Formation and Application of Transformation Knowledge within Dynamic Enterprise Architecture

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Abstract. The study presents the current state of the discipline "Enterprise Architecture" (EA) in the context of digital transformations and architectural models for full-fledged work with these transformations. It is shown that the search for new EA capabilities is associated not with the task of creating EA artifacts but with supporting managers in managing enterprise transformations through the use of EA capabilities. The possibilities of using various EA approaches to reflect the life history of an enterprise as one of the most critical factors in the dynamics of enterprises are analyzed. The approaches "3D-enterprise" and its extension "nD-enterprise", which increase the expressive power of using the resources of time in the life history of the enterprise, are highlighted. Modeling concurrent flows of change is one of the useful properties for managing transformations. The article describes the formation of a scheme of factual, procedural, conceptual, and metacognitive knowledge as a part of EA which includes knowledge not only about the states of the enterprise, but also about the methods and procedures for performing transformations of these states with a reference to the dimension of time. The study shows the use of "nD-enterprise" for solving problems of transformations management of the enterprise based on the indicated knowledge of EA. The actual tasks of EA are considered: the creation and use of the capabilities of the EA for managing the transformation of the enterprise, the flexible but stable implementation of the enterprise strategy, the support of the integrity of EA and some others.

Keywords: Enterprise dynamics, Enterprise architecture knowledge, Enterprise transformation, 3D-Enterprise, nD-Enterprise, Architectural model, Dimension of time

1 Introduction and context analysis

1.1 Background. An overview of the situation

High enterprises variability requires significant abilities of EA in the sphere of seeking and justification of decisions about introducing changes in the enterprise arrangement and these decisions implementation control. At the same time, dealing with changes should consider not only the change drivers generated by the environment and inner enterprise intentions, but also particularities and limitations of real enterprise structure. Thereby the primary attention of this paper is focused on complex and

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large-scale changes of an enterprise as a system which will be denoted by the word 'transformation'. Local changes in the case of changing something in EA are also covered by the examined methods.

It is helpful to consider EA and its models in the context of general turbulence of understanding and of rational application evaluation of both informational technologies and EA discipline. Several years ago, global appeals to across-the-board digital transformation along with cloud computing and agile style propaganda motivated many authors to claim that EA paradigm requires cardinal replacement. Even "EA father", J. Zachman, caved in to this pressure in the publication [1] as his EA framework was under sharp criticism (though in the author's opinion, this criticism was caused by a too primitive interpretation of Zachman's suggestions).

However, not long after, EA discussions became constructive again. The author of this paper conducted the analysis of EA development stating [2] that we deal not with the radical replacement but with the permanent expanding of EA. This conclusion is being justified by growing attention and the number of publications about the necessity and new methods of EA for solving current problems of an enterprise dynamics, in particular, using Zachman Framework (ZF) [3] and its later versions.

One particularity of the moment is the contrariety of classical requirements for EA and the way of practical implementation of these requirements. Zachman suggested regarding EA as the means of accumulation of knowledge about an enterprise, but despite some exceptions, sustainable knowledge forming and management is not observed. It was also suggested that EA should reflect an enterprise change. However, although changes happen with the passage of time, using full value dimension of time in EA is rather an exception than a rule.

1.2 Recent studies and EA tasks

It is specified in [4-6] that introducing EA discipline in organizations is expanding. At the same time, technological destructors and their impact persistently stimulate large-scope transformations in business ecosystems, business units and functions. In these conditions, EA research is still often limited by abilities of ordering the concrete organization resources. However, it is highlighted in the works [4,6] that EA is not just needed as such, but as an ability to quickly solve the problems of enterprise change management and transformation governance and not to just accumulate artifacts.

The papers [7-9] also indicate EA benefits especially in the area of an enterprise dynamics and its information systems (IS) support. It is recommended in [7] to provide profound understanding of key enterprise components dynamic behaviour and formal control of architectural descriptions integrity by means of EA. The studies consider characteristics of a model of an enterprise endeavoring to "change business" in contradistinction to its routine running, and ZF by J. Zachman serves as a framework. The study [8] also builds on ZF and aims at meaty support of the strategic management of small and medium-sized enterprises starting with their business architecture. It should be noted that despite former critical comments many researchers and practices keep using ZF as the conceptual basis.

