Lifecycle Ontologies: Background and State-of-the-Art

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***Abstract*—The problems of creating Lifecycle Ontologies are discussed in the paper. The Ontology of Lifecycle (both as domain and upper ontology), in contradistinction to Lifecycle of Ontology, still remains underdeveloped. The interest in these problems is related to the need in various lifecycle representations and coverings for constructing advanced Product Lifecycle Management (PLM) systems. Such PLM-systems are seen as a keystone for Enterprise Engineering (EE). First of all, some definitions and viewpoints on EE are discussed. Authors suggest an original pyramid of disciplines for EE. Moreover, the main goal is to develop a trans-disciplinary, synergistic approach to EE based on the integration of Ontological Engineering, Lifecycle Modeling and Knowledge Management. It requires the modeling and co-ordination of (at least) three lifecycles: product (complex technical system) lifecycle, enterprise lifecycle and knowledge lifecycle. The problems of lifecycle modeling are faced.**

Keywords-Ontological engineering; granular meta-ontology; ontological system; lifecycle ontologies; enterprise engineering.

I. INTRODUCTION

Nowadays the development of Lifecycle Ontologies for EE is of primary concern. Lifecycle specification and ontological modeling is a necessary prerequisite for deploying EE that becomes a fundamental paradigm for building new generation industrial enterprises.

In this paper we suggest a new trans-disciplinary approach to EE that encompasses Ontological Engineering[16][21][24][25], Lifecycle Modeling[8][20] and Knowledge Management[13]. Moreover, lifecycle engineering is based on three lifecycles – Product Lifecycle, Enterprise Lifecycle and Corporate Knowledge Lifecycle.

Among lifecycle ontologies we pay a special attention to granular lifecycle meta-ontology and upper (top-level) ontology. A general representation of lifecycle ontology by a mind map is given. Lifecycle granulation problems are elicited, fine-grained and coarse-grained lifecycle parts are specified. To model them, we use an extended Allen's logic [18]. As a result, both abstract and visualized lifecycle representations are constructed: they encompass circular, sequential, incremental, parallel-sequential, spiral models. Abstract models are based on Maltsev's algebraic system [19], ordinary and fuzzy partitions and coverings, Archimedean and logarithmic spiral equations [20].

The paper is organized as follows.

In Section II, we present various viewpoints on EE. Some basic disciplines of EE are considered and the corresponding pyramid visual representation is depicted.

Section III presents basic ideas of lifecycle engineering and lifecycle ontological modeling is seen as a basic instrument of lifecycle engineering.

In Section IV, the formal prerequisites for spiral representations are given.

The perspectives of developing and using formal ontological granulation models are discussed in the conclusion.

II. INDUSTRIAL ENTERPRISE ENGINEERING: AN ONTOLOGICAL APPROACH

Nowadays, an extremely broad multi-disciplinary area of EE has been developed based on systems engineering, organization theory strategic management, advanced information and communication technologies. The objective of EE is the design and creation of modern networked enterprise as an open sophisticated holistic system by modeling and integrating its products, processes, resources, organization structures, business operations, etc. In other words, EE considers the formation of enterprise as a sort of engineering activities. Moreover, it tends to examine each aspect of the enterprise, including various resources, business processes, information flows, organizational structures.

A conventional consideration of enterprise as a family of business processes may break its systemic integrity; here, some other approaches are needed, such as constructing generalized enterprise architectures with using agent-oriented technologies [1] and organization ontologies for industrial enterprise [2].

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Let us discuss some viewpoints on the essence and basic disciplines for EE. EE is defined in [3] as a body of knowledge, principles, and practices having to do with the analysis, design, development, implementation and operation of an enterprise. It means the shift from Data Systems Engineering and Information Systems Engineering to Enterprise Ontological Engineering [2]. In [4], three main goals of EE are mentioned: intellectual manageability, organizational concinnity, social devotion.

