Adopting Notions of Complexity for Enterprise Architecture Management

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Abstract

Complexity considerations of enterprise architectures (EA) have become an emerging topic in EA research. However, a brief look into literature reveals a great variety of complexity notions due to the lack of a set definition. In this paper, we identify eight aspects of complexity frequently examined in well-known complexity science literature and group them into four independent dimensions. Based on these, we propose a framework and simple notation to enable authors to explicitly document their interpretation of complexity. Thereby, we hope to get one step further in achieving a shared understanding of complexity in the field of EA research. In order to demonstrate the framework's applicability, we provide an overview of existing literature on complexity of EAs and apply the framework to identify respective complexity notions. Using this approach, we were able to determine currently underrepresented notions of complexity which might be interesting for future research activities.

Keywords

Complexity, enterprise architecture, literature review.

Introduction

Over the last decade, complexity science has become of interest for many scientists. Besides general complexity research many disciplines have developed their own subfield applying general findings to a specific context. There is, for example, complexity economics (Beinhocker, 2006) as counterpart to traditional economics, complex systems biology (Snooks, 2008) and social complexity (Eve et al., 2009). While each of these subfields was able to contribute to its respective discipline in various ways, there is still no agreed-upon definition of the term complexity (Johnson, 2007). The missing conceptual framework and the varying interpretations of complexity in different contexts complicate the field's common acceptance. The same is true for the context of enterprise architecture management (EAM) research. System theory, cybernetics and complexity have been pervasive in EAM literature for several years. Nevertheless, it still seems to be a separate stream of research which is not aligned properly to general EAM research activities. Since various EA researchers apply different notions of complexity, the field's progress is difficult to grasp. Therefore, in this article, we present four different dimensions–each comprising two opposing complexity notions–derived by analyzing well-known complexity science literature. These dimensions can provide clarity about complexity notions and allow researchers to express their individual notion with an agreed-upon vocabulary. Furthermore, we show that the derived complexity dimensions are independent of each other and are usually combined in arbitrary ways. Based on the resulting framework we are able to categorize existing literature concerning complexity in the context of EAM, which we demonstrate by several examples. Thereby, we identify some white spots which might be interesting for other scientists in order to target their research into those directions.

General Complexity Notions Derived from Literature

In the glamour of various success stories, complexity science is still an interdisciplinary research area without a commonly agreed definition of complexity. As a result, it is not surprising that different views of complexity emerged over time. We propose a multi-dimensional framework unifying the most prevalent views on complexity. This enables researchers to clearly state which notion of complexity they are using and might also point to aspects of complexity, which are still underexposed in literature, in particular in EA research. We present four dimensions of complexity, which help to specify independent aspects of complexity.

Organized complexity versus disorganized complexity

The first dimension is based on the number of variables to be considered (Weaver, 1948). It makes a difference, if the system under consideration is described by just two or three variables or by more than one billion. To illustrate the difference, compare the analysis and prediction of a single ivory ball's motion on a billiard table to the analysis of 15 balls each colliding with each other and the side rails. Interestingly, the table with millions of balls might be easier to analyze than the table with 15 balls. The reason is that statistical methods become applicable when millions of balls roll over the table. Although the motion history of each ball cannot be traced, certain important questions such as "On the average, how far does a ball move before it gets hit by another one?" can be answered with practically useful precision. In this sense, disorganized complexity refers to a large number of variables with individually inconsistent variables or with an unknown number of variables. Despite the unpredictable dynamics of particular variables, the system as a whole has specifically ordered and also analyzable attributes. An example for disorganized complexity is the calculation of a police holder's lifetime for life insurers. While it is not possible to predict the exact time of death of a single policyholder, the average life expectancy of customer segments can be determined rather easily. In contrast, organized complexity refers to a moderate number of variables, which are part of an organic whole due to their strong relations. For instance, consider all factors influencing the price of butter. There might be a considerable number of variables, but they can be counted and related due to their influence on the price. In such case, statistical methods are inappropriate since the type of interrelation is often unclear and some variables, e.g. the actual need of customers, are hard to measure.