While considering the corporate IT-architecture, advantage of EA for supporting dynamics looks more evident, especially for IT-infrastructure. Thus, EA examined in [9] is intended for dynamic redefining of optimal cloud allocation of applications and data.

The paper [10] is useful in that it indicates an inadequacy of applying any “extreme” approach in EA. It is noted that AP is often at a point of collision, for example, between proponents of agile approaches and adherents of “nonagile”, “conservative” AP practices, but both of these approaches are just radical simplifications of the real circumstances of the organization. Practice, however, more often requires not one "extreme" ideology, but a set of different approaches meeting different urgent tasks of the enterprise. At the same time, it is indicated in [11,12], as in the publications noted above, that the structures of the EA remain mostly informal in nature, and the interference from the complexity of the enterprise architecture is especially strong with the growth of enterprise variability.

At the same time, there are works aimed at radically more complex and dynamic architectures. So, in [13] the dynamics is extended not only to enterprises, but also to units of its transformable cyber-physical products even after the release of the latter. Note that this can lead to attempts to simulate the dynamics of not only EA as such, but also all the changing elements of reality included in the enterprise environment, which can be quite redundant in practice. Note also that the framework [13] is intrinsically multidimensional; it defines ten architectural dimensions, but there is no time dimension among them. At the same time, the authors admit that many real situations are only intended for study yet.

The paper [14] classifies schools and methods of EA and indicates the qualitative differences of EA at the current stage of "cognitive revolution", and at the stages of previous "revolutions". To reflect the dynamics, the authors, on the one hand, use a conservative division of work with EA into phases, and on the other hand, replace the analysis of the classical EA transition from "as-is" to " to-be " by so-called continuously conducted analysis. Note that this having no alternative replacement seems too “revolutionary”, and that even in the radical work [13] it is reported that the proposed suggestions do not replace, but expand existing architectural schemes and methods.

It is also essential to note a substantially updated revision of the standard fundamental for EA [15] that has recently become operative, where the definitions and requirements for EA and for modelling the enterprise and its EA, including the use of elements of the GERAM approach, are confirmed and refined.

As for EA as a repository of enterprise knowledge, the occurring attempts to consider EA as a discipline of knowledge management or as a means of transforming knowledge in the work of architects indicate the insufficient fullness and readiness of the EA content [16] and low readiness of many specialists [17] to fully use EA as an important system of enterprise knowledge management. J. Zachman's thesis about EA as a means of accumulating knowledge is confirmed [18], but it is insufficiently developed, as is the formation of the normative ordering of this knowledge.

The described context substantiates the direction of this work which proposes a natural order of knowledge categories in EA focused on their use in the tasks of enterprise transformation. The rationality of the proposed order is justified by demon-

strating the way of its application for solving current problems of enterprise transformation.

2 Methodology and structure of the rest of the paper

2.1 Used interpretations of concepts and their interconnections

Understanding of dynamics is used in the article as changes in any characteristics of an enterprise under the influence of external or internal factors ("drivers"). In EA, changes are considered at the architectural level of description, that is, at the level that is sufficiently specific to take into account the specifics of the enterprise, but which is possibly partly aggregated and generalized. The level of aggregation and generalization of EA entities is determined by the enterprise itself. This level is supposed to provide the enterprise with the abilities for effective achievement of its goals, but retains the necessary freedom for engineering decisions for EA implementation.

Transformation means complex changes:

- of material and ideal objects of the enterprise; the changes which are understood by the people of the enterprise, and, on this basis, explicitly accepted by the enterprise;
- leading the enterprise to a new qualitative state which includes visible changes in the enterprise business model proposed to achieve the declared goals;
- having speed and volume which are sufficient to be included in the sphere of meaningful conceptual and architectural design.

With this in mind, the complete methodology of the study included the following steps:

1. analysis and fixation of constraints of transformation time display, first of all, in the approaches of ZF, GERAM and ISO 15704;
2. determining requirements of real enterprises life stories for the full dimension of time in the approach of 3D/nD-enterprise;
3. definition of categories of knowledge about the enterprise, their place in the models of its architecture and the role in transformations placed in the EA itself;
4. definitions and formalized representations of parallel flows of changes (transformations, their parts) in enterprises;
5. eliciting modern problems of managing EA changes including those described in the publications given in subsection 1.2;
6. consideration of approaches to solving these problems based on the approach of 3D/nD-enterprise and knowledge of EA structured within its framework.