In [5], Martin focuses on seven disciplines of EE grouped around value framework: 1) strategic visioning viewed as ongoing cycle of value positioning; 2) enterprise redesign – discontinuous change in the value definition; 3) value stream reinvention – discontinuous change in the value offering; 4) procedure redesign – discontinuous reinvention of value creation; 5) total quality management – continuing change in value creation; 6) organizational and cultural development – continuous value innovation; 7) information technology progress (continuous value enablement).

According to Vernadat [6] EE is the art of understanding, defining, specifying, analyzing and implementing business processes for the enterprise entire life cycle, so that the enterprise can achieve its objectives, be cost-effective, and be more competitive in its market environment. Here, two basic disciplines for EE are enterprise modeling and enterprise integration.

Below, we propose our pyramid of EE Activities (EEA-pyramide; see Fig. 1). Our approach to EE is founded on the integration of System of Systems Concept [7], Ontological Engineering, Lifecycle Modeling and Knowledge Management. It supposes the specification and co-ordination of (at least) three lifecycles: product (complex technical system), enterprise and knowledge lifecycles (Fig. 2).

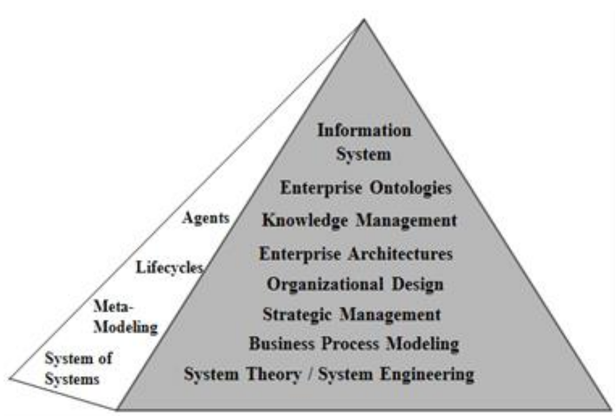

Figure 1. Pyramid of disciplines for EE

On the one hand, a computer-based integration of product lifecycle and knowledge lifecycle leads to the fusion of Product Lifecycle Management (PLM) and Knowledge Management (KM) technologies. The concept of lifecycle represents a basic implementation of systemic approach to complex technical objects that consists in visualizing their state changes for a temporal interval. By the end of XXth century-the beginning of XXIst century the notion of lifecycle has become wider. Now it also encompasses the stage of recycling (getting back used products into a new production process) that underlies the idea of lifecycle conversion [8]. On the other hand, the participation of enterprise at some alliances or consortiums, as well as the formation of extended, virtual or intelligent enterprises [9][10] leads to the prolongation of enterprise lifecycle best stages such as enterprise growth and maturity.

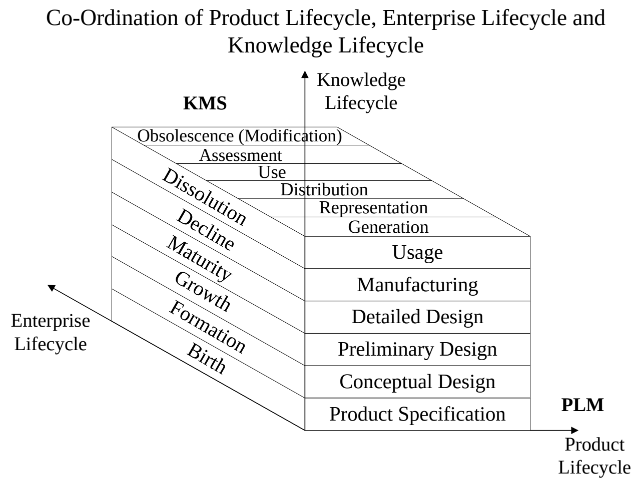

Figure 2. Generalized lifecycle management: towards the integration of PLM and KM

Let us recall that the term «Product Lifecycle» expresses the idea of a circulation of produced artifacts between the fields of design, production and usage (consumption). Product Lifecycle Management is the process of managing the entire lifecycle of a product from its conception, through design and manufacture, to service, disposal and dismantling [11][12]. It integrates data, processes, personnel and organizations to provide product’s information backbone for networked enterprises. The development of PLM-systems requires lifecycle modeling and engineering. It means incorporating a variety of key product lifecycle values into the most critical production and usage time intervals.

