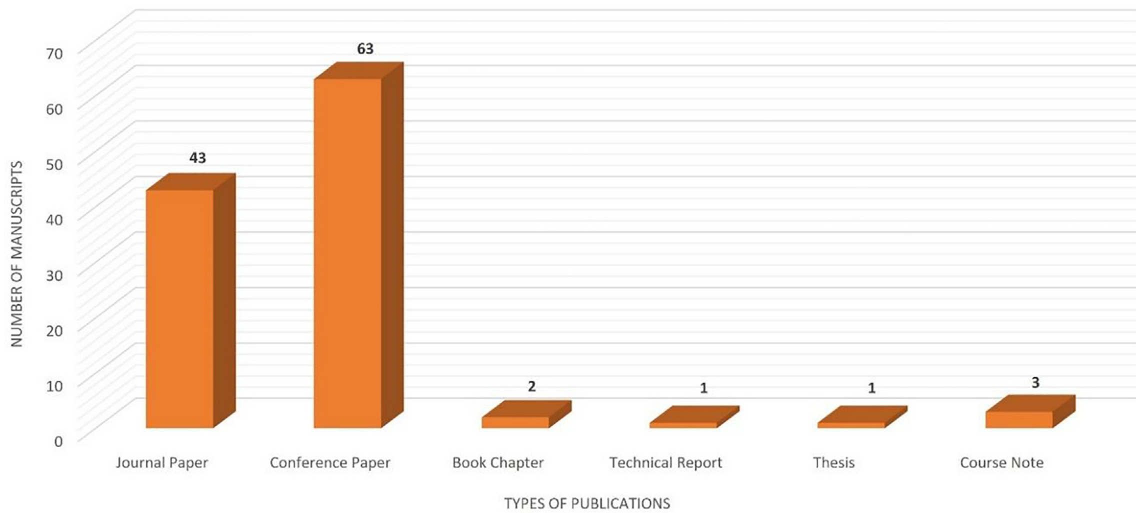


Fig. 2. Distribution of the publication per type.

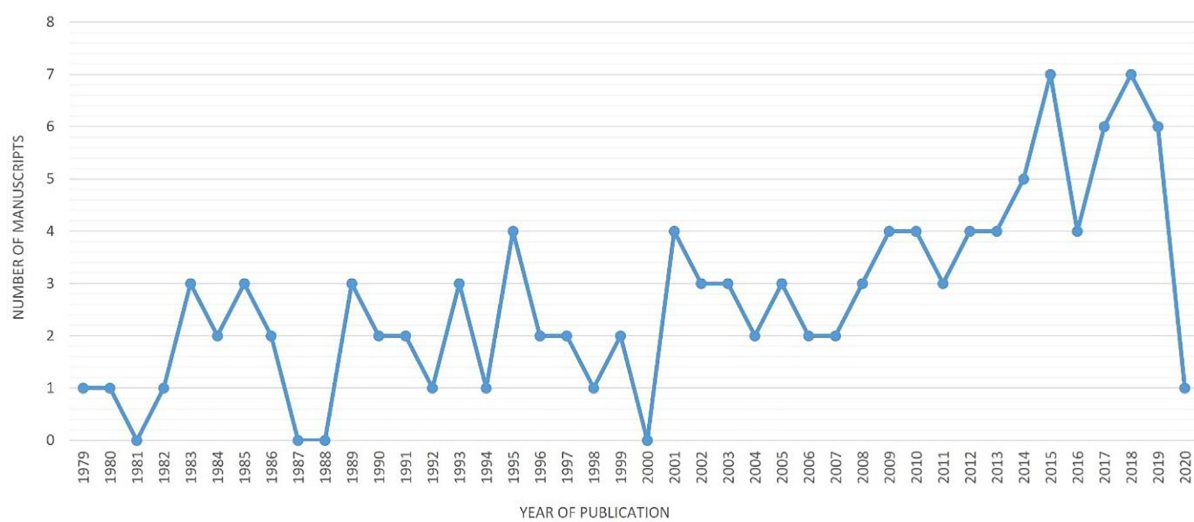


Fig. 3. Distribution of the publication per year.

primary studies is then made and stored in the table form. These include publication year, type, venue, author's name, manuscript's title, problem to be tackled, corresponding solution, proposed method, input data, cloud types covered, target applications, hardware technology involved, cloud-scale level, cloud editing usage, real-time cloud presence, evaluation metrics, advantages and disadvantages of the solution, and future work.

2.3. Analyzing the review

The third phase is done by analyzing the extracted data from the previous phase to synthesize some information so that it can be used to answer our research questions. The analyses cover:

- The publication trends (RQ1). This was done by investigating and classifying the primary studies based on the publication year, types, and venues.
- The up-to-date taxonomy of atmospheric cloud modeling methods (RQ2). To develop the taxonomic classification, the comparative study of the proposed methods from the primary studies was done by investigating the core characteristics of the proposed methods and grouping the method under the same category when it has similar nature of work.
- The summary of the existing cloud modeling methods based on our proposed taxonomic classification (RQ3). This was done by investigating the trends of methods over the years and detailing the characteristics of the proposed methods involved in terms of commonalities, similarities, and differences.
- The forecasting of future research directions regarding atmospheric clouds modeling in computer graphics via research gap analysis (RQ4). This was done by investigating the primary studies' discussion and future work. We looked into the proposed solution's frequency, the pattern of approaches, and information on room for improvement stated in the primary studies.

2.4. Documenting the review

The final phase is implemented by writing a final report to present the results obtained from the analysis phase. Each research

Table 2
Distribution of the publication per venue, hosting at least two primary studies.

Venue	Number of Manuscripts	Type of Publication	Year of Publication
ACM SIGGRAPH Computer Graphics	8	Journal	1979, 1982, 1983, 1984(2), 1985, 1989, 1990
ACM SIGGRAPH Talks	6	Conference	2009, 2010, 2012, 2016, 2018, 2019
Annual Conference on Computer Graphics and Interactive Techniques	6	Conference	1985, 1986, 1993(2), 1995, 1996
Computer Graphics Forum	6	Journal	2001, 2010, 2014, 2017, 2018, 2020
Pacific Conference on Computer Graphics and Applications	6	Conference	1998, 1999, 2001, 2002, 2013, 2018
The Visual Computer	5	Journal	1991, 1993, 1999, 2001, 2005
ACM Transactions on Graphics	3	Journal	1983, 2008, 2012
Computer Animation and Simulation	3	Conference	1995(2), 1997
IEEE Computer Graphics and Applications	3	Journal	1990, 1996, 2019
ACM SIGGRAPH Sketches	2	Conference	2003, 2005
Computers & Graphics	2	Journal	1980, 1992
Graphics Interface	2	Conference	1991, 1994
International Journal of Multimedia and Ubiquitous Engineering	2	Journal	2012, 2015

question's answer is presented in a separate section in this paper (Sections 3.1–3.4).

3. Results

3.1. Analysis of the publication trends

In answering the first research question (RQ1), this section presents the publication trends analyzed from the 113 primary studies classified into three viewpoints – publication type, time, and venue. Fig. 2 illustrates the number of manuscripts based on different publication types. It can be observed that conference papers are the major contributors in the primary studies with 55.75%, followed by 38.05% of journal papers and 6.19% of other types of published manuscripts.

Regarding the distribution of publications on atmospheric cloud modeling over time, Fig. 3 shows the publication trend of 42 years, ranging from 1979 to 2020. It can be seen that the average number of publications is three per year, with a growing trend that reaches its peak in 2015 when seven manuscripts on the topic have been chosen. Later, the trend fluctuated and rose with a high frequency of six or seven manuscripts published in three consecutive years, 2017, 2018, and 2019. Therefore, this result confirms a consistent interest of the computer graphics community to explore and solve the atmospheric cloud modeling problems.

In respect of the distribution of targeted publication venues, Table 2 lists the publication venues which hosted at least a minimum of two publications from the primary studies. It can be derived that the most common venue is ACM SIGGRAPH Computer Graphics (8 out of 113), where the published manuscripts were the preliminary research work, and the classical literature contributed to the existence of atmospheric cloud modeling work beginning from the late 1970s up to early 1990s. It was followed by evenly distributed (6 out of 113) in Computer Graphics Forum, Annual Conference on Computer Graphics and Interactive Techniques, Pacific Conference on Computer Graphics and Applications, and ACM SIGGRAPH Talks. We notice that most of the venues listed in Table 2 are the prominent platforms to publish high-quality manuscripts in the field of computer graphics. Thus, this paper's review results are significantly valuable and beneficial to computer graphics communities and cloud-related research and development.

3.2. Taxonomy of the atmospheric cloud modeling methods

This section answers the second research question (RQ2). We classified the existing atmospheric cloud modeling methods into specific categories based on our analysis of the primary studies. We introduced a taxonomy in a hierarchical subdivision form to represent the entire cloud modeling methods in computer graphics field. Fig. 4 portrays the details of the taxonomy hierarchy.

In this paper, we classified the atmospheric cloud modeling methods into primary and secondary classifications. Table 3 shows the relationship between primary and secondary classifications. The primary classification is divided into four methods: (i) physics-driven methods, (ii) heuristic-driven methods, (iii) data-driven methods, and (iv) hybrid-driven methods. These methods play an important role as a significant foundation for constructing the atmospheric clouds. Also, in Table 3, the corresponding row of the appropriate methods (either physics-driven, heuristic-driven, or data-driven) was highlighted or marked to show the fusion involved in the hybrid-driven methods. Next is the secondary classification. It is divided into two methods: (i) control-driven methods and (ii) hardware-driven. These methods need to be separated from the previous four methods because both methods are exploited to support the primary classification. It can further enhance the proposed methods in terms of flexibility and performance.

3.3. Summary of the existing atmospheric cloud modeling methods

This section answers the third above-mentioned research question (RQ3). We analyzed, summarized, and described the varieties of cloud modeling methods that were identified from the primary studies for solving the computer graphics problems with respect to our taxonomic classification proposed in the previous section.

First, we present the relationship between existing methods in primary classification to the published manuscript count. As indicated in Fig. 5, heuristic-driven methods have the highest publication, that is, 70 manuscripts out of 113 primary studies, followed by data-driven methods (21), hybrid-driven methods (16), and physics-driven methods (6). Fig. 6, on the other hand, shows that methods in secondary classifications were discussed in 50 publications, with control-driven methods that has the biggest number of publications of 38 manuscripts, followed by hardware-driven methods (8) and a combination of control-driven and hardware-driven methods (4). The analysis indicates that control-driven methods were preferred to be incorporated with the methods in the primary classification. We also observe that heuristic-driven methods are the highest among primary classification methods and secondary classification methods, as shown in Figs. 7 and 8 respectively. This observation can also mean that heuristic-driven methods became the preferable target method for controlling and accelerating the cloud modeling process.