Qualitative complexity versus quantitative complexity

The second dimension distinguishes between quality and quantity. Thereby, qualitative complexity refers to the qualitative evaluation of a certain attribute of variables or a system. An example is the "El Farol Problem" (Arthur, 1994). In this multiple-stage game, participants have to decide whether to visit a bar or not in each round. They all prefer to enjoy a drink at the bar rather than staying at home, but the bar has a maximum capacity of seats. Of course, it is less enjoyable to attend an overcrowded bar than staying at home. For each round, it can be determined whether a participant does attend the bar or not and whether he is better off doing so. Remembering the decisions on the other hand will not provide new insights for the next round since the participants´ decisions might change in each round. This game is considered to be a complex problem which needs to be solved by every participant every round. The value of a decision depends on the decisions of all other players. This type of complexity is independent from the number of players, the number of rounds or the memory capacity of players. Researchers studying complex system phenomena use a qualitative notion of complexity as well, such as self-organization (Kauffman, 1996), emergence (Anderson, 2002) or dynamical systems (Gardner, 1970).

Other researchers apply a quantitative notion of complexity. Kolmogorov (1998) proposed a classic measure of quantitative complexity. The Kolmogorov complexity is the length of the shortest computer program capable of generating a given string. Another fundamental quantitative measure to which many complexity measures relate is entropy (Shannon and Weaver, 1949), which can be understood as a measure for uncertainty in a message. Other approaches have been developed to measure (computing) complexity as well, for instance, based on the number and variety of both components and their interactions within a system (Schneberger et al., 2003). Quantitative measures suggest that the quantity of a particular property directly influences complexity. For instance, computer scientists describe the complexity of algorithms as a function of input length. Algorithms are classified according to their asymptotic behavior for large inputs using Landau notation (Bachmann, 1894). Typically, the number of calculations or the amount of memory consumption is of interest to determine algorithmic complexity.

Subjective complexity versus objective complexity

The third dimension of complexity is based on the role of the observer. Objective complexity refers to a notion of complexity that is independent from the observer. Complexity is considered to be a property of the system under observation, much in the same way as mass or volume of a physical body (Fioretti, 1999). Such objective views are prevalent, for example, in the domain of qualitative complexity where system properties like emergence (Anderson, 2002) are investigated. The same applies to most of the developed complexity metrics as their results are free of individual influence (Landauer, 1988).

However, complexity can also be considered to be a property of the relationship between a system and its observer (Rosen, 1977). Thereby, the observer will perceive a system as complex if his/her mental model of the system cannot explain his/her observations. In contrast to the objective complexity notion, the subjective complexity is bound to the existence of an individual observing a system. Researchers define subjective measures, for instance, based on mental categories of the observer (Fioretti, 1999) or as being composed of other objective measures (Flückiger et al., 1995).

Structural complexity versus dynamic complexity

One pole of the fourth dimension is known as structural complexity, which is also known as combinatorial or detail complexity (Sterman, 2000). It covers a pattern of system components, i.e. the number of variables as well as the cause-and-effect-relationships between them. A structural perspective is employed, for example, in network research where cyclic groups, spanning sub-graphs and extended connectivity play an important role (Bonchev et al., 2005). The two well-known measures of complexity, i.e. Kolmogorov complexity (Kolmogorov, 1998) and entropy (Shannon et al., 1949), also apply a structural notion of complexity.

In contrast, dynamic complexity refers to the observation of the multifaceted interdependencies as well as changes of interactions between variables of a system. Therefore, “dynamic complexity arises from the interactions among the agents over time” (Sterman, 2000). In complex systems, the impact of actions often cannot be reversed. Therefore a comparison between system states in the past and the current one is rather difficult. With several interacting feedbacks, determining an exclusive effect of a certain variable is hardly possible since it is likely that other variables change as well. As a consequence, the system behavior interpretation is usually complicated. Additionally, delays in cause and effect have to be considered, which can result in system instability and influence the dynamics of a complex system. Dynamic complexity arises, for example, when systems are strongly interacting with each other and the natural world or if actions influence future choice options (Sterman, 2000). The dynamic complexity notion has also been applied in socio-economics (Forrester, 1961).

