Understanding Interdependencies among Fog System Characteristics

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Abstract—**Fog computing adds decentralized computing, storage, and networking capabilities with dedicated nodes as an intermediate layer between cloud data centers and edge devices to solve latency, bandwidth, and resilience issues. However, introducing a fog layer imposes new system design challenges. Fog systems not only exhibit a multitude of key system characteristics (e.g., security, resilience, interoperability) but are also beset with various interdependencies among their key characteristics that require developers' attention. Such interdependencies can either be trade-offs with improving the fog system on one characteristic impairing it on another, or synergies with improving the system on one characteristic also improving it on another. As system developers face a multifaceted and complex set of potential system design measures, it is challenging for them to oversee all potentially resulting interdependencies, mitigate trade-offs, and foster synergies. Until now, existing literature on fog system architecture has only analyzed such interdependencies in isolation for specific characteristics, thereby limiting the applicability and generalizability of their proposed system designs if other than the considered characteristics are critical. We aim to fill this gap by conducting a literature review to (1) synthesize the most relevant characteristics of fog systems and design measures to achieve them, and (2) derive interdependences among all key characteristics. From reviewing 147 articles on fog system architectures, we reveal 11 key characteristics and 39 interdependencies. We supplement the key characteristics with a description, reason for their relevance, and related design measures derived from literature to deepen the understanding of a fog system´s potential and clarify semantic ambiguities. For the interdependencies, we explain and differentiate each one as positive (synergies) or negative (trade-offs), guiding practitioners and researchers in future design choices to avoid pitfalls and unleash the full potential of fog computing.**

Keywords—fog computing, fog nodes, design measures, key characteristics, interdependencies, trade-offs

I. INTRODUCTION

Enterprises need to continuously re-design and improve their IT infrastructure to adapt to changing requirements from dynamic use cases [1]. As latency, bandwidth, energy, and resilience issues of cloud and edge systems become more and more severe for use cases such as autonomous driving, Internet of Things (IoT), cloud-based AI services [2], or Virtual Reality (VR), the concept of fog computing has increasingly gained importance for enterprises [3, 4]. Fog computing adds decentralized computing, storage, and networking capabilities with dedicated nodes as an intermediate layer between cloud data centers and edge devices [5, 6]. As an extension to the cloud, fog computing allows to move IT resources closer to the edge and enables enterprises to deploy large-scale real-time applications with massive amounts of data and a large number of connected edge devices [3].

However, enterprises should not regard the introduction of a fog layer and its infrastructure nodes as a silver bullet because it comes with unique challenges requiring rigor design and development of fog layers that are efficiently interwoven with cloud and edge layers of enterprises. In particular, the design and operation of a fog layer and its connections to the edge and cloud layer (in the following called a "fog system") inherit various interdependencies among systems' key characteristics that require developers' attention [7]. For example, fog systems entail a more complex network to maintain and increased costs as parts of the former centralized cloud computing capabilities are now spread across smaller, decentralized fog nodes [8, 9]. Naturally, the more the degree of decentralization of fog nodes is increased to deploy nodes even closer to the edge and decrease latency, the more negative is the impact on the cost-efficiency of the entire system. At the same time, an increase in decentralization improves the scalability of the system as new edge devices can be connected and managed more easily with local fog nodes.

Such interdependencies between fog system characteristics can either be (1) *trade-offs* with the improvement of the fog system on one characteristic impairing another (e.g., if the improvement of the system´s security by more sophisticated encryption requires more processing time and increases the latency [10]); or (2) *synergies* with the improvement of the fog system on one characteristic also improving another (e.g., if the increase of bandwidth allows to communicate more data in a shorter time and thereby also decreases the latency [11]).

Due to these interdependencies, enterprises cannot deploy a dominant fog system performing strong on all system characteristics but rather require specialized systems tailored to key requirements for an individual use case and context [7]. Especially for critical use cases, such as healthcare and autonomous driving, enterprises need to understand trade-offs arising from fulfilling use cases' requirements to avoid potential threats and unintended system behavior [12]. Based on the complexity of fog systems and the multitude of potential design measures and characteristics, it is challenging to oversee all potential interdependencies, mitigate trade-offs, and foster synergies. Providing guidance on key characteristics and their interdependencies of fog systems would ensure that developers are aware of potential pitfalls in the design phase of a system and the respective enterprise, save time in the evaluation of design concepts and raise the applicability of fog systems for critical use cases.