The results of steps 1, 2, and partly of step 4 were described in [19,20] but are also indicated here.

2.2 Structure of the rest of the paper

Section 3 reflects the limitations of the main approaches that formed the EA discipline in part of the dimension of the time of enterprise changes. Section 4 specifies the main features of the 3D/nD-enterprise approach, introduces definitions of the knowledge categories about transformations associated with EA, and specifies some EA entities required for transformation management. In Section 5, the approach described in section 4 is discussed through the prism of current EA problems and tasks. In Conclusion, the result of organization of EA knowledge in the 3D/nD-enterprise approach is formulated and the directions for further research and their application are determined.

3 Limitations of the approaches that formed the dimension of time in EA

3.1 Architectural schemes and models of explicit work with time

At the end of the last decade of the 20th century, the first group of approaches, models, and standards was proposed explicitly working with the dimension of the time of enterprise transformation [19-22]. Also in an explicit form, the ISO 15704: 2000 standard [22] fixed the term "life history" of an enterprise which defines an ordered description of a set of enterprise change events tied to a time axis and including many life cycles of transformations. However, the introduction of the dimension of time in these approaches provided different, often insufficient levels of architectural capabilities which will be discussed below.

Much later, a second group of approaches and models emerged suggesting different tools for describing temporal aspects. In works [23,24], the extension of DoDAF framework with universal descriptors of temporal aspects was considered for using them in different EA entities. In [25,26] temporal aspects were proposed for the retrospective analysis of changes in the enterprise performance indicators, as well as for searching and correcting incorrectness in the descriptors of the enterprise's activities. However, these proposals cannot be considered widely spread. It can be assumed that in the case of [23,24], the path from the entities in formal ontologies reflecting primitive temporal concepts to the practical use of the dimension of time by economists, market experts, and other enterprise professionals involved in EA development is too long. In the case of [25,26], each of the proposed approaches aims at solving an important, but a single particular problem. The foregoing is the reason why the abilities of the first group of approaches, models, and standards [19-22] will be considered here, especially as they are actualized nowadays.

3.2 Limitations of J. Zachman's framework, GERAM methodology, and ISO 15704

The ZF framework and Zachman's rules are often interpreted in a simplistic way, as almost mechanical filling the rows of cells in the corresponding table strictly from top to bottom [3]. However, this interpretation contradicts to what Zachman wrote later about his framework application in practice. Besides, the Zachman's framework remains, as shown in Section 1, a meaningful approach to structuring and discussing an enterprise representation, with the ability to move easily from integrated EA models to an in-depth consideration of partial models, aspects, and viewpoints.

Despite its value, this framework has serious limitations and contradictions. The transformation time of the enterprise is represented practically by only two states ("as-is" and "to-be") and the sequence of the EA design phases implicitly related to the time axis, but only within one time slice of EA. A detailed discussion of the shortcomings of time representation in ZF can be found in [27 part 1].

The GERAM framework [21] is more accomplished due to the explicit use of the time axis as the dimension to which the events of the enterprise life history are attributed, which is also included in ISO 15704 [22]. However, this time axis is considered mostly as an illustration and is not graded as needed by architects in particular cases, but only by reflecting on it the standardized phases of the EA transformation life cycle. Thus, the {Views, Life-cycle phases} plane of the GERAM framework carries limitations similar to those of ZF. These limitations are also inherited by ISO 15704 standard in all editions up to [15].

4 3D/nD Enterprise Approach and Model

The limitations and contradictions of the Zachman Framework described above prompted the author of this work to propose a more developed approach and framework to reflect the time of enterprise transformations in the late 1990s. After several discussions and experimental applications in 1997-1999, this approach description was published in 2000 in the article [19] and, in a more complete form, on the resource "CIT-Forum" as the article "3D-enterprise - a model of the strategy of a transforming system" [20]. These publications included the possibility of increasing the number of dimensions of the framework which gives rise to the nD-enterprise approach. The main abilities of using the 3D/nD model are also described in [27 part 1]. For this reason, the main features of this approach will be only briefly named below, and the essence and principles of knowledge organization in EA, related to the time of its transformations, will be presented in more detail.