Next is the analysis of the existing methods' trend over time. Fig. 9 depicts the publication frequency per year for all six driven methods. If we combine both data presented in Fig. 9 and Table 3, one apparent finding is that the heuristics-driven methods are the

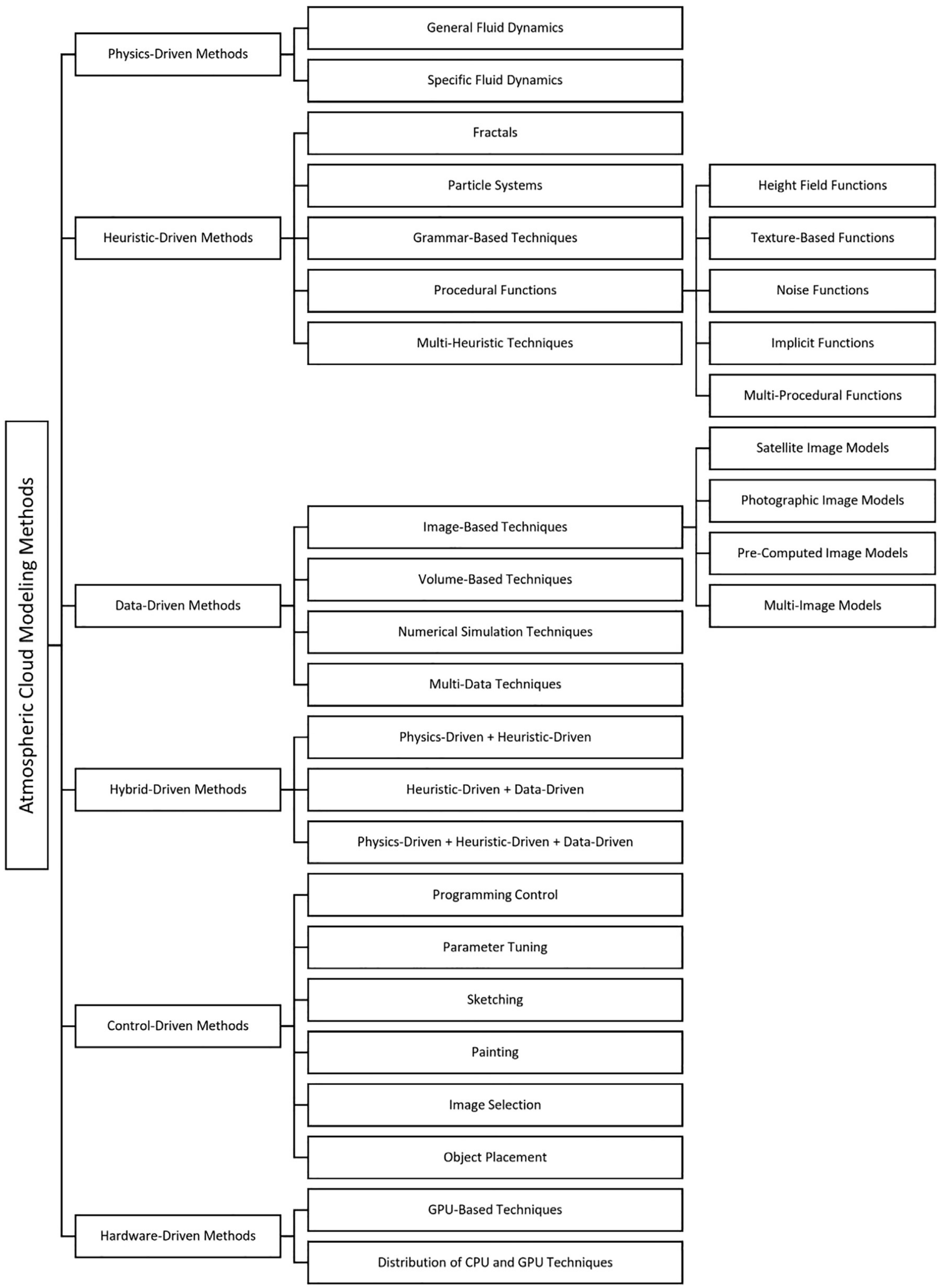


Fig. 4. Taxonomic classification of atmospheric cloud modeling methods.

most discussed in the primary studies. In contrast, physics-driven methods have the least number of discussions. We also observe that data-driven methods are highly recommended from 1996 until recently. The hybrid-driven methods are mostly active during the early 2000s, especially the fusion of heuristic-driven and data-driven methods. On top of this, a pool of hybridization methods was also proposed over the past ten years. As for the methods in secondary classification, the control-driven methods have consistently provided user interaction solutions to support methods in the primary classification, and the hardware-driven methods are frequently employed for the past ten years due to the advancement of the hardware processing technologies.

Table 3
Relationship between primary and secondary classifications.

ID	Year	Author	Primary Classification				Secondary Classification	
			Physics-driven method	Heuristic-driven method	Data-driven method	Hybrid-driven method	Control-driven method	Hardware-driven Method
P1	1979	Dungan		√				
P2	1980	Fishman and Schachter		√				
P3	1982	Norton et al.		√				
P4	1983	Max		√				
P5	1983	Reeves		√				
P6	1983	Voss		√				
P7	1984	Gardner		√				
P8	1984	Kajiya and Von Herzen	√					
P9	1985	Gardner		√				
P10	1985	Perlin		√			√	
P11	1985	Voss		√				
P12	1986	Max		√				
P13	1986	Yaeger et al.	●	●		√		
P14	1989	Inakage		√				
P15	1989	Lewis		√				
P16	1989	Saupe		√				
P17	1990	Ebert and Parent		√				
P18	1990	Musgrave and Berger		√				
P19	1991	Inakage		√				
P20	1991	Stam and Fiume		√			√	
P21	1992	Sakas and Gerth		√				
P22	1993	Nishita et al.		√				
P23	1993	Sakas		√			√	
P24	1993	Stam and Fiume		√			√	
P25	1994	Stam		√			√	
P26	1995	Gamito et al.	√					
P27	1995	Luciani et al.	√					
P28	1995	Raczkowski and Kaminski		√				
P29	1995	Stam and Fiume		√			√	
P30	1996	Lee et al.			√			
P31	1996	Nishita et al.		√				
P32	1997	Ebert		√			√	
P33	1997	Neyret		√				
P34	1998	Dobashi et al.			√			
P35	1999	Dobashi et al.			√			
P36	1999	Nishita and Dobashi		●	●	√		
P37	2001	Harris and Lastra		√			√	
P38	2001	Miyazaki et al.	●	●		√	√	
P39	2001	Nishita and Dobashi		●	●	√		
P40	2001	Trembilski		●	●	√		
P41	2002	Heinzlreiter et al.			√			
P42	2002	Overby et al.	√				√	
P43	2002	Trembilski and Broßler		●	●	√		√
P44	2003	Riley et al.		●	●	√	√	
P45	2003	Schpok et al.		√			√	√
P46	2003	Wang		√				
P47	2004	Bouthors and Neyret		√				
P48	2004	Roditakis			√			
P49	2005	Hasan et al.		√				√
P50	2005	Krall and Harrington		●	●	√	√	
P51	2005	Lipuš and Guid		√				
P52	2006	Man		√				
P53	2006	Rana et al.		√			√	
P54	2007	Álvarez et al.		√			√	
P55	2007	Hufnagel et al., 2007		●	●	√	√	
P56	2008	Bouthors et al.		√				√
P57	2008	Dobashi et al.	√				√	
P58	2008	Wither et al.		√			√	
P59	2009	Batte and Fu		√			√	
P60	2009a	Hu et al.		√				
P61	2009b	Hu et al.		√			√	
P62	2009	Xu et al.		√				√
P63	2010	Dobashi et al.			√			
P64	2010	Hasegawa et al.		√			√	
P65	2010	Ostroushko et al.		√				
P66	2010	Stiver et al.		√			√	
P67	2011	Cui et al.		√				
P68	2011	Gong and Hu		√				
P69	2011	Yu and Wang		√			√	
P70	2012	Do et al.		√			√	
P71	2012	Dobashi et al.			√			
P72	2012	Gong		●	●	√		

(*continued on next page*)

Table 3 (*continued*)

ID	Year	Author	Primary Classification				Secondary Classification	
			Physics-driven method	Heuristic-driven method	Data-driven method	Hybrid-driven method	Control-driven method	Hardware-driven Method
P73	2012	Miller et al.		√				
P74	2013	Abdessamed et al.		√			√	
P75	2013	Qiu et al.	●	●		√		
P76	2013	Yang et al.			√			
P77	2013	Yuan et al.			√			
P78	2014	Alldieck et al.			√			
P79	2014	Dobashi			√		√	
P80	2014	Wei et al.		√			√	
P81	2014	Yuan et al.			√		√	
P82	2014	Zhang et al.		√				
P83	2015	Kang and Kim		√				
P84	2015	Kang et al.		√				
P85	2015	Mukhina and Bezgodov		√				√
P86	2015	Sun et al.		√				
P87	2015	Suzuki et al.			√		√	
P88	2015	Xu et al.			√			
P89	2015	Yuan and Guo			√			
P90	2016	Bi et al.		√				
P91	2016	Goswami and Neyret	●	●		√	√	
P92	2016	Penney		√			√	
P93	2016	Webb et al.	●	●	●	√	√	
P94	2017	Dobashi et al.			√		√	
P95	2017	Iwasaki et al.			√			
P96	2017	Kobak and Alda	√					√
P97	2017	Montenegro et al.		√			√	√
P98	2017	Schneider		√			√	
P99	2017	Zhang et al.		●	●	√		
P100	2018	Cen et al.			√			
P101	2018	Chen et al.			√		√	
P102	2018	Jiménez de Parga and Gómez Palomo et al., 2018		√				√
P103	2018	Murphy et al.		√			√	
P104	2018	Nowak et al.		√				
P105	2018	Schneider		√				
P106	2018	Webanck et al.		√			√	
P107	2019	Goswami		√			√	
P108	2019	Jiménez de Parga		√				√
P109	2019	Rimensberger et al., 2019			√			
P110	2019	Shen et al.		√			√	√
P111	2019	Wright et al.			√		√	
P112	2019	Xie et al.		●	●	√		
P113	2020	Vimont et al.	●	●		√	√	√

Note: √ represents the relevant methods in the highlighted research work and ● represents the hybridized components.

In the next subsections, the summary of existing atmospheric cloud modeling methods in computer graphics are explained in consideration of the researchers involved, the types of specific methods used, and the cloud-related characteristics manipulated.