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Among the existing body of research on fog systems, three research streams emerged that address characteristics and its interdependencies: architecture- and operations-focused research, and surveys of the technological state-of-the-art. First, architecture-focused research on fog systems provides valuable insights on how to implement fog systems and improve them on specific characteristics (e.g., achieving low latency in mobility [13], or high security in healthcare [14]). Second, operations-focused research proposes how to run fog systems with sophisticated optimization algorithms and extensive technical details on computing, networking, and administration (e.g., virtual machine placement for energy efficiency [15]). Third, surveys on fog computing examine the general potential of fog systems, its characteristics, and limitations as well as its current status and state-of-the-art concepts (e.g., elaborating the applicability of fog systems [9]).

However, prior research across all streams mostly focuses on one or a few specific characteristics of fog systems with a limited view on interdependencies among a holistic set of characteristics [7]. When considering characteristics in isolation, we lack an understanding whether critical interdependencies of proposed fog system designs are applicable and relevant for other use cases that are bound by further requirements. For instance, if research on fog systems for latency-sensitive manufacturing use cases does not consider the potentially negative impact of the envisioned design on the maintainability of the system, their system design choices cannot be adapted for use cases like vehicular fog computing in which the management of a large number of entities require sound maintainability [16]. Thereby, the applicability and generalizability of the proposed fog system and respective design measures may be limited. Besides, research that considers interdependencies among the characteristics rather pays attention to trade-offs. In terms of synergies, research addresses them among a few key characteristics (such as latency, bandwidth, energy efficiency, or security) but neglects to consider a broader set of characteristics [7]. The full potential of fog systems stays untapped.

For practitioners as well as researchers to be aware of the possibilities and implications of designing a fog system, they require a broader and more detailed understanding of characteristics, interdependencies, and their manifestation. Without such an understanding, the risk of designing systems that deviate from the targeted behavior due to the overseen, adverse impact of design decisions increases. An analysis of interdependencies among key characteristics could also increase the quality of fog systems by informing about potential pitfalls and synergies to look out for in the design phase. We, therefore, aim to answer the following research questions (RQs):

RQ1: What are the key characteristics of fog systems?

RQ2: How does the improvement of fog systems towards a specific characteristic influence interdependent characteristics?

To answer our RQs, we conducted a literature review comprising 147 articles on fog system architectures to extract key characteristics of fog systems and their interdependencies. Our focus on fog system architectures allowed us to (1) identify the characteristics to target when developing fog systems together with (2) the applied design measures to improve a fog system on a specific characteristic and (3) related trade-offs and synergies for characteristics. Based on the insights derived from the literature, we aggregated a list of 11 key system characteristics and a matrix comprising 39 interdependencies, while considering the design measures to improve a fog system on a specific characteristic and revealing the potential positive (synergy) or negative (trade-off) effect on other characteristics.

By uncovering key characteristics and interdependencies, we extend the understanding of objectives that can be achieved by enterprises when leveraging fog systems while alerting both practitioners and researchers about potential pitfalls to cater to, and synergies to aim for in the design phase. In addition, we clarify prevalent semantic ambiguities of characteristics and interdependencies. This study supports the design of new and improvement of existing fog systems to increase their practical applicability and quality.

The remainder of the paper is structured as follows. First, we introduce fog systems in general before summarizing related work on both characteristics of fog systems and interdependencies among the characteristics. Second, we detail our research method. Third, we describe the aggregated key characteristics together with a short description, reason for their relevance, and design measures to improve fog systems towards a characteristic. Fourth, we present the derived interdependencies among the characteristics. Lastly, we discuss overall findings, their limitations, and ideas for further research.

II. THEORETICAL BACKGROUND

A. Fog Systems

Contemporary IT use cases impose growing requirements on networks, for example, with healthcare applications that cannot afford any delay in processing [17], Augmented Reality (AR) and VR applications requiring extraordinary large bandwidth [18, 19], and IoT use cases that generate a huge amount of data, requiring high reliability and a low latency guarantee across heterogeneous devices in a scalable manner [20–23]. Modern enterprises combining edge and cloud computing increasingly struggle with the growing requirements so that more and more often quality of service requirements cannot be met [24], real-time performance and reliability become insufficient [25], or an inefficient network architecture leads to congested connections and connectivity issues [9, 17, 20]. While increasing the power of edge devices to solve these issues reaches physical and economical limits [9, 26], the concept of fog computing adding an intermediary layer to provide additional IT capabilities closer to the edge has emerged. In general, fog computing is defined as a layered model consisting of virtual or physical fog nodes deployed between cloud and edge layers to provide local processing, storage, and networking capabilities [5, 6].

