

HOLACONF - Cloud Forward: From Distributed to Complete Computing,  
Towards the Realization of Multi-dimensional Elasticity for  
Distributed Cloud Systems

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**Abstract**

As multiple types of distributed, heterogeneous cloud computing environments have proliferated, cloud software can leverage diverse types of infrastructural, platform and data resources with different cost and quality models. This introduces a multi-dimensional elasticity perspective for cloud software that would greatly meet changing demands from the user. However, we argue that current techniques are not enough for dealing with multi-dimensional elasticity in distributed cloud environments. We present our approach to the realization of multi-dimensional elasticity by introducing novel concepts and a roadmap to achieve them.

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**1. Introduction**

For many application domains, user demands for computing systems are never fixed: even with the same computing infrastructures and software, at different times, our demands can be different due to our constraints on performance, cost, and data quality. For example, such demands are known in an interactive data analysis in the cloud<sup>1</sup> and data analytics of equipment operations in smart cities<sup>2</sup>. Such demands are inherent in distributed, heterogeneous cloud environments, including big, centralized clouds and micro clouds at the edge of the network<sup>3,4,5</sup>, where computation, data and network capabilities from these clouds are increasingly virtualized, provisioned and (re)configured as (pay-per-use) utilities in on-demand manners. To deliver tasks in such flexible ways we cannot model resources, costs, and quality in advance (e.g., by means of autonomic knowledge model<sup>6</sup>) due to changing requirements from applications and changing capabilities and (high) availability of distributed cloud resources. That is, depending on the requirements of resources, costs and quality in particular contexts, such as taking more data into the analysis to produce a higher accurate result, we control and (re)configure software systems to meet the demands. Eventually, these systems can return to their previous (normal) behaviors, if such demands are no longer needed, or can move to another behavior, which cannot be modeled at design time, nevertheless, can serve the best trade-offs of resources, costs, and quality under the considered context. The elastic behaviors of such systems must be treated from a multi-dimensional perspective, instead of just resources or costs, when they rely on resources from multiple types of cloud systems.

Researchers realize the paramount importance of being able to formalize, monitor and analyze such multi-dimensional elasticity behaviors to fully exploit elasticity features in cloud computing<sup>7,8</sup>. As such dynamic demands are hard to be captured in advance, in our opinion, existing models and techniques, such as autonomic computing and scalability techniques<sup>6,9,10,11</sup>, are not adequate. New methods for elasticity are needed to provide extensible, rigorous ways to enable the development of elasticity adjustment mechanisms to control resources, costs, and quality to quickly deliver the right expectation to the current experienced demands. Such multi-dimensional elasticity adjustment, control and delivery on the basis of resources, costs and quality are fundamental and crucial and have not been addressed so far.

Toward a “complete computing”, this paper aims at highlighting a novel approach on tackling multi-dimensional elasticity behavior that enables the realization of elastic distributed cloud software in multi-cloud environments. The rest of this paper is organized as follows: Section 2 presents multi-dimensional elasticity concepts. Section 3 examines some current effort on support multi-dimensional elasticity in distributed clouds. Section 4 presents how to realize these concepts. We conclude the paper and outline our future work in Section 5.