Knowledge management [13] is often defined as the process of applying a systematic approach to the capture, structuring, dissemination and use of knowledge throughout an organization to work faster, reuse best practices, and reduce costs from project to project. It is evident that KM becomes more and more important for lifecycle knowledge in case of virtual enterprises. Thus, management of industrial enterprise cannot be generally reduced to resource-driven approach, i.e., Enterprise Resource Planning (ERP) systems of 1st or 2nd generations. Here an ontological approach to lifecycle knowledge management and meta-knowledge formation is of special concern, and PLM-systems are more suitable as a core of further IThybrids and synergistic intelligent technologies [22]. Such systems generate and support a united information-knowledge space in the course of product lifecycle (Fig. 2).

III. Lifecycle Ontologies – a Key to Enterprise Engineering

Currently, the concept of ontology lifecycle is thoroughly developed, but the problems of lifecycle ontology and lifecycle ontological modeling are still not sufficiently studied (some of them remain open).

The lifecycle concept may be analyzed from various viewpoints; different variants of specifying its phases and activities were suggested. In marketing theory products follow such stages as introduction, growth, maturity, and decline. In industry, all products or systems have a particular life span considered as a sequence of stages, which is called product lifecycle (or complex system lifecycle). The aim of cyclic product definition is to realize both products and processes and economic solutions that are better and more intelligent by integrating lifecycle philosophy into technology and economy.

Our ontological approach to lifecycle knowledge engineering supposes the construction of both visual and formal models of lifecycle ontologies. Here, formal models are based on Maltsev's [19] concept of algebraic system, whereas visual representations encompass linear, circular and spiral models.

In this paper, the main attention is paid to lifecycle ontology viewed as an upper ontology for EE. We also introduce the concept of granular lifecycle meta-ontology; it is based on such concepts as granule, level, hierarchy, relations between levels [14].

The term meta-ontology means «ontology over ontologies». Meta-ontology provides us with both appropriate mathematical specification of ontology and necessary tools for representing and merging various ontologies. The need in granular meta-ontology (opposite to conventional singular one) for lifecycle modeling is obvious [23].

Generally, lifecycle granulation supposes the consideration of such problems as: 1) definition of basic granulation principles and criteria; 2) specification and interpretation of lifecycle granules; 3) analysis of lifecycle granulation approaches and techniques; 4) development of formal granular lifecycle models; 5) construction of mappings between various granularity levels; 6) specification of quantitative parameters of both lifecycle granules and granulation process itself.

It is worth stressing that an optimal granulation level does not exist; granule sizes are problem-oriented and depend on investigation context. Some lifecycle phases can be considered in a more detailed way and other – less thoroughly, with taking into account modeling objectives. We also envisage lifecycle representations with various abstraction degrees: a) rather simple circular representation based on either partition or covering; b) more sophisticated spiral representations showing interrelations between lifecycle phases, as well as between its phases and stages.

Let us focus on various forms of representing lifecycle ontologies. Any cycle, as a whole, is characterized by the presence of finite and repetitive parts on some temporal intervals; here key parameters are durations. In case of complex system's lifecycle, two basic granule types are lifecycle stages and phases. Lifecycle stages are coarse-grained parts that are usually divided into lifecycle phases, fine-grained parts, where each phase corresponds to a specific system's state.

One of fundamental resources for lifecycle management is time. A specific lifecycle feature is its heterochronous character, i.e., irregularity related to the difference of temporal criteria and constraints on various stages. In fact, we try both to accelerate design and manufacturing time and slow down usage time. For instance, during the design stage a basic criterion is to decrease design time, e.g. by using concurrent design strategies [17]. Contrarily, on the usage stage we tend to keep or increase reglamentary period, for example, by improving maintenance system.

Two well-known time metaphors – «time wheel» and «time arrow» – bring about lifecycle circular and consequent time models respectively. On the one hand, consequent linear models express such time properties as course, ordering facility, irreversibility. On the other hand, circular time models make emphasis on alternations, reiterations, rhythms, self-sustaining processes. In our paper, we try to reconcile these opposite models by constructing and analyzing spiral lifecycle models. Basic time theories should be envisaged in the context of lifecycle modeling: substantial and relational, static and dynamic, pointwise and interval time.