In the following, we will call the instantiation of a fog layer and its potential connections to an edge and/or a cloud layer a *fog system* that will be our artifact of interest. With the term "system", we take a socio-technical view on fog systems from a system-theoretic perspective that addresses the interaction of individuals and technologies to fulfill use case-specific tasks [27, 28]. Due to the often very close integration of fog systems with edge and cloud layers, the characteristics of fog systems (such as scalability, maintainability, and security) affect the performance of all layers in an interconnected system. Typically, the fog system consists either of one flat layer, several hierarchical organized sub-layers, or clustered groups [29]. Each layer or group encompasses physical fog nodes that typically have more capabilities than edge devices but less than cloud data centers [9]. Depending on their capabilities and location relative to the edge devices, fog nodes can range from gateways acting as a connectivity hub for a small set of edge devices up to local mini data centers providing extensive capabilities for a broad range of edge devices [7]. In rare cases, edge devices can take the role of a (temporary) fog node (such as autonomous vehicles) [30]. The deployment of a fog layer is feasible on the complete continuum between the edge and the cloud, meaning that depending on the use case, the fog layer can have varying physical distances to the edge layer and processing, storage, and networking capabilities between the ones of edge devices or cloud data centers.

B. Related Research

Existing research on fog systems related to characteristics and interdependencies can be differentiated according to four major streams, as shown in Table I.

TABLE I. Research on fog system characteristics and interdependencies

	Characteristics	*Interdependencies*
Examining one or a few characteristics / interdependencies	**A:** Developing architectures or methods to operate fog systems that are optimized towards one or a few specific characteristics. Example articles: [21, 31–33]	**C:** Considering the impact of design choices on interdependencies of the characteristics in focus and common key characteristics. Example articles: [34–37]
Examining and comparing multiple characteristics / interdependencies	**B:** Surveying key characteristics from use cases or existing literature. Example articles: [9, 38, 39], ***this study***	**D:** Synthesizing a holistic set of characteristics and analyzing interdependencies among multiple of them. Example articles: ***This study***

Articles in quadrant A focus, at most, on a limited set of characteristics to optimize a fog system respectively [7]. Based on the issues fog systems were supposed to solve, early research focused on fog systems that aimed to keep the latency at a minimum [21, 31], increase the bandwidth to communicate large amounts of data [32], and improve the energy efficiency to preserve edge devices [33], among others. As further requirements became more and more critical for modern networks (such as security and privacy in healthcare [14], reliability in mobility [40], or interoperability in IoT [41]), increasingly more research on fog systems expanded the set of potential characteristics to focus on. Contemporary articles from quadrant A can be organized into three subcategories: first, research examining use-case or industry-specific fog systems mostly focuses on discussing and improving characteristics that are most relevant for their application (e.g., [14, 42]). Second, research on characteristic-specific fog systems compares different holistic design options to reach the best possible manifestation for one or a few characteristics (e.g., [43, 44]). Third, research on element-specific fog systems considers critical parts of a fog system and aims to improve the system elements towards certain performance characteristics (e.g., [45, 46]).

Building upon the current state of research, articles from quadrant B compare and aggregate multiple characteristics potentially relevant for fog systems. Related articles either derive key characteristics from the objectives other research addressed when designing fog systems (e.g., [7, 47]) or from requirements of common fog use cases (e.g., [39, 48]).

Articles from quadrant A and B partly contribute to quadrant C by also analyzing primarily trade-offs among characteristics. For that, researchers outline disadvantages their envisioned fog systems impose for common key characteristics such as latency or data load (e.g., [34, 49]).

Summarizing, the related work addresses specific characteristics of fog systems and individual interdependencies in isolation or only focuses on characteristics without considering interdependencies. Moreover, related work that accounts for interdependencies mostly focuses on negative ones, namely trade-offs. We, therefore, lack a deeper and broader understanding of how design measures targeting to improve fog systems towards a certain characteristic may affect other characteristics, especially in a positive way (synergies). Accordingly, researchers and practitioners may either oversee potential pitfalls their envisioned fog system inherit which decreases both the quality and applicability, or potential synergies that could even further improve their fog system. There is a lack of research that systematically analyze interdependencies among multiple characteristics, and focus on both trade-offs as well as synergies (quadrant D). With our research, we aim to fill that relevant gap.

