

The state of big data reference architectures: a systematic literature review

Abstract

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1. Introduction

The rapid development of software technologies, the proliferation of digital devices and networking infrastructure of today, have by and large, augmented user's capability to generate data [1]. In the age of information, users are
5 unceasing generators of structured, semi-structured, and unstructured data that if collected and crunched correctly, may reveal game-changing patterns [2].

The unprecedented proliferation of data have emerged a new ecosystem of technologies; one of these ecosystems is big data (BD)[3]. BD is a term emerged to describe large amount of data that comes in various forms from different
10 channels. Within the years, BD has attained a lot of attention from academia and industry, and many strive to benefit from this new material. Howbeit, adopting BD requires the absorption of great deal of complexity and many traditional systems cannot cope with characteristics of this domain.

A recent survey published by Databricks in partnership with MIT Technol-
15 ogy Review Insights, stated that only 13% of companies excel at delivering on their data strategy [4]. In the same vein, Vintage Partners highlighted that only 24% of companies have successfully adopted BD [5]. Sigma computing report presented that 1 in 4 business experts have given up on getting insights they needed because the data processing took too long [6]. Moreover, Gartner

20 approximated that only 20% of companies have successfully adopted BD.

Some of the most highlighted challenges of BD is 'lack of business context', 'organizational challenges', 'BD architecture', 'data engineering', 'rapid technology change', and 'lack of talent' [7]. Whereas similar issues may exist in other domains, it is exacerbated when it comes to BD systems. This is due the
25 inherent complexity of BD engineering, the need for real-time processing, the scalability requirement of these systems, and the sensitivities around data.

Today, majority of BD systems are designed underlying ad-hoc and complicated architectural solutions [8], that do not seem to adhere to similar patterns. This will challenge software architects to design a suitable solution for any given
30 context, creates a foundation for an immature architectural decision, and does not promote the growth and development of BD systems as a whole.

Therefore, since the approach of ad-hoc design to BD systems is undesirable and leaves many engineers in the dark, there is a need for more software engineering research for BD systems. To this end, this study presents a systematic
35 literature review (SLR) on BD (BD) reference architectures (RAs).

2. Why reference architectures?

Conceptualization of the system as an RA, helps with understanding of the system's key components, behavior, composition and evolution of it, which in turn affect quality attributes such as maintainability, scalability and performance [9]. Therefore RAs can be a good standardization artefact and a communication medium that not only results in concrete architectures for BD systems, but also provide stakeholders with unified elements and symbols to discuss and progress BD projects.
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This approach to system development is not new to practitioners of complex
45 system. In software product line (SPL) development, RAs are utilized as generic artifacts that are instantiated and configured for a particular domain of systems [10]. In software engineering, IT giants like IBM have referred to RAs as the 'best of best practices' to address complex and unique system design challenges

[9]. In other international standardization, RAs have been repeatedly used to
50 standardize an emerging domain, a good example of this is BS ISO/IEC 18384-1
RA for service oriented architectures [11].

3. State of the art

Despite the undeniable benefits of RAs, and their potential to solve some of
the complex issues of BD systems, we think that this area is underdeveloped and
55 needs more attention from both academia and practice. This insight is derived
from our preliminary systematic review in academia, and a search for available
big data RAs ([2]).

To the best of our knowledge, one of the most comprehensive BD RA pub-
lished, is the National Institute of Standards and Technology (NIST) BD RA.
60 This RA is published by Big Data Public Working Group (NBD-PWG) with
large set of contributors from academia, industry, non-profit organizations,
agents, and government representatives. This was announced as an initiative
from White house in March 2012, and the the RA was published under the title
'NIST Big Data Interoperability Framework: Volume 6, Reference Architecture'
65 in October 2019.

Given the substantial investment on BD RAs, one might infer the value of
these artifacts, and this can in turn highlights the necessity for more research
in this domain. Another factor that worths mentioning is how vaguely the
phrase 'reference architecture' is defined and institutionalized. For instance,
70 the difference between a 'concrete architecture' and an RA is hardly discussed,
and different domains seem to have defined the artifact slightly differently. For
instance, Cloutier et al ([9]) defined RAs as 'Reference Architectures capture the
essence of existing architectures, and the vision of future needs and evolution
to provide guidance to assist in developing new system architectures'. This
75 definition is derived from the system engineering domain and by the means of
collaborative forum from Steven's institute of technology.

In another effort, Muller et al ([12]) defines RA as 'artifacts that captures

the essence of architecture of a collection of systems. This definition is driven from the product line engineering domain'. Moreover, the difference between
80 RAs and concrete architectures is rarely discussed. Another definition by Bass et al ([13]) stated that 'A reference architecture is a reference model mapped onto software elements (that cooperatively implement the functionality defined in the reference model) and the data flows between them'.

Angelov et al ([14]) defined RAs proposed that 'A reference architecture is a
85 generic architecture for a class of information systems that is used as a foundation for the design of concrete architectures from this class'. Although different authors may have defined RAs with different syntax, the essence remains the same: to reuse the software engineering knowledge for a class of systems, particularly in relation to architecture.

90 Given the failure rate of BD projects, we posit RAs as potential solution to facilitate system development and BD architecture, and aim to explore this area through a systematic literature review. Up to date, there's only one SLR that explored this area ([2]), which is outdated, suffers from methodological clarity, and is published as a conference paper, which implies lack of detail.

95 Based on this, the objective of this review is to find and collate the BD RAs available from the body of evidence, highlight their architectural commonality and point out the limitations. This study can be considered a useful primer for practitioners or academics who are interested in partaking in a BD project.

The research questions are formulated as the following;

- 100
1. **RQ1:** What are current BD RAs available in academia and industry?
 2. **RQ2:** What are major architectural components of these BD RAs?
 3. **RQ3:** What are the limitations of current BD RAs?

4. Review Methodology:

This research follows the guidelines of PRISMA ([15]). In addition, we
105 adopted PRISMA-S ([16]) to improve our search strategy and lastly we have used Barbara et al's guidelines for evidence based software engineering and

systematic reviews [17]. Although PRISMA is a comprehensive guidelines on conducting a systematic literature review, it is derived from the healthcare community and sometimes makes assumptions that may not be relevant to software engineering and information system researchers. Barbara et al [17] has translated many of these assumptions to the domain of software engineering and included many guidelines for lone researchers and projects with small number of researchers.

We have therefore utilized PRISMA as the underpinning of our research design, with complementary studies to reduce bias, improve transparency and systematicity. SLR has been chosen because it is a qualitative research methodology that is aimed at driving knowledge and understanding about the subject matter and the elements surrounding it. Besides, SLR provides a transparent and reproducible procedure that elicits patterns, relationships, trends, and delineates the overall picture of the subject [18].

The main objective of this study is to assess the current state of BD RAs, identify their major architectural components, point out fundamental concepts and discuss their limitations. This objective is achieved in four phases. In first phase, research questions are stated, literature are identified and pooled, exclusion and inclusion criteria are defined, and the quality framework is developed. In second phase, the title of the studies are assessed based on the inclusion and exclusion criteria. After that, the filtered studies are once more assessed based on their title, abstract, introduction and conclusion. After this, full analysis of the studies took place by running each study against the criteria defined in the quality framework. Thirdly, selected pool of literature is coded based on research questions. Lastly, findings are synthesized by the means of thematic synthesis, and themes realized are depicted.

This study builds on the SLR conducted by Ataei et al [2] and aims to improve it by covering the years 2020 to 2022. Unlike Ataei's work, this paper aims to employ thematic synthesis, and provide a more detailed view of BD RAs and their properties.

4.1. Identification

The first phase of the SLR began, by adoption of PRISMA-S ([16]) to develop a robust multi-database search strategy. This extension of PRISMA provided us with a framework of 12 items to increase transparency, systematicity, and reduce bias. For the purposes of this study, following electronic databases were search: ScienceDirect, IEEE Explore, SpringerLink, AISEL, JSTOR and ACM library. To pursue to goal of finding all literature available on the topic, and to avoid overlooking valuable research, abstract and citation databases and search engines such as Google Scholar, and Research Gate was used.