A Framework based on the Identified Complexity Notions

Based on the complexity notions identified in the previous chapter we will now develop a framework in order to be able to categorize existing literature as well as to provide a consistent taxonomy. Therefore, we first show that the identified dimensions are independent from each other. Second, we provide a visual vehicle and corresponding notation to explicitly document individual complexity notions.

Independence of complexity dimensions

Each of the introduced dimensions covers two opposing notions of complexity where each has been applied many times during the last decades. Thereby, all four dimensions are independent but not exclusive. That means that each notion of a given dimension can be combined with every other notion from the other dimensions. We will demonstrate this by providing examples for arbitrary combinations of complexity notions.

Stephen Wolfram became famous for his groundbreaking work in the study of complexity and cellular automata (Wolfram, 1994). For example, he classified one-dimensional cellular automata based on their dynamic behavior. Thereby, he combined the notion of dynamic complexity with the notion of objective complexity since individuals are not involved in the classification process. It is solely based on the patterns created by a cellular automaton. Since the four classes introduced by Wolfram follow a nominal scale rather than an ordinal scale he also applied the notion of qualitative complexity instead of measuring the complexity of cellular automata.

Sterman (2010) applied another combination of complexity notions in the domain of dynamic complexity. In his research, Sterman analyzes how people understand (subjective complexity notion) the behavior of complex systems (dynamic complexity notion). His results show that there is a widespread misunderstanding of stocks and flows, even among highly educated adults. By assuming that there are different degrees to which people are able to understand complex systems he also applies a quantitative notion of complexity. By comparing the work of Sterman with the work of Wolfram we see that both apply a dynamic notion of complexity, but combine it with different notions of the other dimensions.

A similar diverse combination of complexity notions can be found in the area of structural complexity. Milgram (1967), for example, analyzed the structure of complex networks like social graphs and came up with the famous small-world property. It is obvious that he applied an objective complexity notion since the network was analyzed without regard to the relationship with its observer. He also applied a qualitative notion of complexity since his goal was not to measure or to rate the complexity of social graphs but he tried to explain why the median in his experiment was only six hops in the social graph of arbitrary people who tried to deliver a letter to a randomly chosen person.

Frese (1987) developed the idea of comprehensive complexity describing the relationship of a software user to a software system. He applied a structural notion of complexity during his analysis since he introduced patterns as a means to reduce complexity but he realized that the complexity differs dependent on the user. Therefore, he combined the structural notion of complexity with the subjective notion. If the degree to which patterns are present in a software system determines the individually perceived complexity of the user, then Frese also applied the quantitative notion of complexity. By comparing Milgram's with Frese's work we can see again that the same notion of complexity in one dimension (structural) can be combined with different notions of other dimensions (subjective and objective). Hence, we conclude that basically all four identified dimensions of complexity notions are independent of each other since they can be combined in arbitrary ways.

A visual vehicle combining the complexity dimensions

By providing four examples how scientists have combined the previously identified dimensions of complexity we demonstrated their independence. This allows us to design a framework in which each dimension is orthogonal to all the others (see Figure 1).

Therein, the horizontal axis is used to distinguish between the objective and subjective notion – each represented by a single small cube. The vertical axis is used to distinguish between structural and dynamic complexity. The qualitative-quantitative distinction is indicated by the third dimension of the cube. In order to visualize the fourth dimension (ordered and disordered complexity) different colors are used within the cube. The chosen representation clearly shows how the different notions can and have to be combined. We also want to point out that a clear separation of notions within the same dimension is not always possible and that there can be a grey area in between.