III. RESEARCH METHOD

To answer our RQs, we performed a descriptive literature review and followed recommendations from the information systems discipline [50, 51]. Accordingly, we searched for journal and conference articles from IEEE Xplore, EBSCO-Host, ScienceDirect, ACM Digital Library, and ProQuest as they encompass IS literature in general and cloud, fog, and edge computing literature in particular. We aimed to identify literature primarily focusing on architectural aspects of fog systems to identify both the characteristics in focus when designing fog systems together with potential up- or downsides these architectures have for other characteristics. Our research string consisted of two parts accounting for 1. the focus on fog systems and 2. the focus on foundational aspects of fog systems resulting in: "*fog AND (network OR system OR computing) AND (architecture OR design OR setup)*". To ensure that the key contribution of the found literature revolves around designing fog systems and determining their architecture, we applied the search string to the title and keywords yielding 415 articles. Extending the search to the abstract resulted in an excessive number of articles from which a first relevancy check revealed a high share of articles using words from our search string in the abstract without focusing on them but rather on the applicability of fog computing in various setups, benefits over pure cloud/edge computing, operations of a fog system, among others. Thus, we continued with the initially found 415 articles and removed 55 duplicates and 3 books before screening the remaining for relevance. We excluded further 210 articles that focused on other topics than fog computing (n = 25), applied fog computing as a tool (n = 35), examined a generic fog architecture (n = 59), or analyzed the operations of fog systems (n = 91). We assigned articles to the latter three categories if they do not provide specific design measures to set up or improve a fog system in its architecture.

To reveal key characteristics from the resulting 147 articles, we coded the design measures each article proposes (n = 421) together with a description and source as well as the targeted characteristic(s) of the design measure if applicable (n = 217) [52]. For that, we only focused on the core part of articles without sections on future work to ensure that only profound insights are used. We interpreted a text segment as proposed design measure for fog systems if the authors either suggest an explicit setup of fog nodes and how they interact (e.g., a flat hierarchy of fog nodes with all nodes communicating among each other [53]), specific technology to use for processing or communication (e.g., containerized applications [26]), or a particular distribution of roles among the fog system (e.g., select one fog node as a hub to act as a broker between nodes [46]). If we identified a text segment in the article that relates a proposed design measure with its effect on the fog system, we assigned the effect as characteristic to the design measure. For example, we coded the text segment "Low-Power Wide Area Network (LPWAN) seem to be a good selection, since, in comparison to other previous technologies, they provide […] reduced energy consumption" [54] as design measure "Use network technology that requires low energy" and assigned the characteristic "energy consumption".

While coding, we aggregated the characteristics into so-called master-characteristics, that is an aggregation of similar characteristics, by applying the literature coding process of Lacity et al. [52]. Starting with the first extracted characteristics as master-characteristics, we checked for every newly coded characteristic if it fits an already defined master-characteristic. In case we identified a fit, we looked up if it is a synonym or subset and if the master-characteristic´s term and respective definition may need to be changed (e.g., we aggregated "response time", "delay", and "latency" and chose "latency" as designation for the master-characteristic due to its dominant usage) [55]. If there was an overlap of an already defined master-characteristic and newly coded characteristic, we either combined both and adjusted the description or created a new master-characteristic (e.g., we decided to split maintainability into maintainability and scalability). For each of the resulting 11 master-characteristics, we noted a description, arguments for their relevance, and exemplary design measures to improve a fog system in their regard.

To reveal interdependencies, we followed a two-step approach. First, while coding the design measures and related characteristics to be improved, we also noted if the authors state additional effects of the design measure on other characteristics than the one in focus. For example, Imine et al. [56] describe an improved authentication mechanism for fog systems that enhances security but also imposes additional latency and data load on the system. We categorized such interdependencies as trade-off if the fog system is impaired on other than the characteristics in focus; and as synergy if another system characteristic is improved. To cluster the interdependencies, we considered the corresponding master-characteristics of both the primarily targeted and interdependent characteristics. As a second step, we systematically considered all design measures that were assigned master-characteristics but no interdependencies from literature. For these measures, we discussed among the team of authors about their potential impact on other master-characteristics than the one(s) in focus to improve. In case we were able to develop a sufficiently reasonable chain of arguments for an interdependency, we added it to our list of trade-offs and synergies. For example, we found that improving the resilience of a fog system with additional layers of hierarchy leads to a more complex system setup in which the more granular distribution of tasks and required coordination across hierarchies impairs the maintainability of such a system. In total, we identified 18 interdependencies from literature and extended the list with additional 21 interdependencies as propositions.

IV. FOG SYSTEM CHARACTERISTICS

Table II summarizes the identified characteristics together with a brief description, reason for their relevance, design measures to improve, and the underlying references. The characteristics are organized descending based on the number of mentions in the analyzed articles.