We also searched the grey literature on the topic, using the search string "big data" AND "reference architecture*" on Google (in June 2022). The first 40 results were selected for screening. This was done in 'incognito mode' to avoid any personal customization of the google search pages. Reference lists of included studies were manually screened to identify additional studies. This is to achieve the critical component of 'completeness' as suggested by Kitchenham et al [17].

The platform search capabilities varied, but our search strategy remained uniform for most parts. For instance, if a platform did not support wildcards (like asterisk), we just searched twice for the singular and plural version of the word. The only exception that made the selection process longer was Springer-Link, because it did not support bulk download of references in BibTex format. The reproducible search for the chosen databases is as follows:

- ("Document Title":big data) AND ("Document Title":reference architecture) OR ("Document Title":big data architecture)

The reason we included architecture is due to the fact that terms *reference architecture* and *architecture* may have been used interchangeably, and an architecture that is at the abstraction level of an RA, might have been called just an architecture. Therefore it was critical for us to firmly define these terms and then categorize studies based on these definitions. These definitions and our findings are depicted in the findings section.

Our initial search was set to year 2020 to year 2022, as the work of Ataei et al [2] covered the years 2010-2020. Nevertheless, we still included the years 2010 to 2020 to make sure no research is left out or overlooked. These years are chosen
170 firstly because more contemporary researches are focused on the facilitation of big data system development, and secondly there's no SLR that has covered those.

It is worth mentioning that what we refer to by *limit* here should, not be confused with *filters* or inclusion criteria. To achieve these limits, we have
175 utilized databases features. All databases supported the selection of year range, and the language limit was automatically applied by doing an advanced search with the aforementioned keywords.

Our approach to systematic collection of evidence was to search databases using the keywords aforementioned and then bulk download the BibTex files.
180 Majority of the databases supported bulk downloading of BibTex files except for SpringerLink, Google Scholar, and Research Gate. For SpringerLink we downloaded the studies in CSV format and then converted them to a BibTex using a custom script. For Google Scholar and ResearchGate, unfortunately, we had to take the manual path of creating a bib file for the studies.

185 Once all the bib files have been created, we merged them into one large bib file and imported it to a software called JabRef ([19]) for deduplication. 172 studies are pooled initially, out of which 6 duplicates have been identified. We removed the SLR that this study is based on, and also another paper that we could not find the citation for. In the other hand, we found 5 white papers and
190 4 website blogs and added them to the selection pool. At the end of this phase, 173 studies have been pooled.

4.2. Screening and Eligibility

Stage 1 of screening started with assessing the title, abstract, and keywords of the pooled studies. For grey literatures simply the title. This was achieved
195 based on our inclusion and exclusion criteria;

- Primary and secondary studies (including grey literature) between Jan 1st 2010 and June 1st 2022 on the topics of BD RAs, BD models, and BD architectural components were included.
- Research that Indicates the current state of RAs in the field of BD and demonstrates possible outcomes
- Studies that are scholarly publications, book, book chapter, thesis, dissertation, or conference proceedings
- Grey literature such as white paper that includes extensive information on BD RAs

And the studies with the following topics were excluded:

- Informal literature surveys without any clearly defined research questions or research process
- Duplicate reports of the same study (a conference and journal version of the same paper)
- Short papers (less than 5 pages)
- Studies that are not written in English

Disagreement among researchers were resolved using Krippendorff's alpha ([20]). Our aim was not to get involved in a very complicated statistics model, so we've done most of the computations using SPSS, specifically with Hayes' Macro. We made sure that a separate file is created for each variable, and inserted coders as variables and not a constant value. Our

$$\alpha \tag{1}$$

value was within the acceptable range (above 80), and any disagreement was solved by inviting a third person or a moderator. When

$$\alpha \tag{2}$$

value was very low (indicating a low reliability), we stopped the process, and
220 tried to clarify fundamental concepts and categories. The final computed

$$\alpha \tag{3}$$

value was 89.9%.

In stage 2, After excluding papers based on inclusion and exclusion criteria, and as suggested by Kitchenham et al [17], we assessed studies based on their quality. Quality of the evidence collected as a result of this SLR has direct
225 impact on the quality of the findings, making quality assessment an important undertaking. Therefore it is imperative for us to realize how much confidence we can place in the conclusions and findings arising from the evidence collected to form a great whole, that is themes and models in this case.

However, this process comes with some well-known complexities. The most
230 fundamental ones are perhaps firstly defining the term 'quality', and secondly trying to appraise the quality of conference papers that rarely provide enough detail on research methodology and evaluation. Generally, a quality of a study is tightly associated to its research method and the validity of its findings. From this perspective, and inspired by the works of Noblit and Hare on meta-ethnography ([21]), and Dyba et al ([22]), quality of studies is assessed by the
235 extent to which the conduct, design and analysis of a research is susceptible to systematic errors or bias ([23]). That is, the more bias in the selected literature, the more chance to create miss-leading conclusions.

Considering the rather heterogeneous nature of software engineering and
240 information systems (IS) papers, and difficulty of defining quality in studies with varying nature, we first analyzed a few well-established checklists such as Critical Appraisal Skills Programme (CASP [24]), and JBI's critical appraisal tool ([25]). Whereas these checklists could potentially account for the requirements of this study, we opted for something that is more specific to software engineering
245 and IS. We realized for example that, Runeson et al ([26]) provided a checklist designated to help researchers reading and undertaking software engineering case studies. In the same vein, Dyba et al ([22]) proposed a quality criteria based

on CASP checklist for qualitative studies in software engineering systematic reviews.

250 Nevertheless, the challenge is that our study includes a large number of different study types that needs to go through a single checklist. To address this, we developed a criteria made up of 11 elements. These criteria are informed by those proposed by CASP for assessing the quality of qualitative research ([24]) and by guidelines provided by Kitchenham ([27]) on empirical research in
255 software engineering. The 7 criteria tested literature on 4 major areas that can critically affect the quality of the studies. These categories and the corresponding criteria are as following;

1. *Minimum quality threshold:*

- (a) Does the study report empirical research or is it merely a 'lesson
260 learnt' report based on expert opinion ?
- (b) The objectives and aims of the study is clearly communicated, including the reasoning for why the study was undertaken ?
- (c) Does the study provide with adequate information regarding the context in which the research was carried out ?

265 2. *Rigour:*

- (a) Is the research design appropriate to address the objectives of the research ?
- (b) Is there any data collection method used and is it appropriate ?

3. *Credibility:*

- 270 (a) Does the study report findings in a clear and unbiased manner ?

4. *Relevance:*

- (a) Does the study provides value for practice or research

Taken all together, these 7 criteria gave us a measure of the extent to which a particular study's findings could make a valuable contribution to the review.
275 These criteria was disseminated as a checklist among researchers with value for each property being dichotomous, that is 'yes' or 'no' in two phases. In the first phase, researchers only assess the quality based on the first major area

(minimum quality threshold). If the study passed the first phase, it would then go into the second phase, where it was assessed for credibility, rigour and relevance. The quality is agreed if 75% of the responses are positive for any
280 given study with at least 75% inter-rater reliability.

Disagreements regarding the quality was usually resolved through a meeting. While, the meeting could not address the disagreements, a moderator has been invited to the process. Lastly, it is worth mentioning that this quality framework
285 was not used for grey literature. Grey literature were only assessed through inclusion and exclusion criteria.

In the first phase (identification) of this SLR, a total of 138 literature has been pooled from academia, and 24 from grey literature. Some of this literature has been added to the pool by the process of forward and backward searching.
290 For instance, by reading NIST RA, we found out about Oracle, Facebook, and Amazon RAs and included those in the pool of the literature as well.