## 2. Multi-dimensional elasticity in distributed cloud computing systems

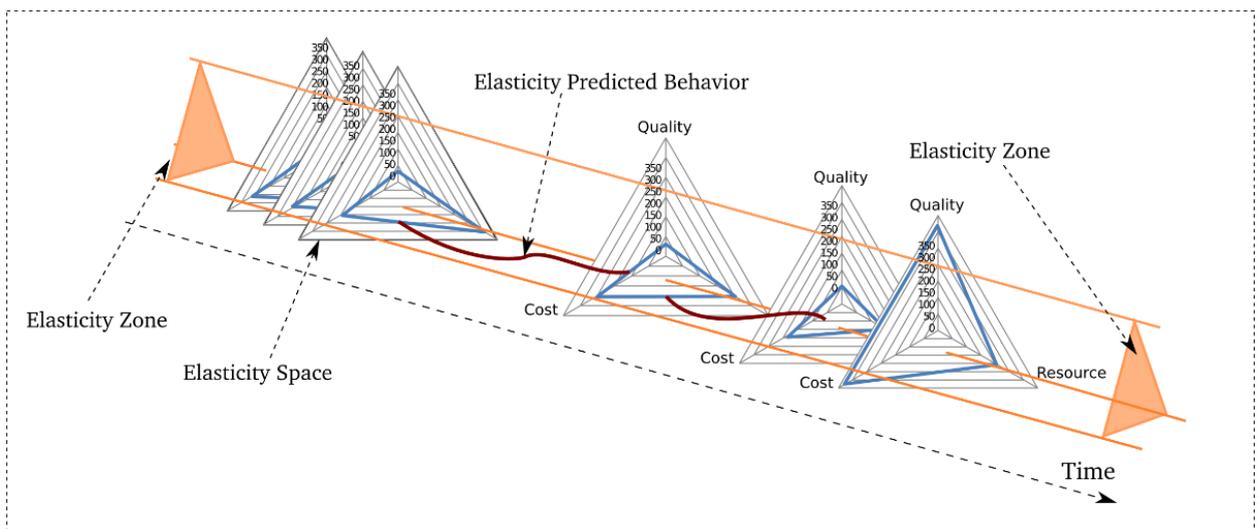


Fig. 1. Elasticity Space, Elasticity Zone, and Elasticity Prediction and Adjustment Functions

Elasticity as a multi-dimensional perspective could be divided into Resources, Costs, and Quality dimensions<sup>12</sup>. Each dimension can be further divided into sub dimensions. For example, Quality can cover performance (response time, availability, etc.) and quality of data (e.g., accuracy and completeness). Resources could be machines in data centers, lightweight IoT gateways, or data from sensors or data marketplaces.

**Which are new concepts for multi-dimensional elasticity?:** Consider a multi-cloud software system<sup>1</sup> whose elasticity is being investigated. Through the time of the system execution, shown in Figure 1, we propose the following important concepts that must be supported for multi-dimensional elasticity realization:

- **Elasticity Zone:** is the required elasticity of a cloud software system that is described by specifying acceptable values for resources, costs, and quality. In distributed clouds where resources are mainly virtual machines/computing resources whose functionality is not really changing, it is highly expected that Elasticity Zones would be based on costs and quality, as resources can be derived from costs and quality. However, when applications require other types of resources whose functionality is changing, such as continuous streaming data resources, Elasticity Zones could specify a combination of resources (e.g., sources of data) and costs and quality

<sup>1</sup> Hence, we use “cloud software systems” in a loosely meaning: it can represent the application, SaaS, PaaS, or IaaS



Project	Multi-Cloud Elasticity	Edge and Cloud Elasticity	Elasticity Zone	Elasticity Space	Elasticity Prediction	Elasticity Adjustment
CELAR <sup>13</sup>	<b>partially.</b> It does not have a coordination among elasticity in different clouds	<b>partially.</b> It enables coordinated elasticity between IoT resources and cloud services <sup>14</sup>	<b>partially.</b> It support static zones through constraints without time-dependent function, although zones can be changed manually during runtime	<b>partially.</b> It partially builds elasticity spaces by interfacing to several cloud monitoring tools	<b>no</b>	<b>yes.</b> Its elasticity strategies and elasticity primitive operations are mapped to underlying operations, such as scale in/out
HARNES <sup>15</sup>	<b>no</b>	<b>no</b>	<b>partially.</b> It uses static thresholds for SLO defined from typical performance metrics	<b>no</b>	<b>partially.</b> It supports prediction for web applications using existing workload and statistical models <sup>16</sup> and for job-level objectives with re-configurable accelerators <sup>17</sup>	<b>yes.</b> It supports scale out/back of VM/machine resources
MODAClouds <sup>18</sup>	<b>yes.</b> It supports cloud bursting and centralized autoscaling controller <sup>19</sup>	<b>no</b>	<b>partially.</b> It supports thresholds defined based on typical performance metrics.		<b>partially.</b> It estimates cost and performance at the design time <sup>20</sup>	<b>yes.</b> It uses Models@runtime techniques
PaASage <sup>21</sup>	<b>yes.</b> soCloud <sup>22</sup> supports a centralized coordinator for elasticity within individual clouds	<b>no</b>	<b>partially.</b> It supports zones through constraints of typical performance metrics		<b>no</b>	<b>yes.</b> SRL <sup>23</sup> supports elasticity adjustment, mainly for VM resources.