3.3.1. Physics-driven methods

Physics-driven methods are physically-based simulations that attempt to generate atmospheric clouds by strictly following the laws of cloud physics. These typically involve fluid dynamics, thermodynamics, and partial differential equations (PDE). Physics-driven methods can be divided into two techniques: (i) general fluid dynamics and (ii) specific fluid dynamics.

3.3.1.1. General fluid dynamics. General fluid dynamics techniques are used as the PDE solvers involving the Navier-Stokes equation to model the cloud formation via the fluidity elements. In computer graphics, Kajiya and Von Herzen (1984) were the pioneers to employ the numerical fluid solver for modeling and simulating the atmospheric clouds. They presented equations to model atmospheric fluid dynamics by taking into account the volume densities. However, some important physics-based parameters, such as adiabatic cooling and temperature, were ignored during the modeling process, affecting cloud visualization's visual quality. Overby et al. (2002) proposed the multi-cloud generation model for simulating cloud formation based on an efficient computational fluid solver via manipulation of the velocity field and momentum conservation. They mixed the fluid solver with the natural phenomenon parameters, considering the buoyancy, relative humidity, and condensation. Besides, Dobashi et al. (2008) presented a method for generating and simulating the cumulus-type clouds based on computational fluid dynamics (CFD). Their method considers the physics-based parameters such as velocity, pressure, vapor density, cloud density, and temperature in the cloud formation process.

3.3.1.2. Specific fluid dynamics. Specific fluid dynamic techniques refer to special mathematical functions or computational fluid solvers to model the cloud formation. Gamito et al. (1995) and Luciani et al. (1995) proposed methods to simulate fluids with an appropriately-high resolution of result quality via 2D turbulence fluids. However, their respective method treated the 2D case only. Consequently, there is a cost to transfer from 2D to 3D representation, which will affect the visual quality of cloud generation due to differences in nature. Recently, Kobak and Alda (2017) introduced

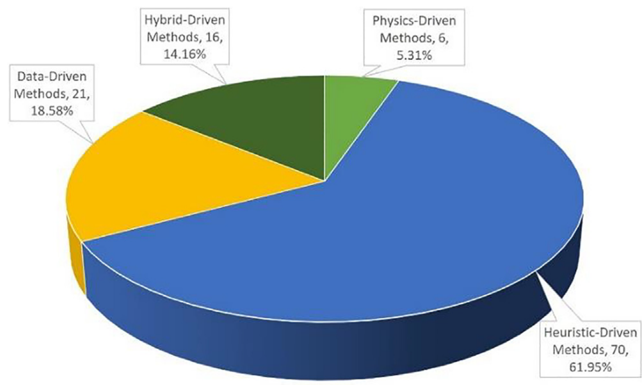


Fig. 5. Distribution of the methods in the primary classification (total of manuscripts = 113).

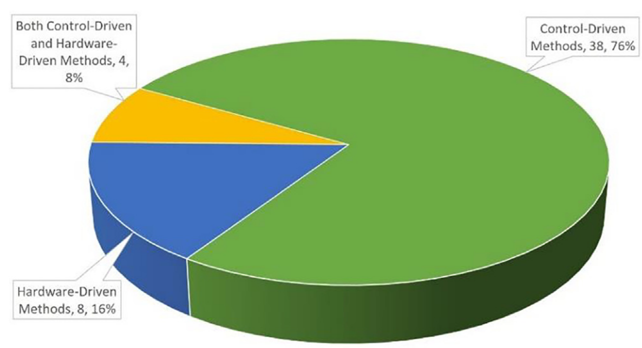


Fig. 6. Distribution of the methods in the secondary classification (total of manuscripts = 50).

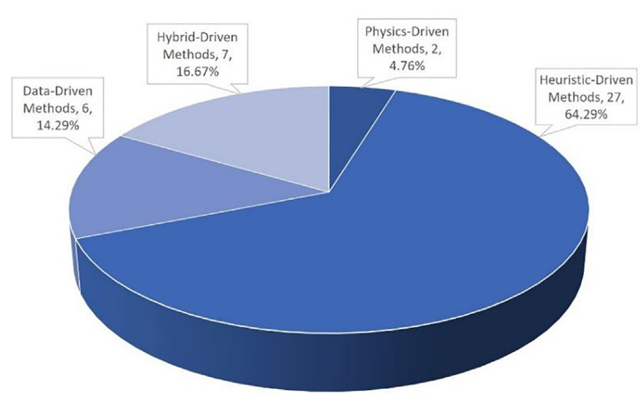


Fig. 7. Distribution of the methods in the primary classification involving control-driven methods (total of manuscripts = 42).

continuous functions that comprise several parameters, including temperature, humidity, and vertical air currents, to model and simulate the atmospheric clouds.

3.3.2. Heuristic-driven methods

Heuristic-driven methods are the rule-based methods that procedurally modeled the atmospheric clouds by using simplified processes and calculations. These methods are the main competitor of the physics-driven methods with less computational efforts to yield highly plausible results. In this paper, heuristic-driven methods are divided into five techniques: (i) fractals, (ii) particle systems, (iii) grammar-based techniques, (iv) procedural functions, and (v) multi-heuristic techniques.

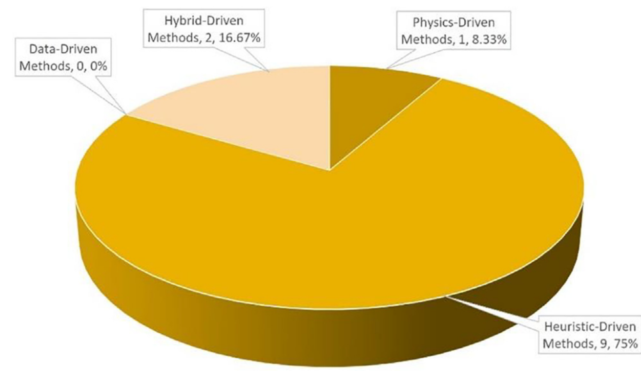


Fig. 8. Distribution of the methods in the primary classification involving hardware-driven methods (total of manuscripts = 12).

3.3.2.1. Fractals. Fractals are mathematical expressions that utilize the recursion features to create a particular object. These methods exhibit similar patterns at increasingly small scales called self-similarity. The approximation of fractals is very useful in modeling natural phenomena such as atmospheric clouds due to its nature in random shape appearance. According to classical literature, Voss (1983) used Gaussian fractal based on the Fourier series and extended his research by exploring and applying the fractal geometry modeling in the following year (Voss, 1985). Nishita et al. (1993) proposed a method to model the clouds using 2D fractals based on the Mandelbrot set. As a result, the Earth with atmospheric cloud coverage can be observed from the outer space.

The generated clouds' quality can also be increased by incorporating fractals with other functions, representations, or algorithms. Raczkowski and Kamiński (1995) presented a simple method to model various types of clouds by manipulating fractals and sine functions to obtain realistic results. Nishita et al. (1996) extended their research work by applying the fractals to the implicit objects called metaballs to represent the cloud shapes. Sun et al. (2015) proposed a novel and practical algorithm for generating 3D volumetric clouds using fractals and the Cube-Diamond-Square algorithm.

3.3.2.2. Particle systems. Particle systems are methods in which the collections of small object representations that, when grouped, they will form a more complex fuzzy object. These complex effects are controlled by specifying individual particles' behavior using properties, including initial position, velocity, and lifespan. Thus it is suitable for modeling the static and dynamics of the atmospheric clouds.

The particle systems method was originally introduced in the field of computer graphics by Reeves (1983). He proposed a method for modeling fuzzy objects such as clouds, fire, and water. The idea was to define an object's volume via the particle systems, which are treated as a series of primitive particles. Reeves hierarchically managed the spherical-based particle systems and employed the repetitive processes to generate and control these particles within a particle system. The use of particle systems was then explored by Inakage (1989, 1991) to model the atmospheric cloud densities by defining the particles with different radii values and distributing them in cube space.

An individual particle in the particle system is typically represented as a simple geometric object. Spherical-shaped particle is frequently adopted compared to other alternatives such as cube, cuboid, ellipsoid, and tetrahedron, due to its simple representation.

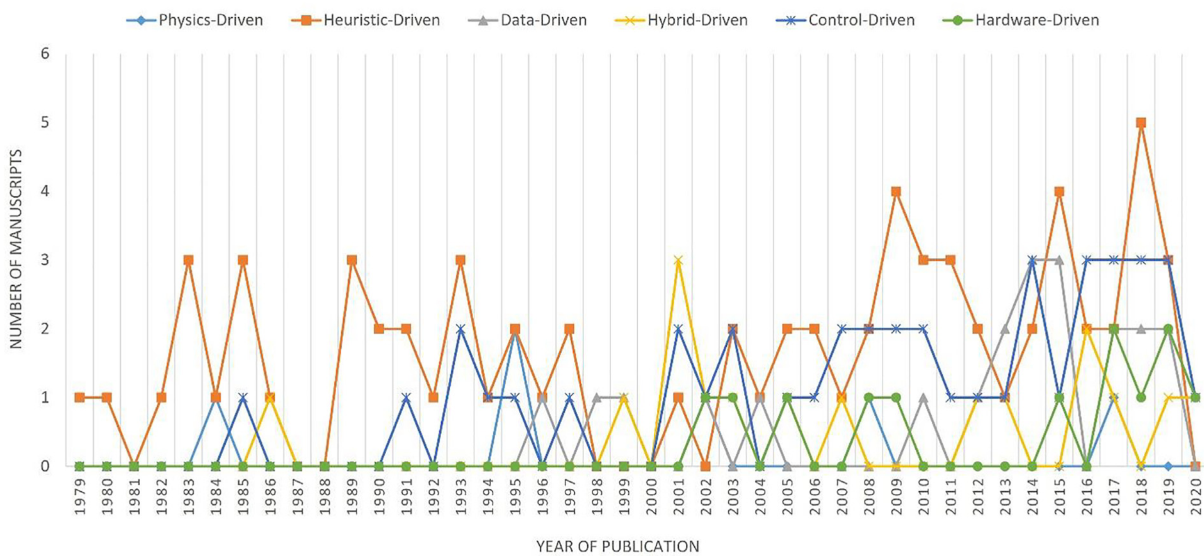


Fig. 9. Distribution of all driven methods in the primary and secondary classifications over time.

Harris and Lastra (2001) developed a cloud model by assuming that a particle represents a roughly spherical volume. Each particle is dependent on several parameters, including a center, radius, density, and color. They gained good estimations of the real clouds by filling the specified space with particles of varying sizes and densities. Their work was then extended by Wang (2003), who modeled different atmospheric clouds, including nimbostratus, cumulonimbus, and altocumulus. He also introduced a method to model cloud formation with the use of texture-splatted particles.