In the screening phase, the literature that were not in-line with our inclusion and exclusion criteria have been eliminated. For example, if the paper was very short and was not on the topic of BD RA, or its ecosystem or limitations, it was
295 excluded. As a result of this phase, 50 papers excluded. In the next phase, by assessing studies against the quality framework, 21 studies from academia, and 12 studies from grey literature pool has been eliminated.

At the end of the selection and screening process, 79 papers have been pooled. The detail of this process is depicted in 1.

300 By the result of this work, 79 articles have been selected comprising of proceedings, journal articles, book chapters, and white papers. Out of the pool of articles, 33.3% are from IEEE Explore, 5.2% from ScienceDirect, 24.5% from SpringerLink, 15.7% from ACM, and 21% from other sources such as Google Scholar and Research Gate. 30 journal articles, 29 conference proceedings, 12
305 book chapters, 6 white papers, 1 Master's Thesis and 1 PhD thesis were selected. 55% of the articles were selected from the years 2016- 2022, 33% belonged to years 2013-2016, and the rest to years 2010-2013. These stats are portrayed in

2

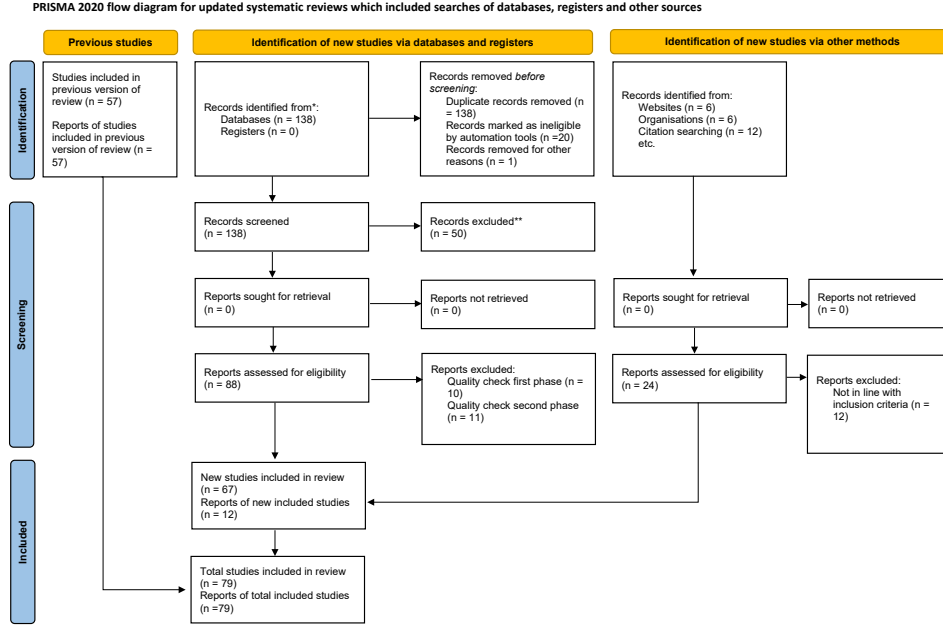


Figure 1: PRISMA flowchart

4.3. Data Extraction and Synthesis

By this stage, research questions have been set, inclusion and exclusion criteria are defined and applied, the quality assessment framework is developed and applied to the pool of studies, and the research embarked on actual synthesis of data. An integral element of this phase is data extraction, in which the essence of the studies are obtained in an explicit and consistent manner.

Precursor to synthesis of the actual data, we first followed the guidelines proposed by [28] for data extraction. Data extraction firstly began by reading the entire pool of literature in order to get immersed with the data [29]. From there on, we followed a structured reading approach and extracted three kind of data; 1) Publication Details (author, title, year, etc), 2) Contextual descriptions (industry, settings, technologies), and 3) Findings (results, the actual RA, events, etc ..)



Figure 2: SLR Statistics

Through process was a bit challenging, as some studies did not describe the method adequately, contextual information were not detailed often, and evaluation methods varied. To overcome this challenge, majority of this process took place in a consensus meeting [30].

After data extraction, we began the coding process. For this step, we've had several approaches ahead of us. Either we could adopt a deductive or a prior approach ([31]) or an inductive or Grounded Theory approach ([32]). Neither of which could be as rigorous as we desired, thus we opted for an integrated approach ([33]). We used the software Nvivo to organize our files and created an initial set of a priori codes based on research questions. These codes are as followings;

1. BD RAs (RQ1)
2. BD RAs Architectural components (RQ2)
3. BD RAs limitations (RQ3)

As the coding progressed, we realized that there is a need to define some of the fundamental areas that seem to not have been well established in academia and practice. For instance, we've been looking for a comprehensive data to discuss the fundamental concepts of RA to further support our initiative, but
340 this was not standardized, and while there was mention of these concepts, they were usually lacking or very short. Furthermore, not many studies discussed the benefits and relevance of RAs for BD systems. We also could not find a study that thoroughly discusses common approaches to developing BD RAs, and the challenges of developing a BD RA.

345 Based on these, therefore, we added the following extra four codes;

1. Fundamental concepts of RAs
2. How can RAs help BD system development
3. Common approaches to creating BD RAs
4. Challenges of creating BD RAs

350 After having coded all the literature pooled, we began the process of turning them into themes. Themes helped us pull together segregated data into one meaningful whole that is above the sum of its constituents. This was not a single step process, and as we started to analyze codes, we have subsumed some first-cycle codes into other codes, and vice versa. This also led to rearrangements
355 and reclassification of the codes. The end of this process was marked, when the emerging themes saturated, and we could not derive a new theme. Many of the themes emerged have been then categorized into higher-order themes.

The last step of data synthesis, was creation of a model based on the higher-order themes to explain relationships and to answer original research questions.
360 The final product of this phase, is a theory, connection with prior theories, and indication of relationships.

Of particular challenge we faced in this phase was the influence of heterogeneity, specifically given the inclusion of grey literature and cardinality of research methodologies in software engineering researches. Thus, to ensure the robustness
365 of the higher-order themes we identified the main sources of variability as;

1) variability of outcomes (some RAs well evaluated in practice, while some other are just compared against other RAs), 2) variability in study designs (methodological diversity that exists in software engineering and specifically creation of RAs), and 3) variability in study settings (contextual factors are often not well reported). Despite the challenges, we created a model that can portray what's available in academia and practice, with relationships clarified.

Last, but not least, to increase the rigour, we assessed the trustworthiness of the synthesis from three aspects; 1) Credibility: is the focus of the research in-line with research questions, and does the thematic synthesis cover data well ? 2) Conformability: are data extracted and coded in the correct way? do all researchers agree on this? would readers agree with the approach ? 3) Transferability: are the findings generalizable, can the findings be applied in different context?

5. Findings

In this section, we map our findings against the research questions in a series of sub-sections. For increased clarity, these sub sections are exact driven by the research questions and models we created in the previous phase. We first begin by explaining fundamental concepts such as RAs and how they help BD system development and then progressively work towards more specific topics such as current BD RAs and their limitations.

5.1. *What are the fundamental concepts of RAs?*

As the complexity of man-made systems grow, procedures, principles, and concepts of software architecture are increasingly applied to address those complexity faced by practitioners [2]. A system abstracted and expressed in terms of architectural concepts, facilitates the understanding of system's essence, properties revolving around it, and evolution of it, which in turn affects quality attributes such as performance, maintainability, and scalability.

In recent years, IT architectures played a pivotal role in the progress and evolution of system development and gained acceptance in maintenance, planning,

395 development, and cost reduction of complex systems [34]. To address ambiguity
about what should be developed to address what needs, an architecture can play
an overarching role by portraying the fundamental components of the system
and the means and ways in which these components communicate to achieve
the overall goal of the system [35]. This in turn creates manageable components
400 that can be used to address different aspect of the problem and provides stake-
holders with an abstract artefact to observe, reflect upon, contribute to, and
communicate with [36]

Many successful IT artefacts today stemmed from an effective RA. A few
good examples are the Open Systems Interconnection model or OSI [37], Open
405 Authentication or OATH [38], Common Object Request Broker Architecture or
CORBA [39], and WMS or workflow management systems [40]. In fact, every
system goes with an architecture, either known or unknown, and it is in the
architecture that the overall qualities of the system are defined

Whereas there are various definitions to what constitutes an RA, they all
410 share the same principle that the concept of patterns plays a significant role.
Some studies have defined RAs as “a predefined architectural pattern, or set
of patterns, possible, partially or completely instantiated, designed, and proven
for use in particular business and technical contexts, together with supporting
artifacts to enable their use” [9]. In Software Product Line (SPL) development,
415 RAs are defined as generic schema that can be instantiated and configured for
a particular class of systems [10].