TABLE II. Fog system characteristics

Characteristic (#coding)	**Description**	**Relevance**	**Design measures to improve the system on the characteristic**
Latency (55)	Average required time from a request to its response including time spent on communication and processing for the entire fog system within and across its layers [48].	Modern applications such as VR require near real-time processing and communication due to the speed of changes in their environment [3, 17, 35].	• Deploy more fog nodes closer to edge devices [35], • Target low utilization of fog nodes to manage peak loads [57], • Introduce more capable connections with larger bandwidths [58], • Improve distribution of loads across fog nodes [59].
Data load (27)	Amount of data that needs to be transferred or stored within the fog system [60].	Modern applications and an increased number of devices and sensors produce massive amounts of data to be managed in the fog system [60, 61].	• Cache content near to end-users [19, 62], • Filter and aggregate data in lower levels of the system [63], • Forward only prioritized/critical data, • Compress data [63], • More peer-to-peer communication [64].
Security (26)	The ability of fog systems to maintain availability, integrity, and confidentiality by defending against unauthorized interception, interruption, modification, and fabrication [65].	Fog systems usually encompass a multitude of nodes, sensors, and actors in potentially critical domains such as mobility and healthcare in which any security breach can have a severe impact [48, 61].	• Introduce peer trust models [66], • Limit access to the fog system [49], • Introduce authentication mechanisms for every layer [44], • Introduce trust mechanisms for edge devices and fog nodes [56, 67], • Allow only validated edge devices or for nodes or registered persons to access the system [68], • Constant monitoring of activities to check for abnormal behavior [49], • Introduce blockchain-based strategies [61].
Interoperability (19)	The ability of fog systems to incorporate different types of entities, in terms of hardware, operating systems, protocols, to collaborate with other systems and third-party entities, and to manage mobile edge devices [66, 69].	With an increasing number of available technologies, protocols, and software stacks, a system provides more value and has a higher potential if it can flexibly incorporate entities independent of their setup [22, 70].	• Facilitate formation of ad-hoc virtual networks to group fog nodes locally and on-demand allowing an easier collaboration [71], • Use open standards that can include different technologies, protocols, hardware, etc. [72], • Use containers [26], • Introduce hubs that can act as a broker between different layers, devices, and nodes [46].

Energy efficiency (16)	The required energy to run entire fog systems as well as single devices and nodes [48].	Besides environmental responsibilities to keep energy consumption as low as possible, devices and nodes often have only limited access to a power supply which can restrict their time to be operational [39, 48].	• Introduce a resource coordinator monitoring and distributing loads across fog nodes depending on available energy [37, 39], • Use energy-efficient network technology such as LPWAN [54].
Computing power (16)	Overall processing capabilities of fog systems.	Due to the amount of data and requirements on latency, modern applications require increasingly more computing power to be processed in a short time [58, 73].	• Use less resource-demanding software stacks to leverage the available computing power more efficiently (e.g., using containers instead of virtual machines [26]).
Resilience (14)	The ability of fog systems as a whole to recover from or adjust to disruptions quickly [74].	Downtime of a fog system or data losses create severe threats if edge devices cannot continue to work or required data is unavailable [20, 74].	• Introduce more redundancies (additional fog nodes, virtualization, network connections) [47], • Form hierarchical groups of fog nodes that can individually replace each other [75], • Keep up-to-date backups of, among others, data and virtual machines to recover the latest status of failed system components quickly [74], • Prioritize emergency/critical data [23], • Distribute fog nodes geographically [76], • Increase peer-to-peer collaboration and communication [35], • Introduce edge twins (i.e., the virtual replication of physical devices) to allow the transfer of their status to substitutes in case of failure [74], • Introduce reliability services dedicated to preparing for and managing outages [63].
Maintainability (13)	Required effort to monitor and maintain fog systems, their entities, connections, and the applied technologies [77].	Due to the potential extent of fog systems and their dynamic connections to heterogeneous and distributed devices, they need to be efficiently maintainable to ensure operations without excessive administrative overhead [23, 34].	• Constant monitoring of edge devices and fog nodes [34], • Using open source or well-established standards [37], • Introduce autonomous sub-systems and self-monitoring/adjusting fog nodes [78].
Cost-efficiency (13)	The total cost of ownership for implementing, operating and potentially expanding fog systems and all their entities relative to the achieved performance [79, 80].	Fog systems must fulfill use case requirements in a cost-efficient manner to be recognized as a valid alternative to pure cloud setups [35, 81].	• Target high utilization of fog nodes and network connections [82], • Use low-cost hardware or technologies and architectures with lower resource demands [80, 81].
Scalability (11)	Potential to expand or shrink fog systems both in terms of users, fog nodes, and edge devices as well as computing power and bandwidth across the fog layer [83].	Fog systems as highly dynamic environments need to be able to react to changes in participants and loads quickly and should be able to include new entities [23].	• Abstract and modularize functions and services to scale them individually [63], • Plan with spare capacities that can be ramped up and down quickly [84], • Introduce additional fog layers to account for specific tasks that can be individually scaled [35], • Introduce hubs that can be easily accessed [85].
Bandwidth (7)	The capacity of data that can be moved through fog systems at any given time [81].	Bandwidth determines the amount of communication possible across a fog system to manage and optimize operations [19, 81].	• Deploy more connections with better data transmission [19] • Set up flat fog hierarchies that allow using available bandwidth more efficiently [82], • Change to data transmission protocols and physical ways of transmission with inherently larger bandwidths (e.g., dynamic bandwidth allocation protocol [81]).