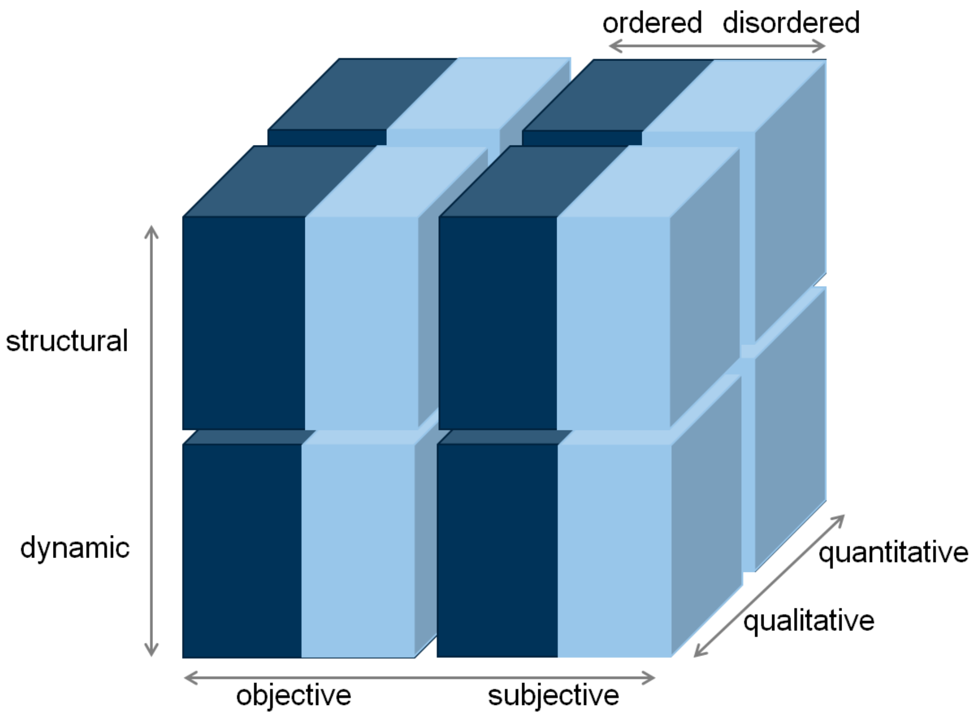

Figure 1. The complexity cube: a framework unifying different notions of complexity.

A simple notation for complexity notions

Although there is no sharp line dividing the two opposing complexity notions in each dimension we propose a simple notation to explicitly document the predominant notions for each work in the area of complexity science. Such explicit documentation facilitates literature research because similar work can be identified more easily.

Since our proposed framework consists of four dimensions, we propose a tuple notation. To define such notation, we first need to define four sets each covering the notions of one dimension:

$$D1 := \{objective, subjective\}$$

$$D2 := \{structural, dynamic\}$$

$$D3 := \{quantitative, qualitative\}$$

$$D4 := \{ordered, disordered\}$$

Based on these sets we can define the set of applied complexity notions (ACN) as a quadruple:

$$ACN := (x_1, x_2, x_3, x_4), x_1 \subseteq D_1, x_2 \subseteq D_2, x_3 \subseteq D_3, x_4 \subseteq D_4$$

For example, if we want to document the applied complexity notions (ACN) of the work of Sterman as introduced in the previous chapter, we can write $ACN_{Sterman2010}$ = (subjective, dynamic, quantitative, ordered).

Demarcating the framework from existing complexity classification work

The concept of complexity can also be found in the information systems (IS) and organizational literature, which mostly centers on task complexity including aspects like component complexity, coordinative complexity and dynamic complexity (Wood, 1986). While the first two aspects apply quantitative, structural and objective notions, the latter applies a dynamic notion. But according to Campbell (1988) task complexity can also be treated as an interaction between task and person characteristics, which applies a subjective notion of complexity (experienced complexity). In the IS discipline, the structure of software as well as performed tasks on software products have been of interest (Banker and Slaughter, 2000). We can see that our proposed complexity framework covers the same aspects as task complexity literature but is not limited to the context of tasks although it does not provide as much details as a context specific framework does.

Applying the Framework to Enterprise Architecture Management

In order to demonstrate the feasibility and benefits of the complexity framework introduced in the previous chapter, we apply the framework to the context of EAM. First, we provide an overview of existing literature concerned with complexity in the field of EAM and provide the ACN tuple respectively. The presented approaches have been identified by performing a structured literature review following commonly accepted guidelines (Webster and Watson, 2003). We consulted the EBSCOhost database, Science Direct, ISI Web of Science and the search engines of ACM, IEEE and Google by using the keywords “enterprise architecture” AND “complex*”. Second, we use our proposed framework to identify prevalent notions of complexity in EA research as well as to indicate currently underrepresented notions.