In software engineering, RAs can be defined as an artefact that transfers
software engineering knowledge as a family of solutions to a problem domain [41].
In another terms, RAs are artefacts that embody domain relevant concepts and
420 qualities, break down solutions and a create a ubiquitous language to facilitate
effective communication, and inform various stakeholders.

Taking all into consideration, and based on the model created based on our
thematic synthesis, five major concept of RAs are identified as the following;

1. **RAs are at the highest level of abstraction:** RAs aim to capture the

425 essence of the practice as an abstraction that portrays elements necessary
for communication, standardization, implementation and maintenance of
certain class of systems. Hence, RAs aim to inject software engineering
knowledge as a set of high-level architectural patterns and do not provide
implementation details such as specific frameworks, vendors or environ-
430 ments. RAs are at higher level of abstraction than concrete architectures.

2. **RAs emphasize heavily on architectural qualities:** RAs, sitting at
a higher level of abstractions are artifacts created for a wider audience and
a bigger context, and are usually used by solution architects to deduce a
concrete architecture in a specific environment ([42], [43]). As a result,
435 RAs pay more attention to architectural qualities.

3. **In RAs, stakeholders are not clearly defined:** Stakeholders are usu-
ally people of the same company involved in the actual design and im-
plementation of the system and do get involved in the product creation
in various phases. Different stakeholders have different concerns and are
440 crucial to the creation of the overall product [44]. A stakeholder can be
a developer, a designer, a product owner, a data scientist or a business
analyst. Notwithstanding, due to the generic nature of the RAs, it is not
feasible to indicate all stakeholders a priori. RAs are at a higher level of
abstraction and tend to provide a generic solution for a class of problems,
445 not a specific context. Therefore, defining and introducing stakeholders
into RAs can potentially decrease their effectiveness ([2], [45]).

4. **RAs promote adherence to common standards:** The design of an
RA is usually guided by existing architectural patterns based on common
pitfalls in practice, the body of literature and various models. For this
450 reason, RAs convey standard approaches and patterns that avoid known
pitfall, facilitate reuse, and decrease complexity.

5. **5. RAs are effective artefacts for system development and com-
munication:** RAs are powerful artefacts that can be used by architects
that design, manage, and utilize complex system. Because RAs are created
455 as assets that codify the best practice and conventions of the industry and

often include architectural descriptions and standards, they can be deemed effective artefacts for system development and communication.

6. How can RAs help BD system development?

Despite the high failure rate of BD projects, IT giants such as Google, Facebook or Amazon have developed exclusive BD systems with complicated data pipelines, data management, procurement and batch and real-time analysis capabilities [36]. Having the resources required, these companies attract the best of talent from around the globe to manage the complexity involved in development of big data systems. Notwithstanding, that's not the reality of majority of organizations that are trying to benefit from big data analytics.

Big data systems sail away from traditional small data analytics paradigms and bring various challenges including rapid technology change challenges [46], system development and architecture challenges [47], and organizational challenges [3]. Moreover, big data systems are distributed in nature and need to account for various kind of data processing usually batch and stream processing. This combined with the complexity of maintaining and scaling data quality, metadata, data catalogs, data dimension modeling, and data evolvability, designing an effective big data system can be perceived a daunting task. BD does not only mean 'big' amount of data, or just volume; other characteristics of BD such as velocity, variety, veracity and variability bring significant challenges to the practice. Although these challenges do not only belong to domain of BD systems, BD exacerbates these challenges because of the following reasons;

1. Distributed scaling is required to address batch and stream processing demands
2. There is a need for real near-time performance (stream processing)
3. Complex technology orchestration is required to create effective communication channels between components and data flow
4. Continuous delivery is required to continually disseminate patterns and insights into various business domains

- 485 5. Two different approaches are required for data processing, stream and
batch processing; or fast and delayed processing
6. Metadata should be managed at scale
7. Dimensional modeling for a rapidly changing schema is challenging

To provide a solution to these challenges, one has to realize the core funda-
490 mentals of BD systems. Academic and practitioners of BD, describe BD as an
interplay of methodology (workflow, organization), software engineering (data
engineering, storage, etc.), and analysis (math, statistics) [48][7]. Therefore,
one can deduce that technology orchestration is a focal matter in BD system
development and maintenance.

495 Positioned on top of this rationale, and based on the result of the SLR syn-
thesis, RAs can be considered an effective artefact that help with component
delineation, interface definition, technology orchestration, variability manage-
ment, scalability, and maintenance of BD systems [45][49]. The purpose of RAs
is to create an integrated environment in which fragmented processes around
500 the system are optimized, responsiveness to change is assured, and delivery of
architectural strategies is supported.

Most authors and practitioners agree that issues around BD software engi-
neering and system development are severe and that this justifies the use of RAs
for BD systems. Starting with a grounded RA means that the software archi-
505 tect can refer to an already designed orchestration of components, interfaces,
inter-communications, and variability points and map them against the organi-
zation's capability framework, desired quality attributes, and business drivers
and vision. This also means that the software architecture or the software ar-
chitecture group is no longer challenged to model a new architecture from an
510 array of independent components that needs to be assembled through effective
interfaces, cache mechanisms, storage, etc.

Taking all into consideration, one can deduce that RAs are artefacts that fa-
cilitates development and homogenization of BD systems. Using RA to address
complex problems have been successfully applied for Database Management Sys-

515 tems (DBMS) [50] and Distributed Database Management Systems (DDBMS)
[51].

7. What are some common approaches to creating BD RAs?

The findings gained from this study led to the understanding that there are not many frameworks available for design and development of RAs. Nevertheless, to address RQ4, we sought to find the research methodology and approaches chosen to develop RAs. One of the most commonly used approaches for developing RAs is ‘Empirically grounded Reference Architectures’ by Galster and Avgeriou ([52]). The research methodology is well-received because of its emphasis on empirical validity and empirical foundation. This methodology
520 is comprising of 6 step process which are respectively 1) Selecting the type of the RA, 2) Selection of the design strategy, 3) Empirical acquisition of data, 4) Construction of the RA, 5) Enabling RA with variability, 6) Evaluation of the RA.

Another seminal work in this area is a framework for analysis and design of
530 software RAs created by Angelov, Grefen, and Greefhorst ([53]). The framework utilizes a multi-dimensional classification space to classify RAs and as a result presents 5 major types. It is developed with the objective of supporting analysis of RAs with regards to their architectural specification/design, goal, and context. This is achieved through three major dimensions, each having
535 their own corresponding subdimensions of design, goal, and context. These dimensions and sub-dimensions are derived by interrogatives of ‘why’, ‘where’, ‘who’, ‘when’, ‘what’, and ‘how’, which is a well-established practice for problem analysis. The interrogative why addresses the goal of the RA, who, when, where address the context, and how and what address the design dimensions.
540 This framework categorizes RAs in two major groups: facilitation RAs and standardization RAs.

Volk, Bosse, Bischoff, and Turowski ([54]) utilized Software Architecture Comparison Analysis Method (SCAM) to compare and examine RAs based

on their applicability. This result of this work was a decision-support process
545 for selection of BD RAs. Two standards that have been observed the most
were ISO/IEC 25010 for choosing quality software products for RAs ([55]), and
ISO/IEC 42010 for architecture description ([56]).