First of all, we shall represent lifecycle stages in the framework of set-theoretic approach as granules obtained by partition. Let us introduce natural denotations for complex systems's lifecycle: D – design; M – manufacturing; U – use; R – recycling. Then, we have

$$LC_1=D\cup M\cup U,\ D\cap M=\varnothing,\ M\cap U=\varnothing,\ U\cap D=\varnothing \quad (1)$$

or $$LC_2=M\cup U\cup R,\ M\cap U=\varnothing,\ U\cap R=\varnothing,\ R\cap M=\varnothing \quad (2)$$

Here, the structure of LC2 (2) expresses the «ecological imperative» of modern manufacturing being tightly related to above mentioned Kimura's lifecycle inversion concept. The first lifecycle partition LC1 (1) may be depicted by sectors of the circle (Fig. 3).

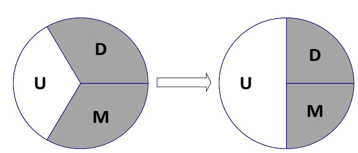

Figure 3. A Circular representation of complex system's lifecycle: an illustration of reducing lead (design and manufacturing) time and increasing period of usage

It is worth noticing that the representation of lifecycle by partition is rather simplistic and does not express many existing interrelations and co-operation links between partially overlapping stages. Moreover, this simultaneous work enables very important functions. For example, the specification is generated by using the information that circulates in both usage and design processes, production technologies ought to be discussed on the edge of design and manufacturing, whereas maintenance requires the collaboration of users and manufacturers. Taking into consideration such factors, we obtain the circular lifecycle model with fuzzy boundaries. For these cases, lifecycle granulation is based on covering (Fig. 4). Here,

$$LC_1=D\cup M\cup U, \text{ but } D\cap M\neq\varnothing, M\cap U\neq\varnothing, U\cap D\neq\varnothing \qquad (3)$$

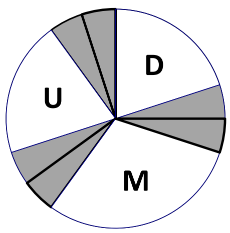

Figure 4. A Circular lifecycle representation on the basis of covering: the presence of collaborative works and fuzzy boundaries between stages

Generally, our approach is based on relational time model and interval time primitives. We use a fuzzy extension of well-known Allen's temporal logic [18] to model the links between lifecycle phases (or lifecycle stages and phases). These are mainly two types of relations: consequence and overlapping relations.

Let us recall that fuzzy quantity is defined as a fuzzy set of the real line. Fuzzy quantities are more suitable to describe flexible requirements on lifecycle parts duration.

We introduce a formal model of lifecycle ontologies ONT_{LC} as a quadruple

$$ONT_{LC} = \langle C_{LC}, R_{LC}, \Omega_{LC}, T_{LC}\rangle, \qquad (4)$$

where C_{LC} is the set of concepts related to lifecycle, R_{LC} is the set of relations between these concepts, Ω_{LC} is the set of operations over concepts and/or relations, T_{LC} is the set of temporal characteristics for lifecycle.

Basic concepts for lifecycle are its phases and stages; therefore, the triple below can be taken as lifecycle systemic kernel

$$\mathrm{ONTS} = \langle S, Rs, Os\rangle, \qquad (5)$$

where S is the set of lifecycle stages (phases), R_s is the set of relations between these stages (phases), O_s is the set of operations used on these stages (phases).

It is worth noticing that each lifecycle phase may be seen as an interval primitive $s=[a^-, a^+]$, where a^- is the starting point and a^+ is the end point of the interval. A fuzzy interval extending the concept of an interval is a special kind of fuzzy quantity that is represented by a convex fuzzy subset of a real line. As a special case, we have

$$ONT_{S1} = \langle S, <_f, \approx_f \rangle, \qquad (6)$$

where $<_f$ is a fuzzy strict linear order relation that is non-reflexive, asymmetric, transitive and linear, $\approx_f$ is a fuzzy simultaneity relation, i.e., fuzzy reflexive, symmetric relation.