Categorizing current EA complexity literature

Buckl et al. (2009) applied a complex adaptive system view on enterprises and used Beer’s Viable System Model (VSM) to derive and classify different duties of an EAM function. They distinguish between reactive and proactive tasks as well as EAM governance. Using a well-accepted cybernetic model Buckl et al. were able to provide a framework to categorize EAM tasks in order to assess the completeness of existing EAM approaches and frameworks. The authors have not attempted to measure how complex an organization is (qualitative notion), focused on the structure of each VSM system (structural notion), classified the enterprise as a complex adaptive system (objective notion) and focused on a manageable number of variables (ordered notion). Consequently, we can express their complexity notion as $ACN_{Buckl2009}$ = *(qualitative, structural, objective, ordered)*.

Zadeh et al. (2012) also used the VSM as well as the Viable Governance Model (VGM) to demonstrate how TOGAFs architecture principles relate to cybernetic concepts. The authors showed that the nine business principles of TOGAF can be mapped to concepts like viability, recursion, cohesion, coordination and homeostasis. The authors relied on Ashby’s law of requisite variety (Ashby, 1956) (quantitative notion) but likewise attributed the system with properties such as homeostasis (qualitative notion). The analyzed principles are mainly concerned with the structure of the system and not with its dynamics (structural notion) and they focus on a manageable amount of variables (ordered notion). Consequently, we can classify their work as $ACN_{Zadeh2012}$ = *({qualitative, quantitative}, structural, objective, ordered)*.

Saat et al. (2009) use chaos theory to derive requirements for the design of an EA planning activity. By attributing properties like sensitivity to initial conditions to the enterprise they clearly apply a qualitative notion of complexity. While looking at structural invariance at different scales (structural notion) they also consider an enterprise’s attraction to specific configurations (dynamic notion). Since the observer of the system is not part of their considerations, the authors apply an objective notion. Because the authors do not use statistical methods they apply an organized notion of complexity. Consequently, we can classify their work as $ACN_{Saat2009}$ = *(qualitative, {structural, dynamic}, objective, ordered)*.

Kandjani et al. (2012) use the concept of EA cybernetics to determine the complexity of global software development projects. They measure the complexity by three different indicators, e.g., by the number of relevant states of a system’s environment (quantitative notion). The used complexity metrics are independent of any system observer (objective notion). By asking for the independence axiom within projects, the authors encourage a decoupled design (structural notion). Finally, statistical methods are not part of their approach (organized notion) resulting in $ACN_{Kandjani2012}$ = *(quantitative, structural, objective, ordered)*.

Janssen et al. (2006) regard enterprises as complex adaptive systems and attribute them properties like emergence and self-organization (qualitative notion) in order to derive requirements for a suitable EAM function. In addition, they provide concrete architectural guidelines, which have been used to design an EA function for a governance agency. These guidelines target at both the enterprise’s structure and dynamics. Furthermore, they do not consider the system's observer nor use statistical methods. Consequently, we can classify their work as $ACN_{Janssen2006}$ = *(qualitative, {structural, dynamic}, objective, ordered).*

Mocker (2009) provides one of the first empirical evaluations of complexity measures. The measures used to quantify the application architecture complexity (quantitative notion) include interdependencies of applications, diversity of technologies, deviation from standard technologies and redundancy (structural notion). Obviously, the observer of the architecture is not part of the measures (objective notion) and statistics play a major role (disordered notion) implying $ACN_{Mocker2009}$ = *(quantitative, structural, objective, disordered).*

Dern et al. (2009) describe an IT architecture governance approach based on complexity measures (quantitative notion). The metric regards the number of IT systems, their information exchange relationships and their homogeneity (structural notion). The architect or any other observer is not part of their considerations (objective notion). Similar to other quantitative approaches, their proposed metric for IT complexity aggregates numbers and calculates ratios, respectively (disordered notion). Consequently, we can classify their work as $ACN_{Dern2009}$ = *(quantitative, structural, objective, disordered).*