Surprisingly, based on the evidence gained from this SLR, most researchers
and practitioners use informal architectural description methods like boxes and
550 lines, except for the works of Geerdink ([44]). In this study, the author used
ArchiMate ([57]) as the modeling language which is a formal and standard
modeling language that is accepted and recommended in ISO/IEC 42010 as
well. Informal methods of modeling can introduce inconsistency issues between
system design and implementation of the system ([58]), do not adhere to a
555 well-established standard and do not promote the development of modeling
approaches. Therefore, one can argue that there is a need for more emphasis
on the modeling language with which different researchers and practitioners
describe ontologies.

Lastly, Hevner’s information systems research framework ([59]) has been
560 used for the development of RA presented by Geerdink ([44]), which is a suitable
research design, since a BD RA is an information system artefact based on
existing literature and business needs.

8. Challenges of creating BD RAs

Among the challenges of developing RAs, perhaps evaluation is the most
565 significant [60]. According to Galster and Avgeriou ([52]), two fundamental
pillars of the evaluation is the correctness and the utility of the RA and how
efficiently it can be adapted and instantiated.

RAs and concrete architectures come with a different level of abstraction
and have divergent qualities. Whereas there are many well-established evalua-
570 tion methods for concrete architectures such as Architecture Level Modifiability
Analysis ([61]), Scenario-based Architecture Analysis Method ([62]), Architec-
ture Trade-off Analysis Method ([63]), and Performance Assessment of Software

Architecture ([64]), none of these can really be directly applied to RAs.

For instance, ATAM is reliant on participation of stakeholders in early stages
575 for creation of utility tree, and RAs, being highly abstract, do not have a clear
group of stakeholders at that stage. In addition, many of evaluation method-
ologies listed make use of scenarios, whereas RAs are highly abstract and are
potentially adopted for various contexts, therefore making scenario creation dif-
ficult and sometimes invalid. Either a few general scenarios are developed to
580 cover all aspects, or a large number of specific scenarios are developed to cover
various aspects of the RA. Each of which can pose threats to validity.

Based on three problems discussed above, available methods of architecture
analysis are not sufficient for evaluating RAs. Various researched tried to ad-
dress this problem. In one Angelov et al ([42]) modified ATAM and extended
585 it to resonate well with RAs. This process took place by invitation of represen-
tatives from leading industries for the evaluation process, and the selection of
various contexts and defined scenarios for these contexts. ATAM was extended
to evaluate completeness, buildability and applicability. Howbeit the selection
of the right candidate and involving them in the process is a daunting task and
590 unfeasible at times.

In Another study by Maier et al. ([60]) as a postgraduate thesis in Eind-
hoven University of Technology, the evaluation of the RA has been conducted
by mapping it against existing reference and concrete architectures described in
industrial whitepapers and reports. Along the lines, Galster and Avgeriou ([52])
595 suggested reference implementations, prototyping and incremental approach for
the validation of the RA.

By the virtue of the findings from this SLR, and by studying the approaches
from Bosch ([65]), Avgeriou ([66]), and Derras et al ([67]), an evaluation frame-
work for a RA can be done through architectural prototype evaluation, which
600 means a concrete architecture of the RA is generated and then evaluated through
a well-grounded method such as ATAM.

9. What are current BD RAs available in academia and industry?

As a result of this SLR and to answer RQ1, 24 BD RA has been found, among which 16 RAS are from academia, 8 from practice, and one through the
605 collaboration of academia and practice. These are described further in Table 1.

ID	Title	Domain	Year
s1	Lambda architecture ([68])	Practice	2011
s2	IBM - Reference architecture for high performance analytics in healthcare and life science ([69])	Practice	2013
s3	Microsoft - Big Data ecosystem reference architecture ([70])	Practice	2013
s4	Oracle - Information Management and Big Data: A Reference Architecture ([71])	Practice	2014
s5	Towards a big Data reference architecture ([60])	Academia	2013
s6	A reference architecture for Big Data solutions introducing a model to perform predictive analytics using Big Data technology ([44])	Academia	2013
s7	A proposal for a reference architecture for long-term archiving, preservation, and retrieval of Big Data ([72])	Academia	2014
s8	Questioning the Lambda architecture; Kappa Architecture ([73])	Academia	2014
s9	Accelerating Secondary Genome Analysis Using Intel Big Data Reference Architecture. ([74])	Practice	2014

s10	Reference architecture and classification of technologies, products and services for big data systems ([75])	Academia	2015
s11	SAP - NEC Reference Architecture for SAP HANA & Hadoop ([76])	Practice	2016
s12	Big data architecture for construction waste analytics (CWA): A conceptual framework ([77])	Academia	2016
s13	A reference architecture for Big Data systems in the national security domain ([41])	Academia	2016
s14	Managing Cloud-Based Big Data Platforms: A Reference Architecture and Cost Perspective ([78])	Academia	2017
s15	A software reference architecture for semantic-aware Big Data systems; Bolster Architecture ([49])	Academia	2017
s16	Simplifying big data analytics systems with a reference architecture ([79])	Academia	2017
s17	NIST Big Data interoperability framework ([45])	Practice	2018
s18	Extending reference architecture of big data systems towards machine learning in edge computing environments ([80])	Academia	2020
s19	A Big Data Reference Architecture for Emergency Management ([81])	Academia	2020
s20	Smart Transportation: A Reference Architecture for Big Data Analytics ([82])	Academia	2020

s21	ISO/IEC 20547-3:2020 BS ISO/IEC 20547 3:2020 Information technology. Big data reference architecture. Reference architecture ([83])	Practice	2020
s22	Phi: A Generic Microservices-Based Big Data Architecture ([84])	Academia	2021
s23	NeoMycelia: A software reference architecture for big data systems ([85])	Academia	2021
s24	Smart teledentistry healthcare architecture for medical big data analysis using IoT-enabled environment ([86])	Academia	2022

Table 1: BD RAs

Within the past years, there has been a considerable attention to the BD domain, and in specific BD system development. For instance, in March 2012, White House announced an initiative for BD research and development [87]. The goal of this initiative was to accelerate the speed of science and engineering
610 discovery, to improve national security, and to improve the knowledge extraction from large and complicated sets of data [88]. This project has been supported by six federal departments and has been given more than \$200 million USD with the goal of substantial progress in the tools and techniques to handle big data.

615 A year later, in June 2013, National Institute of Standards and Technology (NIST) Big Data Public Working Group (NBD-PWG) was launched with considerable participation from across the nation. Practitioners, researchers, agents, government representatives, and none-profit organizations joined in this momentum.

620 One of the results of this project was NIST Big Data Reference Architecture (NBDRA). According to US Department of Defense, one of the main objectives

of NBDRA was to provide with an authoritative source of information on big data that restraint and guides the overall practice. This is arguably one of the most comprehensive and recent RAs available on the fields of big data. NBDRA
625 is made up of two fabrics encompassing five functional logical components connected by various interfaces, representing intertwined nature of security and privacy and management.

Along the lines, other giant IT vendors published their own RAs for big data. In this SLR, 5 BD RA has been collected from the practice, and mostly
630 through white papers. These white papers are from IBM, Microsoft, Oracle, SAP, and a conference in which Lambda was discussed. Among these RAs, arguably Lambda architecture is the most commonly discussed and studied. It is also worth mentioning that there has been other BD RAs found in practice, but they were rather too short or did not reflect the contemporary state of BD
635 analytics and has been eliminated as described in the research methodology section.

In the realm of academia, there has been numerous efforts including a post-graduate master's dissertation ([60]) and PhD thesis ([89]) for creating big data RAs. In addition, few universities have published their own RA. For instance,
640 university of Amsterdam published the BD architecture framework [90].

Last but not least, there has been numerous reference architectures developed recently for specific domains. These studies have been usually published as short journal papers, and many have promised future publication of the full reference architecture as a book. For instance, Klein et al. ([41]) developed a
645 BD Ra in the national security domain, and Weyrich and Ebert ([91]) worked on a BD RA in the domain of internet of things (IOT).