Table 1. Multi-dimensional elasticity support in some EU projects. When we do not have enough information for analyzing a feature, we let the evaluation of the feature blank

### 3. Current Effort in Multi-dimensional Elasticity in Distributed Clouds

In this section, we analyze the current effort from different EU research projects on support multi-dimensional elasticity based on our concepts defined in Section 2. Table 2 outlines some state-of-the-art *multi-dimensional elasticity* support in several EU projects. The analysis is based on the publications available from these projects. Although several of these project support multi-cloud deployments, little support is for *multi-dimensional elasticity* across different clouds, e.g., in the sense of coordination-aware elasticity<sup>2</sup>. Clearly, most projects support elasticity in single clouds then they extend single cloud elasticity for distributed clouds. Thus, features for elasticity adjustment are mostly supported for scaling in/out actions for VM/machine resources and elasticity zones are simply pre-defined constraints for thresholds of traditional metrics, like response time and resource cost. Projects, like MODAClouds and PaaSage, focus on multi-cloud applications, thus they introduce basic multi-cloud elasticity using centralized coordination models. Important concepts in our view, such as Elasticity Zone, Elasticity Space and Elasticity Prediction, have not really been investigated for elasticity in distributed clouds, let alone for distributed edge and cloud systems.

### 4. Realizing Multi-dimensional Elasticity

#### 4.1. Elasticity space and zone

##### 4.1.1. Elasticity Zones

###### **Limitations of current approaches:**

Although constraints on elasticity can be specified through rules, such as in<sup>24</sup>, a formal model of Elasticity Zones has been never proposed. The current way of using rules/policies fails to capture the dynamics of Elasticity Zones w.r.t the time associated with and the properties specified within elasticity requirements. Another issue is that these rules have not covered resources in multi-cloud environments, e.g. data and computing resources from the edge<sup>4,5,25</sup>. Furthermore, we tend to think that Elasticity Zones, as constraints for elasticity, should be defined by the user (developers, operators and providers). However, Elasticity Zones are not just defined by the end user or the provider (by means of rules) but it can be generated automatically by intelligent software.

###### **Approach to multi-dimensional elasticity realization:**

At first, the characteristics of elasticity properties including the value ranges need to be studied. Currently, the main elasticity properties are the number of resources and the prices to be paid; not to mention that elasticity properties based on CPU and memory are too low-level. However, they are not enough, as we need to consider properties about data resources as well as, e.g., sensors and actuators, which are popular in distributed micro clouds<sup>25,5</sup>. Once we define elasticity properties in terms of attributes specified via their mathematical domains and ranges, we can model the formal model for Elasticity Zones by an n-dimensional manifold of which a dimension of an appropriate combination of elasticity properties is event-dependent. Although Elasticity Zones are described through requirements, zones are not static but are associated with events which determine the zones. Examples of such events are a human in the control loop, a prediction function, or simply a pre-defined time trigger. Thus, while the elasticity properties in an Elasticity Zone might not be changed, the values of these properties might be changed.

##### 4.1.2. Elasticity Space

###### **Limitations of current approaches:**

One can see that Elasticity Space is no more than a set of multi-dimensional datapoints, each point representing a set of metrics. Thus, it can be captured by existing monitoring systems<sup>26,27</sup>. However, the concept of Elasticity Space has an important characteristic: due to changes in the requirement, the number of dimensions (or metrics) is not fixed at runtime. A consequence is that cloud monitoring systems should not monitor a fixed set of metrics, which may either not support enough monitoring data for elasticity analysis and control, or may introduce too much monitoring overhead for producing unneeded metrics. Able to support adaptive instrumentation and monitoring of elasticity properties requires a major change in how to engineer cloud monitoring, especially for micro clouds deployed at the edge<sup>3</sup>.

###### **Approach to multi-dimensional elasticity realization:**

An appropriate formal representation of Elasticity Spaces will correlate concrete elasticity property values and sup-

port changes of property values over time. First, we focus on *algorithmic models for Elasticity Space function* for determining Elasticity Space based on their defined Elasticity Zones. We need to provide generic functions for determining and analyzing Elasticity Space, including detecting when a software starts being elastic and ends, and why (under which forces and requirements). We then develop a comprehensive set of Elasticity Space detection function implementations for different common software patterns (e.g., cloud-based patterns) Second, given an Elasticity Space, we need to also develop *operators on Elasticity Spaces*. For example, Elasticity Spaces characterizing different software components can be expected to be merged by a particular operator to create a new Elasticity Space to represent a composition of these components. Such operators will be useful for implementing adaptive elasticity monitoring through monitoring data integration and fusion.