Kandjani et al. (2013) present a co-evolution path model, which is based on the idea of Ashby's law of requisite variety (quantitative notion). The model shows that each time the complexity of an enterprise's environment changes, the enterprise itself has to adjust its complexity. Since this is a dynamic process (dynamic notion) it is unlikely that the enterprise will exactly end up with the required complexity. Therefore, the model describes the path the enterprise's complexity will take along the optimal complexity. The observer is not part of the model (objective notion) and the influence factors are more of a qualitative nature (ordered notion) implying $ACN_{Kandjani2013}$ = *({qualitative, quantitative}, dynamic, objective, ordered).*

Schütz et al. (2013) present a measure to quantify the complexity of EAs (quantitative notion) based on a literature survey. The measure regards the number and heterogeneity of EA elements and their relations (structural notion). Thereby, the heterogeneity is calculated by using the Shannon entropy. In this approach, an individual observer is not considered (objective notion) and the use of statistical methods is obvious (disorganized notion) resulting in $ACN_{Schütz2013}$ = *(quantitative, structural, objective, disordered).*

Lagerström et al. (2013) applied a concept well known in the software architecture domain, namely Design Structure Matrices, to reveal the structure of an application landscape (structural notion). Thereby, they classify applications based on their dependencies into core, control, shared and periphery applications and calculate the propagation costs, i.e. a measure of the potentially affected AL part when changes to a randomly chosen application are made (quantitative notion, disordered notion). A concrete observer of the architecture is not considered (objective notion) implying $ACN_{Lagerström2013}$ = *(quantitative, structural, objective, disordered).*

Summarizing prevalent complexity notions in EA research

In order to get an overview of prevalent complexity notions in the field of EA research, Table 1 lists the analyzed research papers as well as their classification according to the ACN dimensions in chronological order.

Regarding D_1, we can see that both the qualitative and quantitative notions are pervasive in EA research. Furthermore, we can see a trend from the qualitative notion in the beginning to a quantitative notion in current publications. Regarding D_2, we can see that most publications apply a structural notion of complexity so the dynamic notion is currently underrepresented. Regarding D_3, it is obvious that all analyzed publications apply an objective notion of complexity. We are not aware of any publication in the field of EA research applying a subjective notion. Regarding D_4, we find both the ordered and disordered notion of complexity.

EA Complexity publications	ACN D_1	ACN D_2	ACN D_3	ACN D_4
Janssen et al. (2006)	*qualitative*	*structural, dynamic*	*objective*	*ordered*
Buckl et al. (2009)	*qualitative*	*structural*	*objective*	*ordered*
Saat et al. (2009)	*qualitative*	*structural, dynamic*	*objective*	*ordered*
Dern et al. (2009)	*quantitative*	*structural*	*objective*	*disordered*
Mocker (2009)	*quantitative*	*structural*	*objective*	*disordered*
Zadeh et al. (2012)	*qualitative, quantitative*	*structural*	*objective*	*ordered*
Kandjani et al. (2012)	*quantitative*	*structural*	*objective*	*ordered*
Kandjani et al. (2013)	*qualitative, quantitative*	*dynamic*	*objective*	*ordered*
Schütz et al. (2013)	*quantitative*	*structural*	*objective*	*disordered*
Lagerström et al. (2013)	*quantitative*	*structural*	*objective*	*disordered*

Table 1. Overview of EA Complexity Publications Classified by Complexity Notions

Conclusion

Based on well-known work in the area of complexity research, we derived four prevalent dimensions of different complexity notions regarding the role of: measures, time, observers and statistical methods. By demonstrating their general independence, we developed a framework to explicitly document the applied complexity notions. This framework helps researchers to better understand the work of others and allows them to apply their own choice of complexity notions without having to argue for a specific definition of complexity anymore. In order to demonstrate the framework's feasibility, we applied it to the context of enterprise architecture (EA). The classification of existing complexity work in this area allowed us to identify subjective complexity as an aspect not yet covered by EA research. Although the classification is not always straightforward and a sharp distinction is sometimes difficult we hope that the framework will bring clarity to usage of the term complexity in the field of EA research.

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