Through the process of literature review for this SLR, scarcity of big data reference architectures has been witnessed. The studies listed above are prominent research, with great potential to induce concrete architectures. But with
650 all, they are mostly published as short journals and provide with little information about architectural qualities, metadata management, and security, privacy concerns. In another terms, they are notion or brief discussions on reference

architectures in very particular domains.

10. What are major architectural components of BD RAs?

655 To address RQ5, RAs listed in 1 was reviewed and compared to deduce
common architectural components of BD RAs. Some of the RAs collected were
in in the form of a short paper and provided with not much detail, whereas
some of the other such as NIST were quite comprehensive.

Majority of RAs have been inspired or based on other RAs, and this signified
660 the notion that “RAs can be perceived more effective when they are created out
of available knowledge, studied domain, and existing RAs rather than from
scratch”.

To answer this question in a systematic manner, and as a result of our data
extraction, we listed all the components from all the BD RAs listed in the
665 previous section. These components are described in 2.

RA	Components
S1	Streaming layer, batch layer, serving layer
S2	Applicatons, Frameworks and platforms, Software defined infras- tructure, Compute and storage servers
S3	Data sources, Data transformation, Data usage
S4	Data sources, Data Integration, Information Management, Infor- mation Access
S5	Data sources, Data Acquisition and Recording, Information Ex- traction and Cleaning, Data Integration, Aggregation and Repre- sentation, Query Processing, Data Modeling and Analysis, Inter- pretation
S6	Import Engine, Processing Engine, Management Engine, Analyt- ics Engine, Visualisation Engine
S7	Big Data Layer, Archive Layer, Storage Layer, Presentation Layer
S8	Data Source, Real-Time Layer, Serving Layer

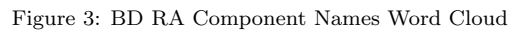
S9	Access Manager, Intel Big Data Analysis Platform, Data Ingestion, Data Sources
S10	Data Sources, Data Extraction, Data Loading and Pre-Loading, Data Processing, Data Storage, Data Analysis, Data Loading and Transformation, Interfacing and Visualization
S11	Data Input sources, Data Processing Platform, Processed Data for Client
S12	Application Layer, Analytics Layer, Storage Layer, Data Sources
S13	Data Providers, Big Data Application Layer, Big Data Framework Provider, Data Consumers
S14	Data Generation, Data Streams, Data Storage, Stream Processing, Data Warehouse, Hadoop Cluster, Machine Learning, Presentation
S15	Batch Layer, Speed Layer, Semantic Layer, Serving Layer
S16	Data Source, Data Integration, Data Analysis and Aggregation, Interface/Visualization
S17	Data Provider, System Orchestrator, Big Data Application Provider, Big Data Framework Provider, Security and Privacy Fabric, Management Fabric, Data Consumer
S18	Data Sources, Data Extraction, Data Loading and Preprocessing, Data Processing, Data Storage, Model Development and Interface, Data Transformation and Serving, Interfacing and Visualization
S18	Data Sources, Data Extraction, Data Loading and Preprocessing, Data Processing, Data Storage, Model Development and Interface, Data Transformation and Serving, Interfacing and Visualization

S19	Data Provider, Big Data Application Provider, Big Data Framework Provider, System Orchestrator, Management Fabric, Security and Privacy Fabric, Data Consumer
S20	Big Data Application Provider, Big Data Processing Layer, Big Data Platform Layer, Big Data Infrastructure Layer, Integration, Security and Privacy, System Management, Big Data Provider, Big Data Consumer
S21	Big Data Application Provider, Big Data Processing Layer, Big Data Platform Layer, Big Data Infrastructure Layer, Integration, Security and Privacy, System Management, Big Data Provider, Big Data Consumer
S22	Acquisition Layer, Refinement Layer, Scrutiny Layer, Training Layer, Insight Layer
S23	Gateway, Stream Processing Service Mesh, Stream Processing Controller, Monitoring, Service Discovery, Query Controller, Batch Processing Controller, Batch Processing Service Mesh, Event Backbone, Data Lake, Query Engine, Event Archive, Semantic Layer, Control Tower, MicroService, Sidecar, Event Queue

Table 2: BD RAs Components

Different studies have chosen different phrases to describe their architectural components, and there seems to be no standard way of modeling BD RAs. The usage of architectural definition languages such as Archimate is scarce, and most studies have used boxes and lines with specifically defined ontologies. This made understanding and comparison of these RAs a difficult task that requires constant translation from one ontology to another.

Initially we’ve done an automated text analysis on these components’ names to try to highlight commonalities and word usage. The word cloud of these components are portrayed in ??



Among the names authors used to name their components, 'big data application provider' seems to have been used the most (5 occurrences), and 'big data framework provider' the next (3 occurrences). This is due to the fact that a few of the RAs are built upon NIST BD RA, and have therefore adopted the terminology. One term that all studies seems to have been using uniformly is 'data consumer' and 'data provider'. Moreover, most studies have chosen the phrase 'layer' to logically group different components of the RA.

10.1. BD Management and Storage

30

nature (Banker, Garrett, Bakkum, & Verch, 2016), and when there is a need for complex relationship between entities, graph databases such as Neo4J are more suitable because of their tree traversal performance (Van Bruggen, 2014).

Choosing the right database or databases, is an important architectural decision that can also include patterns for data access, storage and caching. For
695 example, the practitioners of distributed system that are specialized in micro-services architecture may opt to use Command Query Responsibility Segregation (CQRS) pattern for high performance applications [93]. Therefore, the type of storage and the access pattern are two major architectural components
700 of big data systems.

The current landscape of BD RAs seems to revolve around monolithic storage solutions such as data warehouse and data lake. While the traditional practice of staging data, dimensional modeling, storage in data warehouses, and data marts as customized access layers, may seem ineffective in handling BD loads,
705 we’ve been surprised to still witness some variations of this approach being proposed.

Another architectural component that is popular in BD RAs is data lake. Data lake can be perceived as an ingestion framework that can be given various types of data including internal and external data. The data stored in the
710 data lake is then usually retrieved for transformation. This is the LET (load, extract, transform) approach, comparing to old ETL (extract, transform, load) approaches.

Similar to the way that Business Intelligence (BI) and BD differ in their source data types both in terms of granularity and data structure of it, a data
715 lake and data warehouse are different. In the case of a data warehouse, usually a relational database is used which decreases flexibility when it comes to analysis and can potentially cause considerable costs. In the case of data lake, data of different kind can be stored without the engineer needing to define the schema in advance. This increases the flexibility.

720 Howbeit, this flexibility itself has its own downside and can be abused by data engineers. One can throw different data sets without much regard at all

for how they're structured, which leads to what people refer to as data swamp. Data governance can alleviate some of these issues [94].

Based on the results of this synthesis, we posit that BD RAs are driven by
725 three main paradigms; 1) Enterprise data warehouse paradigm, 2) data lake
paradigm, and 3) cloud based paradigm.

The first paradigm revolves around large monolithic enterprise data ware-
houses, with ETLs, staging environments and a data processing pipeline. A
good example of the first paradigm is S5. The second paradigm is about mono-
730 lithic data lakes with data with similar data processing pipelines happening at
a different stage. A good example of the second paradigm is S22. The third
paradigm is not that far away from the second, but aims to incorporate more
elements of distributed systems. A good example of this paradigm is the S8.

Some RAs sit at a higher level of abstraction. A good example is S21. For
735 these kind of RAs, one cannot assume the nature of the pipelines and if the
storage would be monolithic or not. In S21, there's a depiction of various kinds
of storage in the 'Big Data Platform Layer', indicating that one may choose to
opt in for polyglot persistence.

When it comes to big data management, many of the cross-cutting concerns
740 seems to be overlooked. For instance, we have realized that many BD RAs do
not pay a clear attention to privacy, metadata management and data quality.
While some RAs tend to revolve around security such as S13, and some other
tend to revolve around metadata management such as S15, we could not find a
comprehensive explication of big data management.

745 We could not understand how some of the RAs could account for data source
proliferation and how rapidly they could react to regional data privacy changes.