Bouthors and Neyret (2004) proposed a model to define and create cumulus clouds' shape by storing the quasi-spherical particles in a hierarchical tree structure. The shape of these particles is defined by an implicit field that changes depending on the adjacent particles.

The paper also came across a research work that only focused on modeling and visualizing clouds' non-photorealistic visual appearance by blending the natural phenomena features with the artistic elements into a system. Álvarez et al. (2007) presented methods to generate clouds with cartoon-like and sketching-like effects by allowing the abstraction of the atmospheric clouds' visual and geometric complexity using a particle system. In contrast to the realistic generation of natural clouds, this is a way to produce imaginary-looking cloud types.

The modeling of cloud dynamics is also important in the computer graphics area. Batte and Fu (2009) used the particles to control surface meshes, track the cloud movements, and create clouds' secondary motion. They employed control maps to define particle properties such as radius, emission rate, and secondary motion's amount. Yu and Wang (2011) proposed a particle-based cloud modeling method by presenting a polygon sampling technique to obtain numerous 3D cloud shapes. It was done by first selecting the target 2D shape and then extending it into 3D representation. They claimed to be the first one to introduce the cloud morphing method by using the particle system.

Several research works have proposed methods to gain high performance in the system. Rana et al. (2006) proposed an efficient cloud shape modeling method based on the randomized method to create detailed volumetric shapes of clouds using particle systems. Hu et al. (2009a) proposed a simple real-time method for modeling atmospheric clouds by simulating cloud particles' projected motion into a 2D plane to form the cloud density. Stiver et al. (2010) proposed a particle positioning system for creating cloud appearances via mesh representation. The particles are filled and constrained within the mesh-bounded space to create a fully volumetric cloud. The real-time particle-filling processes were achieved by hashing the mesh into a 2D grid representation. Do et al. (2012) proposed methods that aimed for large-scale cloud generations while considering fewer efforts to model and display various clouds in a real-time environment with lower computational power. By hierarchically managing the particles, the large particles at the top of the hierarchy were subdivided into small-size particles to represent the clouds' details. Abdessamed et al. (2013) used a similar idea proposed by Do et al. (2012) but focused only on modeling the cumulus clouds.

Recently, Zhang et al. (2014) discussed a 3D cloud simulation method whereby atmospheric cloud modeling was one of the important aspects. The 3D cloud was first modeled using particle systems by specifying clouds' atmosphere features in the natural world. The particles were then wrapped with textured images to improve the visual appearance of clouds.

3.3.2.3. Grammar-based techniques. Grammar-based techniques are originated from the formal language theory in which grammar describes how to form strings from a language's alphabet that are valid according to the language's syntax. These modeling techniques are based on a set of rules and symbols that are represented in string form. In modeling the atmospheric clouds, Kang and Kim (2015) and Kang et al. (2015) proposed methods by exploiting the use of recursive L-system (Lindenmayer system) and therefore defining the production rules and the corresponding parameters to conform to the cloud properties, including the shape, density, and direction of cloud growth.

3.3.2.4. Procedural functions. Procedural functions are powerful modeling methods in generating and simulating the atmospheric clouds in computer graphics. In this paper, we divide these methods into five categories: (i) height field functions, (ii) texture-based functions, (iii) noise functions, (iv) implicit functions, and (v) multi-procedural functions.

3.3.2.4.1. Height field functions. These functions are used to create cloud layers by considering the height field features, represented as regions bounded by top and bottom planes. Based on our analysis of the classical literature, we identified that the preliminary research work on cloud modeling methods emphasized manipulating the height field functions due to its simple representation and easy implementation. Dungan (1979) applied these functions to generate semi-opaque clouds over terrain. It was later followed by Fishman and Schachter (1980), in which they created the opaque cumulus clouds as the cloud layers. Max (1983) modeled a cloud volume by defining the region between two height fields. A small number of parameters is sufficient to determine the cloud shape instead of using broad database access. Later, Max extended his research work by modeling height field-based multi-scale cloud distributions (Max, 1986). In the model, the large-scale components were modeled using polynomial functions. The medium-and-small scale component was modeled by a series of sine functions consisting of different wave vectors, amplitudes, and phases.

3.3.2.4.2. Texture-based functions. These functions are used to manipulate one or more arrays of data in the form of texels (texture pixels) for the texture coordinates to generate the cloud shape. Early work was done by Norton et al. (1982) by proposing an anti-aliasing technique that uses the texture function based on the convolution approximation in the frequency domain, named clamping function. They particularly used a tabulated periodic cloud texture function to generate real-time cloud simulations for pilot training. Later, Gardner (1984, 1985) used the texture function using Fourier expansion and Fourier synthesis principles.

Towards manipulating 3D texture functions, Ebert and Parent (1990) introduced a turbulent flow-based solid texture function to define and model gaseous objects' geometry, including clouds. In contrast, Sakas and Gerth (1992) employed a 3D volume density texture function for clouds by considering the distance and pyramidal-volume sampling. Later, Bouthors et al. (2008) implemented a 3D texture function called the Hypertexture to support the multiple scattering model in atmospheric clouds. Xu et al. (2009) used a volume texture function obtained from the mapping of simulation space via probability fields that adopt the fractional Brownian function to get the realistic cloud features. Gong and Hu (2011) used the Modified Midpoint Displacement method to synthesize textures for constructing 3D clouds.

Recently, Mukhina and Bezgodov (2015) proposed a new method for modeling multiple layers of stratocumulus clouds in the atmospheric environment by generating texture function and integrating it with the shader model. They stored all required data in texture function to facilitate for fast accessibility of data. Besides, Murphy et al. (2018) used texture-based functions for modeling their volumetric clouds that take into consideration the system efficiency and artistic interactions in developing workflows for animated films "Cars 3" and "Incredibles 2".

3.3.2.4.3. Noise functions. These functions act as random number generators that have unstructured patterns. These methods are used to refine and give details to the visual appearance of clouds. Preliminary research work was done by Perlin (1985) by introducing the noise function in which the clouds were created by composing a spline function with turbulence function. This function is also known as Perlin noise, which is categorized under the family of gradient noise. Later, Lewis (1989) proposed the solid noise function, which consists of two important algorithms: Wiener interpolation and efficient sparse convolution algorithm. Musgrave and Berger (1990) developed a solid noise function to modulate the refraction index as a part of the proposed mirage model of an outdoor scene. Stam and Fiume (1991) used Gaussian noise at the small-scale level to add interesting visual detail and transparency. At the same time, they adopted Kriging interpolation at the large-scale level to control the cloud shape model. Sakas (1993) presented a new type of noise function called stochastic spectral synthesis to model realistic dynamics of turbulent gaseous-like objects such as clouds in the 2D and 3D environment via Fourier space. All parameters employed were corresponding to the physics-based properties of turbulent fields. The use of Perlin noise was continued by Man (2006). He presented a noise function based on a random number generator for generating the 3D cloud maps that are later mapped onto ellipsoidal-shaped cloud volumes.

Noise functions are frequently applied in movie productions. Hasegawa et al. (2010) developed their modeling tool named *Cumulo* for the making of the film "The A-Team" that was able to convert the basic cloud shapes into level sets and apply multiple generations of the displacement noise for realizing various shapes of the modeled clouds. Miller et al. (2012) modeled modular clouds as polygonal meshes to make the animated film "Puss in Boots". They followed similar procedures as implemented by Hasegawa et al. (2010) by manipulating the volumetric-based level set representation and adding a displacement noise function to produce different types of clouds from clumpy cumulonimbus to feathery nimbus clouds.

Recently, Nowak et al. (2018) presented effective methods for obtaining realistic real-time clouds in the 3D game engine called "Unreal Engine 4″. They proposed several noise functions for modeling clouds. These include simplex, gradient, fast gradient, and Voronoi noise. They also proposed a simplified simulation method for forming cloud phenomena. In contrast, Shen et al. (2019) introduced the cloud complexity principle by applying an improved Perlin noise with a fragment shader model.

3.3.2.4.4. Implicit functions. These functions are used to match and fit the use of implicit representation of atmospheric clouds. Commonly, several simple geometric primitives are used, combined, and blended to produce the final cloud appearance. Neyret (1997) proposed the bubble-based implicit function to model and simulate convective clouds' growth via manipulating potential temperatures and latent heat. Lipuš and Guid (2005) introduced a new implicit function based on Set Theory for blending implicit primitives especially designed for volumetric cloud modeling. Wither et al. (2008) gained some knowledge and ideas from Gardner (1985) and Neyret (1997) to model the shape of cumulous clouds by creating an implicit function that combines a series of spherical primitives which is constrained by the specified 2D outline. Hu et al. (2009b) presented a function that can generate a large-scale distribution of clouds based on several cloud templates that consist of two important components: cloud blocks and cloud sprites. Ostroushko et al. (1993) proposed a mathematical function for modeling various cloud formations by considering the level of detail and cloud size.

The development of a more advanced method has been demonstrated in the last ten years. Wei et al. (2014) implemented a hybrid projection function to generate volumetric clouds from the brush footprints, which rely on projecting and merging the spherical objects and the edges. Penney (2016) modeled clouds in the making of the virtual reality movie "Allumette" via a function called cloud shells, which were then manipulated and turned into voxel grids using the pre-existing volume modeling method as implemented in (Miller et al., 2012). Recently, Webanck et al. (2018) proposed a compact procedural model representing various clouds with different altitudes. It defines the primitive-based field functions to facilitate the modeling of clouds considering large distributions.

3.3.2.4.5. Multi-procedural functions. These functions consist of more than one distinct procedural function to be applied for modeling atmospheric clouds. Based on our analysis, we observed a large number of fusion between implicit and noise functions. Stam (1994) combined the random ellipsoidal blob-based implicit function with the random density field noise functions based on specified mean and covariance. Stam and Fiume (1995) extended their previous work by introducing the diffusion processes, which consist of warped blob implicit function and statistical model of the turbulence field function. Ebert (1997) proposed a new volumetric modeling method that combines the implicit functions with noise and turbulence functions via the perturbation process. Schpok et al. (2003) used a two-tier approach in which the volumetric implicit functions were used at a high-level for controlling the general cloud shape, and the noise and turbulence functions were used at a low-level for adding the cloud details. Recently, Montenegro et al. (2017) proposed a new cloud modeling method by extending ideas from Lipuš and Guid (2005) through the fusion of volumetric implicit function and procedural noise function. They independently assigned the noise to each implicit primitive in different scales before the blending process is done. Schneider (2017) and Schneider (2018) developed various types of 3D noise functions, including Perlin, Inverted Worley, and Perlin-Worley. Schneider also implemented the remap function to model the densities of cloud coverage and cloud type in developing the video game called "Horizon Zero Dawn".