V. INTERDEPENDENCIES AMONG CHARACTERISTICS

I1 Improving latency improves scalability but impairs maintainability, resilience, cost-efficiency, and energy efficiency.

The latency between edge devices and fog nodes can be improved by distributing fog nodes geographically aiming to have each fog node only being responsible for a small set of edge devices with close proximity to the nodes [86]. Such a latency-focused system setup increases the scalability (Synergy 1.1 (S1.1)) of the entire fog system as new edge devices are more likely to have a fog node near connect to. On the other side, geographically far-spread fog nodes are harder to maintain (Trade-off 1.2 (T1.2)) physically when the hardware needs to be checked or changed on-site [35]. Improving latency by introducing additional layers among the fog systems allows for a more fine-grained load distribution but also increases the complexity of the systems and makes it more vulnerable in case of errors if, for instance, more connections or handovers needs to be overseen, thereby decreasing the system resilience (T1.3) [36, 71]. Lastly, using more powerful fog nodes decreases processing times to reduce latency but is usually more expensive (T1.4) and consumes more energy (T1.5) [37].

I2 Improving data load improves resilience and energy efficiency but impairs latency and security.

If the data load between edge and cloud layers of a fog system is reduced by caching frequently used content in fog nodes close to end-users [87], the resilience of the whole fog system to recover from or continue operations in case of connection failures to the cloud increases (S2.1). Furthermore, caching reduces the required data to be communicated across the network and thereby reduces the consumed energy required for communications (S2.2). However, reducing the data load by improved networking (e.g., via network layer virtualization) increases the required execution overhead in nodes responsible for networking which prolongs processing times and results in higher latency (T2.3) [36, 73]. In addition, network layer virtualization causes additional security concerns as it allows easier access to critical system functions (T2.4) [36, 73].

I3 Improving security impairs latency, data load, scalability, and interoperability.

Improving a fog system´s security by the introduction of more sophisticated encryption mechanisms or other availability-, integrity-, or confidentiality-enhancing measures requires additional processing time and increases both latency (T3.1) and data load (T3.2) [56, 88]. Further, if a system´s security is increased by a more restrictive governance and by limiting the access to a system as well as the usage of different technologies, it also negatively affects both the scalability (T3.3) and interoperability (T3.4) of a system as potential new entities may be restricted or not able to join the system at all [49, 66].

I4 Improving interoperability improves scalability but impairs maintainability, security, and data load.

Setting up a fog system in a way that supports a broad variety of physical and virtual technologies helps to scale fast (S4.1) as there are fewer technical restrictions to include new entities [72]. However, supporting such a broad variety requires, on the one hand, more maintenance effort (T4.2) and imposes, on the other hand, additional challenges to secure the usage of all those technologies (T4.3) [63]. Further, a high degree of interoperability causes additional communication across different parts of a fog system or with other fog systems so that the data load is increased (T4.4) [26].

I5 Improving energy efficiency impairs bandwidth and interoperability.

A introduction of energy-efficient networking technology across a fog system, such as LPWAN, significantly reduces the energy consumption but also provides only very limited bandwidth for communication (T5.1) [54]. In addition, edge devices and fog nodes need to be configured for the usage of such technology so that they cannot easily be used with other technology, thus reducing the interoperability of a fog system (T5.2).

I6 Improving computing power improves latency but impairs energy efficiency and cost-efficiency.

With more available computing power, data and request processing can be accelerated to decrease latency (S6.1). However, that measure comes at the cost of increased resource consumption resulting in a decreased energy efficiency (T6.2) and higher overall costs (T6.3) if the more powerful nodes are less utilized [58, 89, 90].

I7 Improving resilience impairs data load, cost-efficiency, scalability, and security.

Introducing redundancies and backups of computing capabilities and databases allows a fog system to continue running or re-instating quickly in case of failures [47]. However, the handling of backups causes additional data load (T7.1) in the system as these are often stored in the cloud layer [91]. Increasing the resilience by dynamically forming hierarchical groups of fog nodes that can replace each other in case of failure also requires additional data load (T7.1) as there needs to be constant exchange among nodes to check on the status and group behavior [75]. Redundant and less utilized computing capabilities reduce the cost-efficiency (T7.2) of the system and increase the effort and cost to scale (T7.3) if it needs to grow at the same pace as the number of participants. Including a broader set of stakeholders in the system to avoid critical dependencies and risk of system failure if a single stakeholder fails increases the difficulty to keep the system secure (T7.4) as more stakeholders need to be supervised and continuously checked for security [39].