10.2. Data Processing and Application Interfaces

There are two major data processing activities that a BD system encom-
passes. These processes generally fall into stream processing and batch process-
750 ing. Stream processing or fast processing is required for sensitive operations and
time critical processes such as checking a fraudulent credit card, and batch pro-

cessing required for a long-running continuum of data analysis such as regression analysis.

The decision on required type of processing for a context-specific architecture
755 is determined by the characteristics of the data being analyzed, that is primarily variety, volume and velocity.

For instance, most algorithms for stream processing are using in-memory
stateful data structures such Hyperloglog to compute values in real-time. A
streaming component can be tailored to adopt specific windowing approaches
760 such as tuple-at-a-time and a micro-batch processing. When in fact, these techniques are not required for batch processing. An architect may opt for MapReduce and Bulk Synchronous Parallel (BSM) processing for batch-oriented requirements or go for a streaming processing based on a specific performance requirement set to handle velocity and volume of data.

765 Various studies have provided different level of abstraction when it comes to describing data processing. While some studies like S19 describe the processes in the data processing pipeline, some others like s15 have just abstracted it to 'batch processing' or 'stream processing'.

Moreover, we realized two category of data processing. First category utilizes
770 two different architectural constructs for batch and stream processing, while the latter tends to process both in one architectural component. This is a difference that can be seen between Lambda and Kappa, and the RAs that have been derived from the two. Some RAs such as S17 have used three architectural constructs, namely batch, streaming and interactive.

775 BD interfaces are communicated in two different ways, either the RA only presented a 'serving or access layer' (S21, S17), or several components that are each specific to a different requirement (ML, BI, etc). The latter can be witnessed in S16.

10.3. *BD Infrastructure*

780 Another major area that is discussed in the RAs is the concept of infrastructure. Different authors have taken different approaches to communicate this.

Some have presented it through a standard architectural description language such as S6, which clearly defines the technology layer, and some have not mentioned the concept of infrastructure, but it's rather implicitly conveyed such as S22 and S23. Some other have presented with both infrastructure and platform layer such as S21 and S17.

For instance, one major component of a NIST BD RA (S17) is called big data framework provider which includes 'computing and analytics', 'data organization and distribution', and 'infrastructures such as networking, computing and storage'.

Despite the former two major components, BD infrastructure is more of a layer than a component. A layer in which the RA lays out a possible computing and networking design of a BD system. This is crucial, as practitioners of BD have been commonly architectonic underlying distributed paradigms and horizontal scaling.

Therefore, CAP theorem, ACID and BASE transactions, data consistency, service discovery, and tail latency are potential architectural challenges one should consider. Should a BD system adopt an event-driven approach through an event backbone such as Kafka that is discussed in S23? Or should it stick to REST based communication. What is the overhead of context switch and networking in the case of RPCs among services?

All and all, as a result of this SLR, a component of a BD infrastructure has been witnessed as a common pattern, in various forms and approaches. We consider platform layer of BD as a major architectural component of these systems. Whereas one might argue that infrastructure is an architectural component of any system, the design challenge is more significant in the case of BD systems as these systems are usually distributed in nature.

Lastly, our findings depicts the fact that many of RA presented are not designed underlying completely distributed architecture while BD systems can benefit from this paradigm. An exception to this is S23, which is absorbing many patterns from event-driven microservices architecture.

11. What are the limitations of current BD RAs?

To answer the RQ3, RAS collected for this SLR have been appraised to point out limitations. To arrive at this objective systematically, we first described each
815 RA with its limitation briefly. This is portrayed in 3.

RA	Description/Limitations
S1	One of pioneers of BD architectures, and perhaps the oldest one, does not address data quality issue, does not address seem to address changes in landscape of data, seem to be hitting the bare minimum requirement of BD systems
S2	This RA is specifically designed for the domain of healthcare and life sciences, does not seem to cover data quality, is overly abstract, resembles to n-tier architectures, and pivotes on IBM specific softwares such as LSF process manager, LSF application center, and LSF data manager.
S3	This RA seems to be covering a very general scenario of big data analytics, without any attention to either metadata or security. It flows from data sources to data transformation, and into data usage, but it's unclear how data quality is assured, how it will support changes in data landscape, and how it will respond to changes. In addition, the RA is heavy influenced by MapReduce and seems to revolve around it, while MapReduce may not provide the best of performance in comparison to newer approaches such as acyclic direct graph used in Apache Tez and Spark.

S4	<p>A classically designed RA with 3 main phases of ingestion, processing and providing. This RA has underlying mechanisms that facilitates 'right-time' flow of data through the system. This is achieved by having two architectural constructs for strongly typed data and weakly typed data. While this was annotated as the data quality part of the RA, it does not seem to account for data ownership and changes in data landscape. In addition, this RA utilizes data mart for access and performance, which can affect the overall modifiability negatively.</p>
S5	<p>This RA the augmentation of traditional data warehouse architectures with a few new components to account for stream processing. The RA defines three kind of storage, data warehouse, sandbox and raw data archive that communicate with each other through data load components. There seems to be many moving parts in this RA, and privacy and metadata is clearly addressed. Nevertheless, the RA is lacking in the area of security, data provenance, scalability and modifiability. We can't tell how data ownership is place, and how data quality is addressed. It's also driven mostly by traditional warehouse way of thinking, like staging environments and data marts.</p>
S6	<p>This RA seems to be portraying the bare minimum requirements for big data analytics with no mention of security, privacy, metadata, or data quality. The RA is published as a short paper, so many details are missing.</p>
S7	<p>This RA provides with bare minimum components for data analytics, without any clear delineation on stream processing. The RA seems to be done in quite a reductionist manner, with no attention to privacy, security, metadata, and data quality. Data storage seems to be only associated to hardware, and thus it's unclear how data is evolved and scaled.</p>

S8	Kappa is perhaps the predecessor of Lambda, aiming to address some of the limitations of it. The major different between Kappa and Lambda is that Kappa has a unified processing layer for batch and stream process, which eliminates the complexity of maintaining two separate systems, reduces costs, and can potentially increase data quality. Nevertheless, this architecture, does not discuss metadata, security, privacy, data quality, and maintainability in details.
S9	This is BD RA designed for healthcare application by Intel. This RA is not elaborated in detail, does not seem to account for cross-cutting concerns such as security, metadata, privacy, and data quality. The concept of access manager seems to be vague, as we could not understand how the access is managed. This RA seems to be a simple instance of a Hadoop ecosystem with some extras added
S10	A comprehensive RA that aim to cover many aspects of data engineering. Nevertheless, we did not find any notion of metadata management, neither was a discussion on security and privacy challenges. While this RA could work successfully for a regular BD workflows, we are unsure how data quality is met and how scalability is achieved.
S11	This RA is made up of three major phases, ingestion, processing and presentation. It is designed around Hadoop ecosystem, and provides with bare minimum necessary to conduct data analytics. We could not find a discussion on metadata management, security, privacy or data quality. The pipeline is using a data warehouse, specifically Data Warehouse, and uses it to communicate to the Hadoop side of things. We are not sure how unstructured is handled, and how data lineage is achieved.
S12	This architecture is specifically designed for waste management, and seems to be using an approach similar to Kappa. The data takes a generic flow from data sources to application, without any clear identification of data quality, privacy and security concerns.

S13	This RA is specifically deigned for the security domain and seems to have a lot of inspiration from NIST BD RA. The RA is layed out in fabrics just like the NIST one, and unlike many others, does mention cross-cutting concerns such as security explicitly. However the concept of data ownership is not discussed, there's no mention of metadata or privacy, and the evaluation is not extensive. That is, we cannot ensure how the derived solutions from this RA can scale.
S14	A generic RA that resembles to Lambda architecture, with stream and batch processing being processed in different nodes. This RA utilizes data warehouses and hadoop cluster for data processing. It was unclear how the security, privacy, metadata, and data quality is achieved. Maintainability aspects are not discussed as well.
S15	This RA extends the Lambda architecture by adding a semantic layer. It has a great focus on handling metadata in a right manner, but it does not seem to have any identification of other cross-cutting concerns such as privacy, security or data quality. It also adopts the idea of separate batch and stream layers, which makes modifiability and cost harder.
S16	This RA clearly segregates stream data from other data, and defines clear interfaces for ingestion of different data types. It then passes the data directly to a distributed storage (Hadoop's HDFS), and retrieves it later for deduplication and cleaning. While the RA seems to have addressed the minimum requirements of data anlytics, it does not seem to address cross-cutting concerns such as metadata, security and privacy. It is also unclear on how data quality is achieved.