4.1 3D/nD-enterprise

In the 3D/nD approach, EA is represented by a set of states of the EA model ordered by reference to the full-fledged dimension of time. Distinctive features of the 3D/nD-enterprise approach are:

- Description of not two, but many states of an enterprise in time as a set of logically integral sets of its cell models (these cell models are similar to cells in the ZF) for different moments and/or intervals of time by explicitly introducing the axis of astronomical time.
- Reflection of the enterprises dynamics for different echelons of management at different time horizons by splitting the dimension and axis of time into two or three sub-axes on which states and events of short-term, medium-term and long-term plans and actions respectively are located.
- Reflection of real multithreading of making changes to EA in which different working parts of the architecture (WP - working parts of the EA, EAWP) are changing each with their own speeds and, conditionally, in their own streams of time, partially in parallel - synchronously or asynchronously - with other parts of the architecture, but while maintaining the ability to synchronize actions and control the integrity of the EA content.
- The approach openness, in particular, to changing the set of project phases or stages of the enterprise development program and to possibilities of expanding the number of dimensions by adding important for managing the running of the architectural process and the development of the enterprise as a whole. Examples of such dimensions are "Generalization-concretization", "Specialization and competence of personnel" (including subject experts, IS developers and enterprise architects), "Methods and tools for modeling", "Technological units and agents" (including people, industrial robots, software agents), etc.

One of specific problems solved due to the described differences is the use of forecasts fragments of EA state in the long-term horizon to form the EA state in the short-term horizon. The purpose of this is to increase the validity and sustainability of architectural solutions in general. An illustrative scheme for solving this problem is given in [27 part 2, Fig. 2]. The dimensions of nD-models can support work with investment support for the development of an enterprise (for example, in the form of analysis of an investment projects portfolio), with an analysis of the effectiveness of the proposed IS and IT blocks, for example, determining the degree of usefulness of specific services to ensure the work of an end user or services of other levels.

For nD-models, the requirement was introduced to define the links of each model-cell with the nearest cells reflecting the previous and future states of the architecture component to reflect the actions and the overall progress of the transformation. On this basis, we can talk about the change in EA in time both at a large-aggregated level of phases and stages of development and at the micro level of changes in particular elements of EA.

4.2 Formation of knowledge components categories about transformations for including them into models of 3D/nD-enterprise

The definition of the EA knowledge components is given using a number of working architecture constructs.

The state of the EA model at the moment $t_{(n)}$ is considered as an integrated model $EAM(t_{(n)})=\{cem_{i,j,t} |_{i=1 \dots I,\ j=1 \dots J,\ t=t(n)}\}$. Here $cem_{i,j,t}$ is an analogue of a primitive model or cell in ZF (row and column intersection) or the intersection of the life cycle phase and aspect on the Vies axis in GERAM. The main differences in 3D/nD are the ability to flexibly define a set of such cells and assign time points $t_{(n)}$.

The components of the EA knowledge with the purpose of their application in the dynamic EA transformation are associated with the cell models $cem_{i,j,t}$, with the procedures for transforming the model cell from one state to another, with the procedures for monitoring the integrity of the entire EA model or the EAWP selected from it, as well as procedures for solving specific problems of enterprise transformation. Considering the amended categorization of Bloom [28], as well as the ways of applying knowledge in the processes of enterprise transformation, the following categories stand out as the main ones from all EA knowledge.

Specific knowledge for $cem_{i,j,t(n)}$:

- • model $cemd_{i,j,t(n)}$ of factual knowledge - a description of the representation of EA or EAWP state fragment reflected by this model-cell;
- • model cemp-$T_{i,j,t(n)}$ of procedural knowledge - a prescriptive model of transformation of $cem_{i,j,t(n)}$ into the next time-controlled state $EAM(t(n+1))$;
- • model cemp-$C_{i,j,t(n)}$ of procedural knowledge - a prescriptive model for controlling the correctness of connections $cem_{i,j,t(n)}$ with adjacent models-cells within the point of view *j*, aspect *i*, time stream in which a specific transformation is performed.