The fusion between texture and noise function was implemented by Hasan et al. (2005) by generating the cloud texture function using Perlin noise and turbulence functions. Recently, Goswami (2019) presented a method for modeling and animating realistic cumulus-type cloudscape by employing the spherical thermal unit called parcels managed hierarchically as an implicit function at a high-level. As for low-level, the method projected parcels to cloud maps using 2D noise function on planar as Hypertexture function.

3.3.2.5. Multi-heuristic techniques. In this paper, this category is created to unite and prove multiple implementations of the heuristic-driven methods. The fusion of fractal and procedural functions in cloud modeling can be seen in (Saupe, 1989) by presenting a method that blends the Mandelbrot-Weierstrass fractals and Perlin's turbulence function as proposed in (Perlin, 1985). In comparison, Stam and Fiume (1993) modeled gaseous-like clouds as the density distributions of blob-based implicit functions based on turbulent wind fields at the high-level and using Spatio-Temporal Fourier synthesis as fractals at the low-level.

The fusion of fractal and particle system was done by Cui et al. (2011) by proposing a new method called the Fractal Particle method in which they created the clouds with smoke-like effects. The fusion of particle systems and rule-based cellular automata method was implemented by Bi et al. (2016) in order to realize the 3D modeling and visualization of clouds. Recently, Jiménez de Parga and Gómez Palomo (2018) and Jiménez de Parga (2019) proposed an advanced cloud modeling method to generate cumuliform clouds that consider Gaussian noise function, fractal, L-system, and optimized metaball-based implicit functions.

3.3.3. Data-driven methods

Data-driven methods are based on real data as a base reference so that the virtual clouds to be produced will be as close as possible to the actual cloud appearance. In this paper, we divide the data-driven methods into four categories: (i) image-based techniques, (ii) volume-based techniques, (iii) numerical simulation techniques, and (iv) multi-data techniques.

3.3.3.1. Image-based techniques. Many image-based techniques have been used in computer graphics. In this paper, these techniques refer to the process of using either a single 2D image or a series of 2D images as the primary reference for extracting the real cloud characteristics so that it can be later used in modeling and rendering the virtual clouds. In this paper, we divide the image-based techniques into four categories: (i) satellite image models, (ii) photographic image models, (iii) pre-computed image models, and (iv) multi-image models.

3.3.3.1.1. Satellite image models. These models refer to the Earth observation imagery captured by satellite technology from outer space, which consists of many atmospheric parameters. Lee et al. (1996) introduced the metacomputing method to handle various satellite image resources to generate clouds for weather information visualization. Furthermore, they also proposed methods for estimating the height field of clouds from the satellite images. Dobashi et al. (1998, 1999) proposed an image-based cloud modeling in which the realistic clouds were generated from the satellite images using metaball representation. The distribution of cloud density is defined by a set of metaballs where the parameters are automatically specified, making the result of synthesizing the clouds similar to the original satellite image. Yuan et al. (2013) presented various methods for modeling large-scale stratus and cirrus clouds by extracting the cloud shape from the satellite images. The proposed methods include a retrieval method for physically-related cloud properties, a segmentation method, and a spectral mixture of images method. Later, Yuan and Guo (2015) extended their previous work (Yuan et al., 2013) by recreating the cumulus clouds from high-resolution Landsat8 satellite images.

3.3.3.1.2. Photographic image models. These models refer to the images taken by using the camera technology from the ground or aircraft. Dobashi et al. (2010) proposed a simple method for modeling clouds from a single photograph. Their method can synthesize three types of clouds: cirrus, altocumulus, and cumulus by computing the intensity and opacity of clouds for each pixel from an input photographic image and storing it as a cloud image. The cirrus cloud was modeled by directly using the cloud image as a 2D texture map. The cumulus and altocumulus clouds were modeled by generating 3D density distributions concerning the cloud image features. Dobashi et al. (2012) explored the use of photographic images of real clouds to estimate the parameters of a non-uniform density model using an optimization method in which the goal is to minimize the objective function which is based on the difference of the color histogram between the synthesized image and the photographic images. The important parameters are the color pixels, sky colors, incident lights color, and color histogram. Dobashi (2014) extended his previous work (Dobashi et al., 2012) by presenting an inverse approach to simulate cloud formation via pre-determined cloud shapes and automatic color computation based on real photographic images. Their work's complete solution was presented in (Dobashi et al., 2017), which involves combining cloud shape generation via cloud formation processes based on atmospheric fluid dynamics, control feedback method via a pre-determined contour line, and optimization method.

Instead of using a standard representation of the 2D photographic image, Alldieck et al. (2014) presented a novel image-based technique for modeling clouds by generating a realistic sky populated with visually similar clouds to the hemispherical photographic image. They also introduced the pixel-wise extraction method for simulating the cloud appearance via opacity and intensity features. At the same time, Yuan et al. (2014) presented a method for estimating a symmetrical cumulus cloud shape from a single photographic image applicable for real-time applications such as flight simulations and video games.

3.3.3.1.3. Pre-computed image models. These models refer to the methods that calculate the images in advance even though they will consume much time to prepare the pre-computed data. This kind of work was done by Heinzlreiter et al. (2002) in which they presented a technique by using alpha-blended billboard textures. A series of pre-computed images are generated for each cloud object at the pre-processing step, starting from defining the ellipsoidal geometry, representing the voxels, determining the density distribution of water vapor, and lastly, becoming the cloud data. Recently, Chen et al. (2018) computed the cumulus clouds from natural images and stored the normalized cloud images into a database. Later, these pre-computed clouds are selectively acquired via their proposed cloud retrieval system.

3.3.3.1.4. Multi-image models. These models consist of more than one image-based technique to be applied for modeling atmospheric clouds. Cen et al. (2018) recently proposed a novel method to extract relevant cloud characteristics from satellite and photographic images to construct large-scale cloud scenes with details. In particular, this involves the modeling of 3D coarse clouds by extracting the cloud parameters from satellite images, the generation of cloud image by implementing the optimization method based on the conditional Generative Adversarial Network (cGAN) concerning cloud contour and photographic images, the mixture of surface details based on previous generated 3D coarse clouds and cloud image, and the particle sampling.

3.3.3.2. Volume-based techniques. Volume-based techniques can be an alternative for modeling clouds. Different from image-based techniques, the volume-based techniques are used by manipulating 3D data representation. Based on our analysis, the previous work only focused on developing methods that employ a pre-computed volume database as the key component. Suzuki et al. (2015) proposed a retrieval system for cloud volumes using a pre-computed database based on the numerical analysis of atmospheric fluid dynamics. The searching of the optimal cloud volume retrieval from a database is done by computing the similarity between the converted query shape to query volume and the available volumes in the database based on the sum of the squared differences of densities between them. Recently, Wright et al. (2019) created art-directed cloud formations in an immersive virtual reality environment during the making of 2D animated short film Disney's "A Kite's Tale" by adopting a customized modeling toolset that can manipulate the volumetric database of clouds.

3.3.3.3. Numerical simulation techniques. Numerical simulation techniques are based on the real data obtained from calculating real situations of natural cloud phenomena, which are normally used in atmospheric science studies such as meteorology, atmospheric chemistry, cloud physics, aerosol research, and remote sensing. Most of the current research work in this category used weather simulation or forecast data to model and visualized the atmospheric clouds. Early work was done in (Roditakis, 2004) by proposing a modeling technique based on the real-world data to construct a 3D volume from point clouds. He presented the cloud volume computations and the interpolation of cloud top and bottom height estimations from concurrent ground-based and satellite observations.

The use of weather forecast data was implemented by Yang et al. (2013). They proposed a technique to model the stratus clouds by computing the numerical simulation data points from weather forecast data and applying the interpolation method of data points to produce the stratus clouds completely. Xu et al. (2015) presented a technique to model and render large-scale cloudscapes from weather forecast data, covering the stratus and cumulus clouds. They used a new optical model to generate primitive data and adopted a splatting technique to generate multi-resolution, axis-aligned slices of cloud volumes. Recently, Rimensberger et al. (2019) computed the numerical simulation values by considering the cloud water content and map air pressure.

3.3.3.4. Multi-data techniques. These techniques consist of more than one data-driven technique to be applied for modeling atmospheric clouds. Based on our analysis of the existing cloud modeling methods, we identified the presence of mixed image-based and volume-based techniques. Iwasaki et al. (2017) proposed a new cloud modeling technique using a single photographic image and an example of a volumetric cloud dataset. They used the optimization-based texture synthesis method to acquire the cloud shading parameters from the photographic image and employed a physically-based fluid simulator to prepare the volumetric cloud dataset.

3.3.4. Hybrid-driven methods

Hybrid-driven methods are a combination of two or more methods from the above-mentioned driven methods. The proposition of these advanced modeling methods might produce better results than the solutions provided by a single driven method. In this paper, three types of combination methods were identified from the analysis of the existing of atmospheric cloud modeling methods: (i) fusion of physics-driven and heuristic-driven methods, (ii) fusion of heuristic-driven and data-driven methods, and (iii) fusion of physics-driven, heuristic-driven, and data-driven methods.

3.3.4.1. Fusion of physics-driven and heuristic-driven methods. Early work of combining the driven methods was done by Yaeger et al. (1986) in which the computational fluid dynamics were engaged with the particle systems via particle decomposition to model clouds in the generation of the simulated planet Jupiter for the film "2010". The fusion between the Coupled Map Lattice (CML) as a heuristic-based method and physical simulation of atmospheric fluid dynamics was proposed by Miyazaki et al. (2001) for modeling and simulating the cloud formation processes. In comparison, Qiu et al. (2013) presented a method for simulating 3D clouds using CML and a series of spherical harmonics. Recently, Goswami and Neyret (2016) presented an efficient physics-based procedural model for modeling the cumulus clouds by coupling the Lagrangian model based on smoothed particle hydrodynamics and volumetric-based noise function. In contrast, Vimont et al. (2020) proposed combining the Eulerian-based method and noise function for modeling large-scale cloudscapes by considering the water bodies and terrain topology features.

3.3.4.2. Fusion of heuristic-driven and data-driven methods. A combination of heuristic method and image-based technique was significantly done by Nishita and Dobashi (1999) in which they modeled complicated cloud surfaces by applying fractals to the metaballs and making use of a satellite image of clouds simultaneously to generate realistic shape and color of clouds. Their work was improved by introducing an efficient cloud modeling method that combines the cellular automata-based heuristic method and satellite image model to model clouds that are viewed from outer space (Nishita and Dobashi, 2001). In contrast, Gong (2012) used computer vision technology to extract 3D structure information of clouds from images and employed particle systems technology to fill in the 3D cloud volumes.