TABLE III. Overview of synergies (green) and trade-offs (red) among fog system characteristics derived directly from literature (*) or from systematically analyzing design measures

Interdependencies among fog system characteristics		**…has a positive, no, or a negative impact on:**										
		Latency	*Data load*	*Security*	*Inter-operability*	*Energy efficiency*	*Computing power*	*Resilience*	*Main-tainability*	*Cost-efficiency*	*Scalability*	*Bandwidth*
Improving a fog system on…	*Latency*					T1.5*		T1.3*	T1.2*	T1.4	S1.1	
	Data load	T2.3*		T2.4*		S2.2		S2.1				
	Security	T3.1*	T3.2*		T3.4*						T3.3	
	Interoperability		T4.4*	T4.3*					T4.2		S4.1*	
	Energy efficiency				T5.2							T5.1*
	Computing power	S6.1				T6.2				T6.3*		
	Resilience		T7.1	T7.4*						T7.2	T7.3	
	Maintainability	T8.2*		S8.1		T8.3						
	Cost-efficiency	T9.1*					T9.4	T9.2				T9.3
	Scalability		S10.1*						T10.2			
	Bandwidth	S11.1*			T11.4					T11.3	S11.2	

I8 Improving maintainability improves security but impairs latency and energy efficiency.

Maintainability requires both an effective way to monitor a fog system as well as efficient mechanisms to update or repair (parts of) the system [34]. On the one hand, improving the monitoring also helps to detect unwanted system behavior, for instance, caused by hostile intrusion early and thereby improves security (S8.1). On the other hand, running additional services for more advanced monitoring or self-controlling sub-system mechanisms requires more processing that can increase the latency (T8.2) [34] or decrease the systems' energy efficiency (T8.3).

I9 Improving cost-efficiency impairs latency, resilience, bandwidth, and computing power.

A cost-efficient system setup that targets a higher utilization of fog nodes by deploying less of them (or fewer layers) increases the system´s latency (T9.1) as nodes naturally will have a larger distance to the edge devices and peak loads cannot be covered with unutilized capacity so that waiting times increase [80]. In addition, fewer fog nodes also increase the impact of partial system failure and time to recover if certain nodes fail which decreases the system´s resilience (T9.2). Lastly, deploying fewer fog nodes to save costs also decreases the total available bandwidth (T9.3) and computing power (T9.4) across a fog system.

I10 Improving scalability improves data load but impairs maintainability.

The introduction of additional sub-layers within a fog layer allows to distribute and manage tasks more efficiently at specifically responsible nodes so that additional edge devices and their tasks can be attached easier which increases the scalability of a fog system [83]. Complementing the additional layers with data aggregation services can also facilitate scalability by reducing the burden newly attached edge devices may impose on a fog system [83]. While the additional layers and the data aggregation also reduce the data load (S10.1) across a fog system, that setup causes additional administrative overhead which increases the effort for maintenance (T10.2). Further, a modularization of fog nodes and services allows to scale more individually and therefore more efficiently but also impairs the maintainability when each module needs to be maintained individually (T10.2). The trade-off therefore depends less on the actual scaling but on providing a fog infrastructure that scales easily and efficiently.

I11 Improving bandwidth improves latency and scalability but impairs cost-efficiency and interoperability.

Increasing the bandwidth across a fog system decreases the risk of congested connections and thereby reduces the latency for communication, especially in times of peak loads (S11.1) [81, 82]. In addition, having spare bandwidth across the system allows scaling faster if the data load of additional edge devices and fog nodes can be handled without causing congestions (S11.2). Spare bandwidth, on the other hand, decreases the cost-efficiency (T11.3) of a system as utilization decreases and potentially more bandwidth is set up than required [19]. Further, if the increase in bandwidth depends on certain communication technology and protocols to be used, interoperability of the system is decreased (T11.4) as entities within the system need to adhere to related standards.

VI. DISCUSSION

A. Principal Findings

With our research, we were able to identify 11 key characteristics of fog systems (see Table I) and 39 interdependencies among them (see Table II). Concerning the key characteristics, latency is mentioned significantly more often (n = 55) than any other characteristic (n = 27 for data load as second most) indicating that the focus of proposed design measures lies on the primordial reason for the introduction of fog systems. To address another relevant issue of cloud and edge systems, namely that they nowadays produce too much data for too little bandwidths causing increasingly more data congestions [3], design measures are rather defined to reduce the data load with fog systems (n = 27) than to increase the bandwidth (n = 7). In this regard, key characteristics for fog systems differ from the general development of cloud technology and networking that aims to continuously enlarge the amount of transmissible data.