S17	This is perhaps the most comprehensive BD RA found in this SLR, and has been heavily funded by the government of the USA. While this RA is a good tool to facilitate open discussion, design structures, requirements, and operations inherent in BD, it is more of a high-level conceptual model of BD, rather than an effective BD RA. Some of the limitations witnessed in this RA is in its brief mention of metadata management (only discussed in lifecycle management), unclear approaches to attain data quality and data ownership, and potential monolithic coupling of components in big data application provider.
S18	This RA segregates data extraction and data loading phases, and tend to adopt the idea of segregating stream and batch processing layers. Nevertheless, we could not find the identification of cross-cutting concerns such privacy, security or metadata management. We could not understand how data quality is achieved. There are also three storage designed, but seems like all data will eventually be stored in one giant storage. This poses a threat and create a bottleneck.
S18	This RA segregates data extraction and data loading phases, and tend to adopt the idea of segregating stream and batch processing layers. Nevertheless, we could not find the identification of cross-cutting concerns such privacy, security or metadata management. We could not understand how data quality is achieved. There are also three storage designed, but seems like all data will eventually be stored in one giant storage. This poses a threat and create a bottleneck.
S19	Driven from the NIST BD RA, this RA is more or less identical with BD RA, but tailored specifically for emergency management. We skip explanation for this RA, as the limitations discussed for NIST BD RA, can be applied to this one as well.

S20	Driven from the NIST BD RA, this RA is more ore less identical with BD RA, but tailored specifically for emergency management. We skip explanation for this RA, as the limitations discussed for NIST BD RA, can be applied to this one as well.
S21	This RA shares all the fundamental components with BD RA, and seems to be very similar. However, the phrase fabrics seem to be changed to multi-layer functions. Therefore this RA, just like NIST is too abstract and leaves many architectural decisions unknown such as data storage, data quality assurance, and data ownership. It is unclear on how storage should be approached, and the overall structure resembles to a monolithic data pipeline architecture.
S22	One of the few RAs that tend to absorb the concept of microservices into BD development. Nevertheless, the RA seems to be driven by the idea of one data lake for all data storage, which can be a daunting task to scale and maintain. The concept of metadata does not seem to be discussed, and other concerns such as security, privacy, data quality and data provenance are unclear.
S23	This RA absorbs a lot of patterns from microservices event driven architectures and reactive systems and tend to absorb them into the BD development. While there's been a clear attention to cross-cutting concerns such as metadata, and privacy, security does not seem to be well discussed in the study. The RA also tends to use data lake as the single source of storage which can be challenging to scale.

Table 3: BD RAs and Their Limitations

Except for one case (S22), all the architectures and RAs found as the result of this study, were designed underlying monolithic data pipeline architecture with four major components being data consumer, data processing, data infrastructure and data providers. To discuss the integral facets that embroil these

820 architectures, one must look at the characteristics of these architectures and the ways in which they achieve their ends, with quality attributes surrounding it.

The process of turning data into actionable insights in these architectures usually follow a similar lifecycle;

1. **Data Ingestion:** system beings to ingest data from all corners of the
825 enterprise, including both transactional, operational and external data.
2. **Data Transformation:** data captured from the previous step is then cleansed for duplication, quality, and potentially scrubbed for privacy policies. This data then goes through a multifaceted enrichment process to facilitate data analysis.
- 830 3. **Data Serving:** at this stage, data is ready to be served to diverse array of needs ranging from machine learning to marketing analytics, to business intelligence to product analysis and customer journey optimization.

The lifecycle depicted is indeed a high-level abstract view of prevalent BD systems. Howbeit, it highlights an important matter; these systems are all oper-
835 ating underlying monolithic data pipeline architecture that tends to account for all sorts of data. This means, data that logically belong to different domains are now all lumped together and crunched in one architectural constructs, making maintainability and scalability a daunting task.

While architectures in software engineering have gone through series of evo-
840 lution in the industry, adopting a more decentralized and distributed approaches such as microservice architecture, event driven architectures, reactive systems, and domain driven design , the data engineering, and in specific BD ecosystems do not seem to be adopting many of these patterns. The whole idea of 'monolithic data pipeline architecture with no clearly defined domains and ownership'
845 brings significant challenges to design, implementation, maintenance and scaling of BD systems.

This architecture and design process if done underlying current prevalent approaches, can bring about colossal losses, and leave many managers disappointed. Nevertheless, we don't claim that all these architectures will fail,

perhaps some have proven to be successful in a specific context. There are two threats to maintainability and scalability of these systems; 1) *Data source proliferation*: as the BD system grows and more data sources are added, the ability to ingest, process, and harmonize all these data in one place diminishes, 2) *Data consumer proliferation*: organizations that utilize rapid experimentation approaches such Hypothesis-Driven Development and Continuous Delivery constantly introduce new use cases for data to be consumed in different domains. This means that variability of the data rises, and the sum of aggregations, projections, and slices increases, which in turn adds more work to the backlog of the data team, slowing down the process of serving the data to consumers.

Another limitation that we came across was that the concept of metadata has been poorly discussed. For instance, S5 discussed the limitation of metadata management systems, stating that most metadata solutions are ad-hoc. The researcher then went ahead and introduced a layer for metadata management in the RA, but as a non-integrated component. For instance, the author did not discuss how data provenance can be achieved through the RA and underlying which logical flow one can do linear analysis.

In another case, NIST BD RA only discusses metadata in a sentence, and in sub-activity named ‘metadata management’. The RA only states what are essential metadata information and how they are used. Except for S15 and S23, metadata has not been accentuated enough and metadata layer is not thoroughly discussed. This is a noticeable limitation in current BD RAs, as metadata plays an important role in BD systems, addressing wide range of challenges such as privacy, security, data provenance, and linear analysis.

Based on that, one can argue that any BD system can benefit from a well-defined metadata layer as a means for bridging data stored in different platforms such as on-premises or on cloud, reducing complexity, facilitating access management, facilitating data governance, and potentially the creation of data mesh.

Furthermore, white papers collected from IT giants tend to pivot the RA around their services, which can potentially reduce its applicability, hinder RAs

openness, and even affect architectural qualities. In these white papers, alternative technologies or vendors are typically not discussed which leaves the architect with a small pool of options.

Lastly, privacy and security does not seem to have been discussed enough, or it has been mostly marginalized. For instance, we have not found an architectural component that allows for data scrubbing, or we did not understand how one can achieve security in-between data pipelines. Specially, in regard to privacy and with recent global movements towards increased privacy, BD architects are now increasingly challenged to design underlying the shadow of regional data privacy policies. Placing this challenge next to security challenges of package management, endpoint proliferation and DDOS handling can further signify more research on BD RAs.

Many of core architectural decisions revolving around security and privacy, if not addressed in an initial phase, can result in massive losses and potential bottlenecks. Lastly,

12. Improvements

1. The findings yielded by investigating the research questions of this SLR should constitute many discussion points around the research and practice of BD systems. However, the manuscript is completely missing a discussion section. One should expect that the results of SLR can inform the current knowledge and provide several research directions for future research.
2. Last, one of the core challenges with the paper is to situate it within an ongoing scholarly conversation. The authors currently reference a fairly diverse set of papers, but remain at a fairly abstract level when it comes to elaborating how your work builds upon and expands existing work. In turn, this makes it difficult to appreciate theoretical implications of your work.

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