A combination of heuristic method and numerical simulation technique was presented by Trembilski (2001) in which he proposed two approaches for modeling and visualizing the clouds from meteorological weather simulation data, which is engaged with traditional fractals and fractal Brownian motion method respectively. This work was extended by Trembilski and Broßler (2002), whereby they presented surface-based transparency computation methods for producing high-performance visualization of clouds. They mixed the weather simulation data with a modified form of the bubble-based implicit function implemented by Neyret (1997) for computing the cloud surfaces. Riley et al. (2003) combined the metrological data with hydrometeor particle systems based on particle concentrations for the development of multi-field visualization considering the clouds' accuracy. A similar idea was done by Hufnagel et al. (2007), where they combined the use of spherical-based particle systems and weather forecast data.

Recently, Xie et al. (2019) analyzed the weather forecast data and developed a spherical-based particle system to construct the basic cloud shapes while considering the real-time aspect of visualizing the clouds depicted in level-of-details implementation of cloud scenes.

A combination of heuristic method, image-based, and volume-based technique was done by Krall and Harrington (2005). They used various noise functions, satellite images, and a pre-computed volume database in spherical-based voxel data format to produce volumetric clouds. Zhang et al. (2017) presented a more complicated combination of cloud modeling method. They modeled large-scale clouds from satellite images that adopted the multispectral data processing method. The multispectral data processing methods use various parameters in their computation, including cloud base height, cloud top height, ground temperature, cloud top temperature, and cloud shadow. The method also use implicit function based on the lapse rate model that considers temperature lapse rate and cloud base temperature, the fractals for cloud shape refinement, and the particle systems via particle-filling methods.

3.3.4.3. Fusion of physics-driven, heuristic-driven, and data-driven methods. Combining these three driven methods was done by Webb et al. (2016), where they manipulated more than a thousand cloud pieces in their database that could be recombined into larger and varieties of cloud shapes in the making of the animated film "The Good Dinosaur". The cloud pieces were generated by using the fluid simulations, noise functions, and satellite images.

3.3.5. Control-driven methods

Control-driven methods refer to the methods that allow the user to interactively control atmospheric clouds' characteristics via interaction with the interconnected system to get the desired outcome while running the system. These methods are the opposite of the previous literature's automation methods due to its freedom to modify the cloud properties. In this paper, we divide the control-driven methods into six categories: (i) programming control, (ii) parameter tuning, (iii) sketching, (iv) painting, (v) image selection, and (vi) object placement.

3.3.5.1. Programming control. Early work was done by Perlin (1985). He developed an interactive synthesizing system via Pixel Stream Editor for modeling and designing realistic computer-generated visual images. Perlin adopted high-level programming control that manipulates the programming syntax in the programming language for facilitating the computer programmers or software developers to model the cloud as one of the examples of demonstrated objects.

3.3.5.2. Parameter tuning. Parameter tuning methods are based on the modification of specific properties of clouds and other atmospheric components. Previous work on controlling the noise functions was preliminarily done by Stam and Fiume (1991). They allowed the user to control the noise level to add the visual details and edit the low-level component's opacity properties. Riley et al. (2003) focused on controlling the noise function to add details to the cloud-scale weather. Schpok et al. (2003) created an interactive system that allows users to easily model and animate visually plausible clouds via cloud attribute controls consisting of several noise filters. Krall and Harrington (2005) added more precise user controls for modeling different cloud volume parts with diverse noise functions.

Regarding the control of turbulent functions, Stam and Fiume extended their work where the user can control the cloud motion in the large-scale level and tune the statistical parameters of turbulence and wind function at the small-scale level (Stam and Fiume, 1993, 1995). Sakas (1993) also proposed a method to enable the turbulent function's parameter control by considering the intuitive and physics features. In contrast, Ebert (1997) proposed user-defined parameters to control the blending of the implicit function density with the turbulence function density, the overall cloud density, and the detailed refinement of cloud shapes.

Regarding the control of physics-related parameters, Miyazaki et al. (2001) developed an interactive system for modeling various types of clouds by enabling the user to specify the conditional parameters including temperature, velocity, and cloud density to control the cloud shapes. The user also can interact with the atmospheric features and boundary conditions to perform the cloud simulation. Overby et al. (2002) developed an interactive numerical fluid simulator that allows the user to interact with a physically-based simulated environment to produce the desired cloud formation. Hasegawa et al. (2010) designed the *Cumulo* tool to control the displacements and advection velocities via point attributes surface of the cloud base shape. In recent literature, Yuan et al. (2014) permitted users to specify the sun intensity, sun direction, and cloud extinction parameter for estimating the cloud shape from an input image. In comparison, Goswami and Neyret (2016) developed the key aspect controllers where the user can easily manipulate the temperature profile, condensation level, and the atmosphere mixing ratio to realize real-time efficiency and scalability of large atmospheric cloudscapes.

Regarding the control of particle system properties, Álvarez et al. (2007) developed a non-photorealistic cloud visualization system that gives the user freedom to define the particle parameters via center, radius, and mass. They also allowed the user to control the cloud density function's weight and level of subdivisions for cloud surfaces. In (Hufnagel et al., 2007), the user can specify the threshold parameter to control the accuracy of the metaball-based implicit function. Batte and Fu (2009) provided the artistic editing of control maps to define the particle radius, emission rate, and secondary motion. Montenegro et al. (2017) focused on realizing the real-time generation of the desired cloud model via different particle parameter configurations.

Advanced control methods were implemented in the recent literature. Schneider (2017) proposed a method to artistically author real-time volumetric cloudscapes for video game environments. The authoring system allows the user to define the cloud type, coverage, transitions, and visual details parameters via the generation of cloud map and multiple-choice noise functions. In (Goswami, 2019), the user can specify the atmospheric cloudscape region, tune the noise generations, and control the percentage ratio of maximum cloud coverage. Shen et al. (2019) created non-photorealistic artistic styles of user-defined clouds by applying the aesthetic principles to the sky characteristics. The user can intuitively create the cloud shapes via geometric manipulations of sparse points or splines.

3.3.5.3. Sketching. Sketching methods refer to drawing the initial object in rough shape, which then becomes the reference for further refinement. Dobashi et al. (2008) proposed a method for controlling the cloud formation process. The user sketches the contour lines based on a specific camera position to be the target shape for modeling a cloud. In the same year, Wither et al. (2008) developed a sketch-based interface for modeling cumulus clouds where it allows the rapid generation of 3D cloud surfaces via the sketching of 2D outlines by the user. In contrast, Stiver et al. (2010) proposed a freehand sketching system based on multiple strokes to control volumetric clouds' modeling artistically.

In the recent literature, Suzuki et al. (2015) proposed a sketch-based retrieval system for cloud volumes by using a pre-computed database in which the user sketches the desired cloud shape at the desired position on the screen, and their system automatically searches for the optimal cloud volume from the database. Chen et al. (2018) used a similar idea as implemented in (Suzuki et al., 2015) but improved the performance and accuracy of retrieving the natural cloud images from the database. Later, Dobashi et al. (2017) extended their previous work in (Dobashi et al., 2008) by proposing a method that incorporates the user feedback controller via contour line sketching with the automatic parameter adjustment via inverse optimization method. Webanck et al. (2018) described methods that allow the user to intuitively control and author the cloud cover and cloudscape animations over large distances easily. They claimed to be the first researchers to allow user-controlled authoring of animated cloudscapes by using a continuous density field morphing algorithm that considers the terrain height field and the wind field while providing a unified handling of different clouds. Their methods enable the user to sketch a set of input images representing the different cloud layers' cover map.

3.3.5.4. Painting. Painting methods refer to refining a base object's visual appearance via a specific drawing medium to produce the desired results. Wei et al. (2014) proposed a new painting interface for modeling the volumetric clouds by developing a Chinese brush's imitations, capable of controlling a static 2D texture footprint and a dynamic 3D footprint via the motion and pressure of a stylus pen. Penney (2016) developed an immersive and intuitive virtual reality interface for modeling clouds by painting the cloud geometrical shapes (shells) using a proprietary modeling tool. Murphy et al. (2018) introduced artistic control of traditional texture-based approaches. Murphy's work allowed the user to create and change the complex cloud shapes that are cumbersome to be modeled in the previous work. Recently, Wright et al. (2019) used a custom toolset that allows art-directable shapes via a recursive set of surface grooming tools for modeling the cloud shapes. In contrast, Vimont et al. (2020) provided the user with a painting interface that can paint directly into physics-related features such as temperature, water content, humidity, and velocity fields.

3.3.5.5. Image selection. Image selection methods refer to the user's input control to be the target reference for modeling and visualizing the clouds as close as possible to resemble the original image. Yu and Wang (2011) proposed a polygon sampling technique that enables users to model various cloud shapes from a 2D image accurately. Dobashi (2014) presented a method for controlling the cloud formation so that the simulated shapes become similar to the user-specified cloud shape parameters extracted from an image. Webb et al. (2016) created the art-directable cloudscape composition method via a library of 1200 cloud pieces that consist of satellite image elements where the user can recombine them into larger cloud sizes and more varieties of cloud shapes.

3.3.5.6. Object placement. Object placements are methods that let the user positions any bounded-volume or particle objects in particular 3D space based on the outdoor scene's requirement. One example of early work was done by Stam (1994) in which the user is allowed to place the ellipsoidal-based blobs randomly to generate an individual cloud. Harris and Lastra (2001) developed an editing application that allows a user to place particles and build clouds interactively best-suited for video game development. Rana et al. (2006) presented an intuitive and interactive cloud macrostructure editor for designing the cloud shapes by placing the cube-based bounding volumes that represent the clouds. Hu et al. (2009b) developed the cloud modeling system that allows users to generate realistic atmospheric clouds in a 3D virtual environment with good randomness by placing several cuboid-based bounding volumes (sprites) to control the cloud distributions. Do et al. (2012) provided the user with the ability to build up the cloud shapes via the positioning of seed particles in large spherical particles and control the other particle parameters. Abdessamed et al. (2013) developed an interface to let the user place several spherical-based particles in the scene representing the implicit-shaped clouds.

3.3.6. Hardware-driven methods

Hardware-driven methods refer to exploiting the advancement of computer hardware technologies to handle and process various scales of cloud data. Several previous works involved using the central processing unit (CPU) and the graphics processing unit (GPU) to achieve fast computation. Even though many hardware-driven techniques were proposed in the past ten years to tackle issues related to the representations, modeling, rendering, and animations of the atmospheric clouds, in this section, we will explain and focus on related cloud modeling only. This paper divides these methods into two categories: (i) GPU-based techniques and (ii) distribution of CPU and GPU techniques.