Conceptual (generalized according to GERAM) knowledge related to $cem_{i,j,t}$:

- generalized for $\forall t(n)$ model-description $cemd_{i,j,t(0)}$ for representing the admissible states of the EA and EAWP, reflected in the model $cem_{i,j,t}$ in its dynamics (for example, the general procedure for choosing and describing the data location scheme in the corporate network of the enterprise);
- generalized for $\forall t(n)$ prescriptive model cemp-$T_{i,j,t(0)}$ for representing the rules of possible transformations $cem_{i,j,t}$ from the state $t(n)$ to the next states in time;
- generalized for $\forall t(n)$ prescriptive model cemp-$C_{i,j,t(0)}$ for checking the correctness of connections $cem_{i,j,t}$ with adjacent cell models within the selected point of view *j*, aspect *i*, and time flow (for example, a set of unified procedures for calculating the truth of compliance with the rules of connectivity of elements in cell models and between them);
- similarly, generalized for $\forall t(n)$ prescriptive models cemp-$E_{i,j,t(0)}$ for solving other possible dynamic problems of enterprise development management (for example, in the style of dynamic capabilities of EA [3] and as competencies management).

For integrated models and different EAWPs, similar units of knowledge are formed, associated with subsets composed of $cem_{i,j,t(n)}$, covered by the corresponding integrated model, a specific EAWP, or the entire EA model. The category of metacognitive knowledge is used to expand the amount of EA knowledge. Models of such knowledge can be related with any primitive or integrated model of EA through their specific subject and are not described here.

One EA transformation stream is defined as the union of elementary transformation streams of all cell models affected by one planned transformation and related to one EAWP.

The elementary transformation stream is defined as a set $\{cem_{i,j,t}\}$ ordered by t in which i and j are constants that determine the occurrence of $cem_{i,j,t}$ in one EAWP, and the rule $t(m) \le t \le t(m+k)$ holds, where $[t(m);t(m+k)]$ is the minimum time interval that contains the given stream in one definite transformation.

Multithreading is defined as the possibility of partially parallel execution of transformation streams for one or different EAWPs.

5 Discussion of actual EA problems and conclusion

5.1 Examples of current EA problems and discussion of their solutions based on EA knowledge

The publications discussed in Sections 1 and 3 pose a number of partly classical and partly new problems and tasks related to enterprise transformation management for EA. These include the following:

- • support for flexible strategic management of enterprises;
- • support for the dynamic capabilities of EA as its transforming abilities;
- • dynamic search and analysis of incorrectness in the EA model;
- • support for the dynamic digital transformation of the enterprise, taking into account the heterogeneous values systems of the stakeholders;
- • building EA providing dynamic changes and consistent use of actual working knowledge of different contents and forms by individuals as actors of different types.

The methods of solving the first three problems are discussed in more detail below, and general features associated with the other two tasks are commented. The issues of support for extreme options of an enterprise behavior are considered separately.

5.2 Supporting flexible strategic enterprise management

This problem can be divided into two separate problems, and the first one is to apply the knowledge of EA to form an architecture that implements a mission and a new strategy. The principles of solving this problem in the 3D/nD-enterprise approach are stated in [19,20,27 part 2]and are indicated here in subsection 4.1. The second one is the use of EA methods for flexible but sustainable management of the implementation of the formed strategy. The scheme of such management, based on separation and linking of models and facts of strategy and tactical actions, is proposed in [29]. This scheme itself and the method of its use refer to the generalized prescriptive knowledge about EAWP or EA in general.

5.3 Support for dynamic EA capabilities as its transforming abilities

It is shown in [3,5] that it is important to move away from the interpretation of EA as a method of creating its artifacts to dynamic decision making by managers based on EA discipline. To this end, the "dynamic capabilities of the EA", including procedures and actions defined for managers in order to support their decision-making based on EA are explored. The solution to this problem in the 3D/nD-enterprise approach can be based on combining prescriptive knowledge (like $cemp_{i,j,t(n)}$ models) and other required related knowledge in EA with knowledge elements in the normalized competency model [30]. Then the following is assumed:

- inclusion in the nD-enterprise scheme of the dimension of managers abilities and abilities of the enterprise as a whole according to the rules [30], and the prescriptive knowledge of the EA, aimed at fast involving managers in the work to implement the dynamics of the enterprise;
- inclusion of relationships in the descriptions of potentially affected by the transformation of architectural elements and prescriptive knowledge of EA, aimed at solving a specific type of problem or task (for example, the problem of assessing the cost of enterprise transformations, the task of detecting the redundancy of stored data or organizational structures, etc.).