#### 4.2. Elasticity analysis and prediction

##### Limitations of current approaches:

We can categorize elasticity analysis in the cloud into: (i) frameworks which monitor cloud systems, (ii) monitoring frameworks which are elastic, and (iii) monitoring frameworks for elastic properties. However, many of them are not much different from traditional performance analysis - albeit supporting new metrics and running in the cloud. For example, a scalable framework for data collection and aggregation is introduced in<sup>28</sup>. The cost of Amazon EC2 spot instances is analyzed in<sup>29</sup>, and<sup>30</sup> discusses cost-effective strategies for using such instances. The work in<sup>31</sup> improves existing monitoring systems using custom metric aggregation scripts and service model information. A mechanism for adapting cloud allocation is presented in<sup>11</sup>, using an aggregator that monitors the workload at each service tier. In<sup>27</sup> cloud resource usage is monitored. The works in<sup>32</sup> and<sup>33</sup> present comprehensive monitoring systems collecting both virtual infrastructure and service level information. Monitoring performance and data delivery is also the focus of<sup>34</sup>, tailored for a specific virtualization framework. An elastic monitoring framework for cloud infrastructures is presented in<sup>26</sup>.

Predicting elasticity work, such as<sup>35,36</sup>, is still very much focusing on a single dimension. Such analysis is not enough. We need to focus on elasticity relationships. Work like in<sup>37</sup> is just an initial step because they focus on building the platform but definitions and algorithms for understanding complex elasticity relationships among components are still open.

##### Approach to multi-dimensional elasticity realization:

First, one important class of algorithms is *for elasticity dependency analysis* which can help us to understand novel metrics characterizing the elasticity dependencies among different components of an elastic system. These functions address several important questions, such as which part of the software system can be elasticized and under which context? We have learned from the Amdahl law that certain parts of an application cannot be parallelized and it does not make sense to parallelize these parts if we would like to achieve a higher speedup for the application. Is a similar point valid for elasticity? Which parts of an cloud system should be in the focus of the elasticity control, and why? Answering these question also helps us to determine where we could focus the elasticity controls to meet elasticity requirements. Hence, the dependencies among different parts of cloud systems w.r.t. elasticity capabilities must be detected.

Second, we should focus on *algorithms for elasticity prediction function*. Formally, a prediction function  $epf$  would take two parameters:  $ez$  as an Elasticity Zone and  $es$  as an Elasticity Space. Then the function  $epf(ez, es)$  would produce a predicted Elasticity Space  $pes_o$ ,  $eps(ez, es) \rightarrow pes_o$  which illustrates the predicted elasticity behavior. Since prediction is a complex matter, we should focus on developing a comprehensive set of elasticity prediction functions for common software patterns<sup>38</sup> and common elasticity views (e.g., cost-centric, quality-centric, single cloud site, cross clouds, etc.). The rationale is that these patterns and views are building blocks of complex distributed cloud software; having such functions for them would make substantial impact on programming elasticity in cloud software.

#### 4.3. Elasticity Patterns

##### Limitations of current approaches:

There exist performance and scalability best practices and patterns in cloud<sup>39,40</sup> but not really elasticity patterns, although we see cloud patterns discussing elastic components<sup>38</sup>. For elasticity adjustment functions to change the elasticity behavior, underlying platforms on which an elastic system is running has to supply management functions

which, e.g., can adjust the resources a software uses, the performance of a database, and the throughput of underlying network function. We have seen such functions in different types of clouds and cloud network systems, but there is a lack of unified way to capture and represent them. Furthermore, management functions for distributed micro clouds at the edge have not been studied together with centralized clouds to provide a uniform view on cross distributed cloud elasticity. Therefore, it will be very hard for programming elasticity features across multiple clouds.

#### **Approach to multi-dimensional elasticity realization:**

To overcome specific set of management functions for specific platforms, we need to work on a *common model for Elasticity Primitive Operations* (see Figure 2) that will be offered via API. We need well-defined APIs for elasticity primitive operations. The tricky part is to have a common view on multi-dimensional elasticity w.r.t. resources, cost, and quality so that such primitive operations will be supported across cloud environments, including clouds at the edge, using common notations. We can collect existing solutions and patterns into a knowledge base that can be queried to identify common software patterns associated with elasticity behaviors learned from, e.g., machine learning techniques<sup>41</sup>. In parallel, developers and providers can develop different elasticity adjustment functions for different patterns in their systems. Several benchmarks and profiling configurations would be then executed to collect elasticity behaviors, and machine learning is used to understand elasticity. In the knowledge base a set of Elasticity Primitive Operations will specify elasticity capabilities for individual components, topologies of components, or the whole system. Both user-defined and machine learning mechanisms are supported for establishing elasticity capabilities.