3.3.6.1. GPU-based techniques. In GPU-based techniques, graphics hardware is used to help accelerate the computation processes. These techniques are specifically reliant on the robustness of the hardware graphic pipeline to boost up the performance. Trembilski and Broßler (2002) used graphic hardware to support atmospheric cloud modeling by computing polygon's opacity level. Hasan et al. (2005) presented an efficient method to perform all possible computations in GPU. In modeling the clouds, the GPU is used to generate the noise functions in a lookup table. Bouthors et al. (2008) worked on cloud surfaces modeling by representing and computing the depth maps using an efficient GPU technique. As for Xu et al. (2009), modeling procedures were run on the programmable graphics hardware by manipulating the fragment shaders. Lastly, GPU was used to create the stratocumulus clouds via noise functions (Mukhina and Bezgodov, 2015) and to modify the parameters and the blending of primitives in real-time (Montenegro et al., 2017). They also used the GPU's power to compute the cloud densities, noise functions, and turbulence functions parallelly via the graphics device's main kernel and shared memory. Shen et al. (2019) implemented a non-photorealistic system that considers cloud elements in the sky environment where the system's algorithm can be easily implemented on the GPU. In comparison, Vimont et al. (2020) exploited the GPU texture memory to store the cloud layers and thus improve the performance of cloud simulation.

3.3.6.2. Distribution of CPU and GPU techniques. Distribution of CPU and GPU techniques refers to dividing the computational tasks between CPU and GPU, respectively. Schpok et al. (2003) developed a system that uses CPU to generate the slicing geometry, sample implicit functions, optional coarse noise evaluation, and shadow accumulation and exploit GPU to compute the transparency cutoff and noise functions via vertex and pixel shaders. Kobak and Alda (2017) implemented parallel computations and executions of CPU and GPU processors separately via a multi-threaded mechanism to model the convective cumulus clouds. Jiménez de Parga and Gómez Palomo (2018) and Jiménez de Parga (2019) aimed to prove their hypothesis on the possibility of optimizing the complexity of the referenced algorithms with CPU and GPU programming techniques in modeling and visualizing the clouds. CPU is used to calculate and store cloud-related information in voxel representation. At the same time, GPU is used to compute the uniform random noise functions.

3.4. Future research directions

This section answers the fourth research question (RQ4). Several research issues, current patterns of research work, and future

Table 4
Summary of the research issues, questions, and directions.

Research matter	Research questions	Research direction
Multi-type cloud modeling	- How to model different cloud types with different representations and characteristics? - How to handle computing power due to heavy processing data? - How to maintain and balance the tradeoff between high visual fidelity and real-time performance system?	- Explore the possibilities of using multi-tier or multiple data structure approaches to represent the respective cloud types. - Introduce the generalized cloud model that supports different types of clouds. - Integrate cloud modeling with scene management schemes via level-of-detail simplification. - Design and construct an effective and efficient data structure to represent various cloud types.
Scalability of cloud coverage modeling	- How to handle large-scale cloud coverage efficiently in a real-time environment? - How big is the size of the cloud data to be handled? - How to manage intensive memory usage? - How to manage high computational cost? - What are the other external features that could contribute to the generation and appearance of atmospheric clouds?	- Exploit the use of high-end multi-core CPUs and hardware-accelerated GPU. - Manipulate parallel processing power in the distributed systems as implemented in the render farm and cloud computing. - Incorporate efficient scene management schemes via visibility culling techniques. - Consider the interaction of sky, sun, ground, and shadows to be part of cloud modeling.
Immersive VR-based cloud modeling	- How to realize immersive and intuitive user interactions for cloud editing in a VR environment? - How to coordinate effectively between the user, virtual cloud objects, VR input device, and VR output device? - How to achieve high frame rates for performing the VR environment?	- Design and develop a fully immersive VR system via ease-of-use gesture interactions of VR devices. - Design a real-time synchronous interaction and communication among users, systems, and related VR devices. - Optimize the VR content via scene management schemes. - Propose a low-latency VR environment.
Improvement of existing cloud modeling methods	- How to accelerate the computation involved when running the physics-driven method? - To what extent the formal grammar methods can be used in modeling the atmospheric clouds? - To what extent can the existing cloud modeling methods be hybridized to yield high visual fidelity and high performance?	- Exploit the power of hardware-accelerated methods via high-end CPU or GPU. - Integrate with scene management schemes via optimization or compression methods. - Enhance the L-system technique. - Explore and adapt the possibilities of exploiting the other formal grammar methods in cloud modeling. - Design an excellent framework or system architecture that could support multiple methods in one workable system.
Imaginary-shape cloud modeling	- What kind of objects could be modeled using atmospheric cloud representation? - What kinds of atmospheric cloud characteristics could be transferred to the imaginary-shaped object? - How to transfer the cloud characteristics to the targeted object to be modeled?	- Investigate the cloud retargeting method. - Consider several parameters such as the boundary of the imaginary-shape object, denseness of the cloud characteristics, and the cloud movements' dynamics.

Table 5
Examples of the multi-type generation of atmospheric clouds.

ID	Year	Author	Cloud type
P9	1985	Gardner	Cirrus, cumulus, and stratus
P45	2003	Schpok et al.	Cirrus, cumulus, cumulostratus, and stratus
P46	2003	Wang	Altocumulus, cumulonimbus, cumulus, cumulus congestus, nimbostratus, and stratus
P63	2010	Dobashi et al.	Altocumulus, cirrus, and cumulus
P70	2012	Do et al.	Cirrus, cumulus, and stratus
P106	2018	Webanck et al.	Altocumulus, altostratus, cirrus, cirrostratus, cirrocumulus, stratus, stratocumulus, nimbostratus, cumulus, cumulonimbus, cumulus humilis, cumulus congestus, and cumulonimbus capilatus
P108	2019	Jiménez de Parga	Altocumulus castellanus, altocumulus lenticularis duplicatus, altostratus undulatus, cirrus castellanus, cirrus uncinus, cumulus, cumulus humilis, cumulonimbus calvus, cumulonimbus incus, and stratocumulus
P113	2020	Vimont et al.	Altostratus, cirrus, cirrostratus, and cumulus

research directions are discussed. It would give some ideas and insights for the researchers to plan their future research and development. Table 4 indicates the summary of research questions and directions that could contribute to the modeling of the atmospheric clouds.

3.4.1. Modeling of the multi-type atmospheric clouds

The ideal modeling and visualization of the atmospheric clouds should cover multiple types of clouds into a system that represents the natural, real-life atmospheric environment. Based on the previous literature, few methods supported the multi-type generation of clouds (see Table 5). The challenging task would be to account for the cloud types with different characteristic descriptions, height levels or altitudes, and detailed cloud classifications based on genera, specifies, and varieties. The cloud modeling system should consider the formation and integration of stratiform, cumuliform, and cirriform clouds in the 3D virtual environment to produce the atmospheric model's natural phenomena. The researchers might explore the possibilities of using the multi-tier, or multiple data structures approaches to represent the respective cloud types or, if possible, to introduce the generalized cloud models that could support different types of clouds. Note that the computing workloads will be growing in line with the increasing complexity of generating multi-type clouds. Simplification schemes might be required to encounter this issue. Moreover, there is a demand to construct an effective and efficient data structure to represent these various cloud types.

3.4.2. Modeling scalability of the atmospheric clouds

Many computer graphics researchers previously attempted to solve different scales of atmospheric cloud problems, from the modeling of the *simple cloud models* (e.g., Fishman and Schachter, 1980; Kajiya and Von Herzen, 1984; Stam and Fiume, 1991; Sakas and Gerth, 1992; Ebert, 1997; Neyret, 1997; Overby et al., 2002; Schpok et al., 2003; Rana et al., 2006; Hu et al., 2009a) to *small-scale cloud coverage or landscape-size* (e.g., Gardner (1985); Harris and Lastra (2001); Miyazaki et al. (2001); Trembilski and Broßler (2002); Wang (2003); Hasan et al. (2005); Man (2006); Hu et al. (2009b); Ostroushko et al. (1993); Stiver et al. (2010); Dobashi et al. (2012); Mukhina and Bezgodov (2015); Kobak and Alda (2017); Nowak et al. (2018); Goswami (2019)) to *large-scale cloud coverage* (e.g., Dobashi et al., 1998, 1999; Hufnagel et al., 2007; Yuan et al., 2013; Yuan and Guo, 2015; Zhang et al., 2017; Cen et al., 2018; Webanck et al., 2018) to *multi-clouds for large coverage with the interaction of external features* such as terrain, sun, and wind (e.g., Vimont et al., 2020). In general, it is a difficult task to handle large-scale cloud coverage due to the vast amount of data involved, large data storage, intensive memory consumption, and high computational cost. With the technological advancement in hardware and software, large-scale coverage of cloudscapes and planet-sized cloud environments could be realized. The researchers could explore the possibilities of using the high-end multi-core CPUs, hardware-accelerated GPU, parallel computing in the distributed system, and cloud computing capability to generate and visualize large-scale clouds via hybridizing the existing methods or incorporating the efficient scene management procedures.

3.4.3. Immersive virtual reality cloud modeling system

The involvement of users in controlling, editing, or authoring the generation of atmospheric clouds is one of the crucial elements to yield satisfactory results. Based on the previous literature, few studies focused on modeling clouds using virtual reality (VR) technology (e.g., Penney, 2016; Wright et al., 2019). Penney (2016) adopted a VR modeling tool to paint the desired lightweight cloud models and create a layout of the cloud scene but spent a multi-hour session to finish the task. Wright et al. (2019) focused on solving the challenges of creating, designing, and compositing cloud environments for VR while maintaining the balance between the system's performance and visual quality. Both of them have not mentioned any specific VR devices used in their research work. Exploring and introducing VR-based methods would be a tremendous demand for realizing the Fourth Industrial Revolution (Industry 4.0). There is currently a lack of immersive and intuitive user interaction in the full 3D space environment for the cloud editing process. Therefore, VR technology could be a preferable future platform that could provide a higher level of human–computer interactions. VR input devices such as VR wand controllers, data gloves, and the VR output devices such as the head-mounted displays (HMD) and VR glasses could be exploited for manipulating, editing, sculpting and viewing the virtual clouds intuitively and immersively in the real 3D virtual environment. The main challenging tasks would be to tackle the effective coordination among the user, VR input, and output devices concurrently and update the changes made for the atmospheric clouds in interactive rates or, most preferably, the real-time rates. There must be methods to achieve and maintain significant factors such as high-speed performance, fast computation time, low memory consumption, and ease-of-use interaction system during the run-time process.