Among the interdependencies, we derived most interdependencies not directly from the literature but by systematically analyzing the design measures towards their impact on other characteristics than the ones in focus (21 of 39). This provides further evidence for our initially described research gap that a significant number of interdependencies among fog system characteristics are currently not discussed in literature and accordingly may not considered for proposed design measures. In addition, there are more trade-offs (30) than synergies (9) which underlines the importance for practitioners as well as researchers to be aware of potential pitfalls when designing a system optimized towards a certain characteristic. Most synergies arise when improving the bandwidth or data load of a fog system (each 2) while most trade-offs appear when improving latency, resilience, or security (each 4).

In most cases, the interdependencies are unidirectional, meaning, for instance, that improving scalability impairs maintainability but improving maintainability does not necessarily impair scalability. In some cases, the interdependencies are bidirectional trade-offs. For example, reducing the data load by network virtualization weakens the system´s security while introducing additional security mechanisms increases the data load. In only one case, we found adversarial interdependencies. While reducing a system´s data load, for instance, by caching often used data in fog nodes close to the edge devices also improves the resilience of a fog system, the improvement of resilience, for instance, with up-to-date backups increases the data load. Summarizing, for most interdependencies, the improvement of one characteristic only has an unidirectional effect on other characteristics for which synergies should be leveraged as much as possible while trade-offs should be thoroughly considered and mitigated, if possible. For the bidirectional trade-offs, the choice of design measures depends on the relevance of the affected characteristics for the specific use case and the impact strength of each design measure.

B. Implications for Research and Practice

While prior research mostly treated characteristics in isolation (e.g., [21, 33, 37]), we synthesized existing research and detailed a set of key characteristics that allow to better differentiate among potential objectives for fog systems. Our results guide future research and raise attention both on what fog systems can achieve (characteristics) and how it can be achieved (design measures). With our descriptions, we also support resolving unclarities and conceptual ambiguities in synonymous or overlapping characteristics as described in our coding process (see Chapter III). For instance, we synthesized “response time” [92] and “delay” [93] to the master-characteristic “latency” [91].

Additionally, we overcome the notion of prior research focusing only on single interdependencies among a few specific key characteristics (e.g., [34–37]) by providing interdependencies among the entire set of synthesized characteristics. With our approach of coding design measures and systematically analyzing them we were able to reveal 21 novel interdependencies, indicating that a major part of interdependencies has not been discussed in literature so far.

Further, we differentiate the interdependencies in positive (synergies) and negative (trade-offs) ones to better guide research in future design choices. On the one hand, pointing to adverse effects of improving a fog system towards a specific characteristic should motivate researchers to discuss mitigating trade-offs. On the other hand, raising awareness on synergies among fog system characteristics should stimulate the reflection on how to even improve already proposed fog systems with the right design measures.

For fog system developers, we provide a brief overview of characteristics, related design measures, and interdependencies to raise awareness of what a fog system can achieve and where potential pitfalls or potential for improvement lies. Enterprises that run edge systems or provide edge devices and cloud providers that seek to collaborate with fog systems can leverage our overviews when describing their requirements for the fog system to work with.

C. Limitations and Future Research

Our study comes with limitations paving the way for future research. With our focus on literature mainly addressing the architecture of fog systems, we were able to derive both relevant characteristics and interdependencies among them in terms of the general design of the system. As we considered the design as most relevant for the quality of a system, we excluded the perspective of operating a fog system that may have an additional impact in combination with the system´s design on the performance towards key characteristics. Future research including the operations perspective could provide additional valuable insights and even enhance the applicability of fog systems.

As the interdependencies among the key characteristics are derived from literature examining design measures for fog systems to perform well on specific characteristics, a practical validation in an experimental fog system setup or empirical validation, for instance, through expert interviews is required.

To further improve the understanding of fog systems and enhance both their general quality and applicability, a more thorough analysis of design choices for fog systems to optimize for certain characteristics would be valuable. With that, a guide could be developed that provides an overview of possible design choices and, built upon the found characteristics and their interdependencies, outlines the expected strengths and weaknesses of the resulting fog system

D. Conclusion

As fog systems are highly complex and offer a vast multitude of architectural options on various levels, their design in general and for specific use cases still is a significant challenge. Our research adds structured insights to the existing body of knowledge in the understanding of the most important characteristics for fog systems as well as resulting synergies and trade-offs to look for when setting up fog systems. With that, we inform practitioners by providing applicable design options and their impact and researchers by providing a foundation for further analyses on fog system design.

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