Another important issue is to *deduce Elasticity Patterns*. Based on the information collected, existing elasticity solutions and patterns are analyzed to deduct new elasticity patterns from the document solutions and to extend the existing elasticity patterns. This also deals with composite elasticity patterns which are built from multiple of these fundamental patterns in a coordinated fashion.

#### *4.4. Elasticity Adjustment Function*

##### **Limitations of current approaches:**

One of the most active research tracks in elasticity is for elasticity control or adjustment. Yang et al.<sup>9</sup> support just-in-time scalability of resources based on profiles. Kazhamiakin et al.<sup>42</sup> consider KPI dependencies when adapting the service based applications. PRESS<sup>43</sup> and CloudScale<sup>44</sup> are examples of application resource elasticity frameworks which use prediction for reducing the number of over and under estimation errors. Malkowski et al.<sup>45</sup> support multi-level modeling and elastic control of resources for workflows in the cloud. Guinea et al.<sup>46</sup> develop a system for multi-level monitoring and adaptation of service-based systems. Different research works have focused on elasticity control of storage resources and quality, e.g., for deciding how many database nodes are needed<sup>47</sup>. Wang et al.<sup>48</sup> propose an algorithm for software resource allocation considering the loads, analyzing the influence of software resources management on the applications performance. Yu et al.<sup>10</sup> propose an approach for resource management of elastic cloud workflows. Kranas et al.<sup>49</sup> introduce elasticity as a service cross-cutting different cloud stack layers (SaaS, PaaS, IaaS).

While we can use such specific models for adjusting specific aspects in multi-dimensional elasticity, there is no theoretical foundation on how elasticity adjustment functions should look like by combining these models for multi-dimensional elasticity realization. Moreover, adjusting resources, costs and quality in micro clouds is not in the focus and is not coordinated with adjusting centralized cloud resources.

##### **Approach to multi-dimensional elasticity realization:**

The Elasticity Adjustment Function controls elastic software to ensure that their Elasticity Space should move within the expected Elasticity Zone. First, this will have to deal with different scales: individual components, topologies of components, and the entire software systems. Second, such adjustment functions can be developed for single clouds or multiple clouds. We develop such functions based on the following steps:

*Step 1: Elasticity Pattern Selection:* Elasticity behaviors will be used by the Elasticity Adjustment Function to determine the right elasticity control actions (and configurations). Thus, we search the right patterns that should be used to control the elastic systems.

*Step 2: Select primitive operations:* The cause and effect of primitive operations must be determined in order to select the right actions for the adjustment. In the knowledge base, we must parameterize primitive operations to estimate their effect, as it is likely that effect information in the knowledge base is not enough.

*Step 3: Selecting and generating Elasticity Adjustment Function:* We envision that each Elasticity Adjustment Function must be defined in particular views (e.g., topology or deployment sites) of a cloud system. Hence, we model an Elasticity Adjustment Function as a workflow of Elasticity Primitive Operations with concrete parameters suitable for the given context. When information about the topology and patterns are clear, we might pickup an existing adjustment function to apply. However, different techniques and AI planning methods would be useful for the generation or parameterization of a new or existing Elasticity Adjustment Function. However, we do not believe that automatic generation will work on all cases, e.g., for interactive elasticity adjustment. Therefore, humans are needed to augment the generation process or solving the conflicts- through the so-called human-in-the-loop management in elasticity operation management<sup>50</sup>.

## 5. Conclusions and Future Work

To exploit elasticity capabilities of multiple distributed cloud resources spanning through centralized data centers and edge devices, we need to focus on novel concepts supporting multi-dimensional elasticity. We explain why more formal concepts and rigorous development need to support multi-dimensional elasticity. From a detailed analysis of the state of the art, we show our approach to the realization of multi-dimensional elasticity by integrating various concepts into the lifecycle of cloud software systems. Currently, we are extending our iCOMOT prototype<sup>2</sup> with these concepts. We are testing them atop distributed, heterogeneous cloud computing environments.

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