5.4 Dynamic search for logical incorrectness and control of the EA model integrity

The logical integrity of EA or EAWP models control at the time *t(n)* can be performed according to different control policies. An example of the main idea of using the EA knowledge for such control is:

- calculation of the truth of the compliance with the mutual correspondence rules at the level of consistency of cells in EAWP provided by the models cemp-$C_{i,j,t(0}$ and cemp-$C_{i,j,t(n)}$ (possibly also{cemp-$C_{i,j,t(k)}$ |k=n-1,n,n+1});
- expansion of these calculations to cell-models included in EA and EAWP as a subset of EAMWP(*t*), selected from the set EAM(t_1,t_N) of all cell-models {$cem_{i,j,t}$ } for the moments *t(n), t(n +1)* and possibly for later ones.

5.5 General possibilities for solving two other problems

The need to support the dynamic use of working knowledge of different content and forms. Many works, including [13,14], indicate the need for semantic support for different actor types in part of working with heterogeneous information. Control of EA representations by means of combined ontologies and logical inference (reasoning) is often considered. In this regard, it is necessary to point out the conclusions of the works [31,32] about barriers on the way of combining ontologies of different authors or formulated for different situations. At the same time, [31] shows the direction of solving such problems by applying the proposed principles of dynamic enterprise knowledge management and multimodal knowledge storages development. Such

architecture is quite compatible with the nD-enterprise approach in which there are no restrictions on the means of description or the level of knowledge formalization.

The need to support the dynamic integration of different parties of the enterprise ecosystem based on the axiological approach. The digital transformation of enterprises based on values is considered important in many works. Naturally, the question arises about the "digitalization of values". However, axiology is a very broad and "shaky" field for digitalization; therefore, it is better to carry out digitalization of values with a focus on solving specific problems. An example of such a problem is the search in the ecosystem of the enterprise and beyond those parties that are compatible with the enterprise needs and values [33]. To solve this and a number of other problems, the model of the space of digital values representations has been developed in [34]. Such a model can be included in the nD-enterprise by adding to nD the necessary dimensions of the values proposed in [34].

5.6 Support for extreme versions of enterprise behavior

The work [13] mentioned above expands EA dynamics not only to the enterprise, but also to the units of production which, similarly to assemblies of operating systems, can be modified at any moment *t* after their release. Assuming that such an upgrade must also be accompanied by a change in the enterprise, the architect can plan changes that are not only broad in the composition of objects, but also continuous. Taking into account the processing claims of products consumers, the enterprise will have to support a variety of product architectures and enterprise states. The EA knowledge structures fundamentally described in Section 4 and approaches to knowledge application discussed in this section do not show any barriers to support such extreme decisions. Still, it can be assumed that for most enterprises this may be quite redundant in practice.

In this regard, in this work, the concept of so-called "Continuous Architecture" from [35] is not applied to the entire life history of the enterprise, but is deliberately limited to EAWP and selected time intervals [*t(n);t(n+k)*]. Such a solution is aimed at more reliable control of EA integrity with the planned allocation of control points in time for checking and ensuring formal and meaningful criteria for EA integrity.

6 Conclusion

Analysis of current works in the field of enterprise architecture confirmed the usefulness of EA as a discipline and showed the need for its development for the conditions of increasing variability of enterprises and their environment. This need is associated with solving old and new types of enterprise transformation problems. For the specified conditions, this work shows the effectiveness of introducing the dimension of time, proposed earlier in the 3D/nD-enterprise approach. For this approach, the formation of a schema of factual, procedural, conceptual, and metacognitive knowledge of EA is shown. This includes knowledge not only about the states of the enterprise,

but also about the methods and procedures for performing these states transformations with an interrelation to the dimension of time. Besides, ways of using this knowledge for solving modern problems of enterprise transformation are demonstrated.

The main directions of further research and development of the 3D/nD-enterprise approach and work with knowledge about transformations should consider embedding rich knowledge management functions in architectural processes and in EA tools, in particular, search and selection of EA knowledge management tools, taking into account the multimodal architecture of the knowledge previously proposed in [31].

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