Table 6
Examples of the generation of imaginary clouds.

ID	Year	Author	Type of imaginary clouds
P58	2008	Wither et al.	Rabbit, sheep, and ship
P59	2009	Batte and Fu	Animation character
P64	2010	Hasegawa et al.	Bunny
P69	2011	Yu and Wang	Ateneal, cow, elephant, and teddy
P70	2012	Do et al.	Bubble man, animation character, and 'K' character
P73	2012	Miller et al.	Buildings and trees
P80	2014	Wei et al.	Chinese character for 'home' and duck
P94	2017	Dobashi et al.	Skull
P106	2018	Webanck et al.	Contrails, 'EG' logo, heart, and hole
P108	2019	Jiménez de Parga	Rabbit

3.4.4. Exploration and improvement of existing atmospheric cloud modeling methods

There are plenty of atmospheric cloud modeling methods that have been proposed for the last four decades to solve different problems of interest. This section highlights the existing methods that have few studies based on our review and analysis of the primary studies. These include the physics-driven methods, grammar-based heuristic-driven methods, and hybrid-driven methods.

Developing the physics-driven methods is a challenging task due to its complexity and computational burden (e.g., Kajiya and Von Herzen, 1984; Yaeger et al., 1986; Gamito et al., 1995; Luciani et al., 1995; Miyazaki et al., 2001; Overby et al., 2002; Dobashi et al., 2008; Qiu et al., 2013; Goswami and Neyret, 2016; Webb et al., 2016; Kobak and Alda, 2017; Vimont et al., 2020). However, if these methods are incorporated with hardware-accelerated methods or computation compression methods, realizing the physically-accurate atmospheric clouds would be possible in the future.

The use of grammar-based heuristic-driven methods is not fully explored yet in modeling the atmospheric clouds. To the best of our knowledge, there are only a few numbers of researchers that proposed and implemented these kinds of methods (e.g., Kang and Kim, 2015; Kang et al., 2015; Jiménez de Parga and Gómez Palomo, 2018; Jiménez de Parga, 2019). Future wise, it would be better to upgrade existing L-systems' capability or explore and adopt the other types of formal grammar methods that are available off-the-shelf.

Besides, the hybrid-driven methods could be a promising solution for the future especially considering the fusion of any components of physics-driven, heuristic-driven, and data-driven methods into one system that is currently lacking exploration (e.g., Webb et al., 2016). The researchers may need to design a proper framework or system architecture that could produce high visual quality and performance.

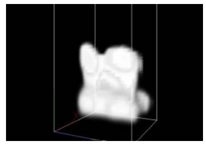
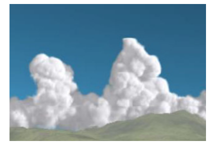
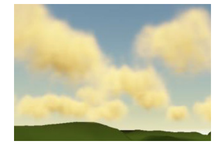
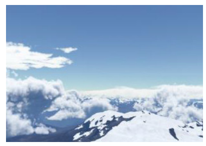
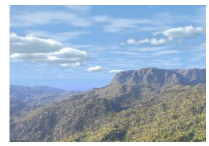
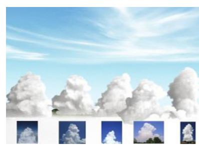
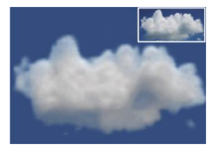
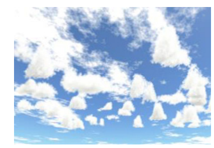
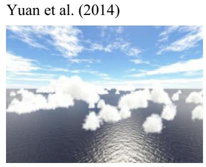
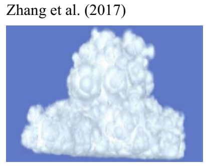
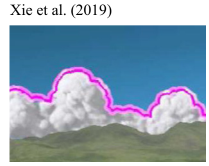
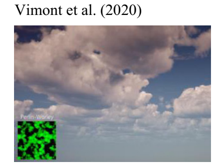
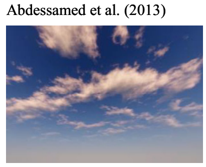
3.4.5. Modeling of the imaginary clouds

There is a great demand for modeling and displaying virtual clouds in movie productions. In this paper, the imaginary clouds refer to the 3D non-gaseous objects that have the cloud characteristics and visual appearances either statically or dynamically, for example, the animals, trees, skull, font characters, and cartoon characters. Based on current literature, only a few studies can be referred for this purpose (see Table 6). The challenge is to transfer the cloud characteristics to the targeted object to be modeled. The researchers also need to consider and fulfill the boundary appearances, density distributions, and dynamical aspects of the imaginary clouds.

4. Discussion

In this section, the atmospheric cloud modeling methods are discussed. The advantages and disadvantages of each driven method are explained. The discussion covers several important aspects, including visual quality, performance, data dependency, complexity, interactivity, and technological factors of the proposed methods. Table 7 shows some examples of the results produced from the modeling of atmospheric clouds taken from the selected manuscripts.

Table 7
Examples of outputs from the existing works.

Method	Resulting images		
Physics-driven methods	 Overby et al. (2002)	 Dobashi et al. (2008)	 Kobak and Alda (2017)
Heuristic-driven methods	 Webanck et al. (2018)	 Goswami (2019)	 Jiménez de Parga (2019)
Data-driven methods	 Yuan et al. (2014)	 Iwasaki et al. (2017)	 Cen et al. (2018)
Hybrid-driven methods	 Zhang et al. (2017)	 Xie et al. (2019)	 Vimont et al. (2020)
Control-driven methods	 Abdessamed et al. (2013)	 Dobashi et al. (2017)	 Schneider (2017)
Hardware-driven methods	 Mukhina and Bezgodov (2015)	 Montenegro et al. (2017)	 Shen et al. (2019)

The atmospheric cloud modeling methods were proposed and discussed for more than forty years due to the cloud's complexity, from various cloud types, irregular shapes and boundaries, dynamic movements, and large cloud scenes. In general, it is a challenging task for the researchers to design, model, and simulate all the exact cloud features to be the virtual clouds, especially in the field of computer graphics. Even though existing classical geometric modeling solutions are available for creating objects in computer graphics, they are mostly used for solid and rigid body objects, but not for the amorphous gaseous representation of the atmospheric clouds. Therefore, the specific methods to tackle the cloud-related problems were proposed.

Physics-driven methods are one of the solutions to solve the realism-oriented problems and thus produce highly visual image quality of the clouds. The results obtained from using these methods are physically-accurate because they are strictly following the laws of real cloud physics. However, most of these methods involve complex mathematical models and calculations to represent complicated physical features. They require a large amount of memory and computational time to execute the cloud model effectively. Therefore, their performance is slow and is not suitable for real-time and interactive applications.

Heuristic-driven methods are introduced to solve performance-oriented problems with fewer efforts and computations than physics-driven methods. These methods can yield visually convincing cloud models via simplification of calculations, rules, and procedures. The heuristic-driven methods are suitable for real-time applications due to its capability to achieve and maintain real-time rates during runtime processing. However, oversimplification processes will affect visual realism and miss some important cloud features. Furthermore, these driven methods lack physically-accurate features and hard to model the dynamics of cloud formations. Note that the deterioration of performance could occur if a vast number of cloud geometries and primitives are used to represent the entire cloud scenes.

Data-driven methods are other alternative solutions to achieve great visual results by relying on actual generated or captured data as the key input and base reference. These methods can achieve high frame rates during runtime. Due to these data dependency methods, the input data must be wisely chosen to avoid the visual artifacts or undesirable results, such as using the lower resolution of input data that has produced aliasing issues for the generated cloud shapes and boundaries. Besides, the data-driven methods commonly involve the extraction of significant parameters from input data. However, it is a challenging task to select meaningful parameters so that they could be used for reconstructing the virtual clouds. Besides, the process of extracting or pre-computing the parameters might consume much time.

Hybrid-driven methods can solve the realism- or performance-related problems that could not be done by the single driven method. Modeling of various cloud types or multi-tier handling of cloud scales could be implemented. Nevertheless, these methods have increased in terms of the design complexity compared to the single driven method, thus taking a long time for implementation. In general, these methods inherit the main issues that occurred in the single driven method. For example, hybridizing the physics-driven method with other methods leads to high computational time, intensive memory usage, and slow speed performance.

Control-driven methods focus on solving user-oriented problems. They provide freedom and flexibility for the users to control the cloud modeling processes in many forms, as described in the previous sections. Effective user controls would lead to realistic visual quality, high-speed performance, or tradeoff between both measurement criteria. However, it is difficult to interactively or artistically define and adjust the related controllers by trials and errors, especially for novice-level users. Consequently, it will consume much time by making the repetitive activities of parameter selection, placement, adjustment, or refinement. Moreover, lack of consideration of the users' different levels, including knowledge, skills, and experience, would affect the effectiveness and efficiency of achieving the more outstanding results.

Hardware-driven methods are exploited to cope with the computing-oriented problems constrained by current hardware processing technologies. These methods can help accelerate the processing time by adopting the power of central or graphics processor technologies, and this capability has led to the development of real-time atmospheric cloud applications in the last ten years. Nonetheless, it is challenging and problematic for programmers to adapt the atmospheric cloud model requirements with the specific-designed architecture of CPU or GPU by different technology creators. Poor hardware programming skills and limitations of current hardware functionalities would lead to the speed performance's deficiency in executing the cloud model.

5. Conclusion

In this paper, we have presented and conducted a comprehensive review of the atmospheric cloud modeling methods in computer graphics. We highlighted a set of main findings based on the pre-determined research questions. We have carefully chosen 113 primary studies by explicitly accounting for several inclusive and exclusive selection criteria in the review process. We firstly analyzed the publication trends based on the types of manuscripts, years, and venues of publications. We then introduced an up-to-date taxonomic classification of the existing atmospheric cloud modeling methods divided into six main categories: physics-driven, heuristic-driven, data-driven, hybrid-driven, control-driven, and hardware-driven methods. All the driven methods and its divisions were summarized and discussed against the proposed taxonomy. Finally, we depicted several significant challenges that need to be solved and would be future research prospects to model atmospheric clouds. This review is expected to provide valuable information and quick reference for the readers, especially the researchers and practitioners, to understand, explore, adopt, or improve the existing atmospheric cloud modeling methods to solve any specific problems of interests or involve the issues in the particular domain.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflict of interest

The authors declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Declaration of author contributions

The roles of each author are listed as follows: **Muhamad Najib Zamri**: Conceptualization, methodology, investigation, analysis, writing - original draft preparation; **Mohd Shahrizal Sunar**: Supervision, validation, writing - reviewing and editing.

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