More generally, we can use the linguistic variable «Time» with a linguistically ordered term set such as {almost simultaneously, a bit later, later, much later, very much later}.

IV. SPIRAL LIFECYCLE REPRESENTATIONS

The essence of spiral lifecycle model consists in integrating two contrary time models: linear model and circular model. Linear time model expresses such time properties as irreversibility, directional character, ordering facility, course, whereas circular time model makes emphasis on alternations, reiterations, rhythms, self-sustaining processes. Spiral time models tend to reconcile these two contrary cases.

Let us recall that in polar coordinates each point on a plane is determined by a distance from a fixed point r, $r \geq 0$ and an angle $\varphi \in[-\pi, +\pi]$ from a fixed direction: $M = (r, \varphi)$. A spiral is a curve that winds around a fixed center point at a continuously increasing or decreasing distance from the point. Here, we consider two spirals, namely, Archimedean spiral and logarithmic spiral. The first one is the locus of points corresponding to the locations over time of a point moving away from a fixed point with a constant speed along a line which rotates with constant angular velocity. It is given by the equation $r = a + b\varphi$, where modifying the parameter a will turn the spiral, while b controls the distance between successive turnings. In the context of lifecycle, we interpret these spiral parameters in the following way: φ is the time interval, a is the productivity index, b is the level and r is system's state.

The Archimedean spiral has the property that any ray from the origin intersects successive turnings of the spiral in points with a constant separation distance. Hence, such lifecycle features as time acceleration on early phases of lifecycle (for instance, decrease of design time) or time deceleration on later phases (increase of usage period) cannot be taken into account by using the Archimedean spiral (Fig. 5). Oppositely, in a logarithmic spiral these distances, as well as the distances of the intersection points measured from the origin, form a geometric progression (Fig. 6).

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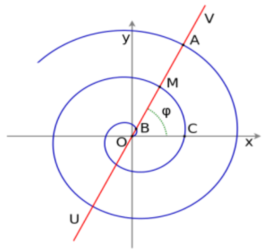

Figure 5. Archimedean spiral

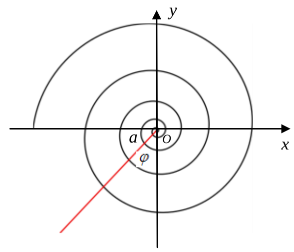

Figure 6. Logarithmic spiral

In particular, the spiral model is the most suitable approach to system's lifecycle knowledge engineering. The amount of knowledge is not equal for different lifecycle phases. One possible pitfall of using the spiral model is the number of rounds needed in developing a complex system (such as an aircraft). The pitfall can be avoided by using as reliable as possible methods in knowledge acquisition and elicitation. Mostly this knowledge representing a level of lifecycle granulation is expressed by a sort of Zadeh's generalized constraints [14] and circulates in a linguistic form, for instance, «to build a more detailed representation of maintenance phase» or «to take into account more knowledge about recycling».

Let us give an example of spiral lifecycle representation (Fig. 7). The starting point in product's evolution is a need formation in the usage (consumption) sector and the final state of the product is its disposal (elimination) interpreted as «a black hole». Spiral model phases are located in three sectors: design, manufacturing, usage.

Let us describe the main lifecycle phases for aircraft. Numbers in the Fig.7 describes the lifecycle phases. At the beginning of the lifecycle we have the identification of social need for a new product and formulation of appropriate product functions (phase 1). This phase is drawn as a circle belonging to the exploitation sector. The second step is the evaluation of production scales (a number of possible users) and the assessment of plausible product's price (phase 2) for the period of design solutions and specification of basic production indices.

Design stage itself starts with forming a specification (phase 3) and performing its analysis to generate feasible design proposal (phase 4). This step is shown by a circle on the boundary between exploitation and design sectors, because basic product's functions and a first draft of specification are given by a customer, whereas these specifications are converted into design proposal by a contractor. To illustrate the importance of this phase let us take the example of aircraft's lifecycle (Fig. 7). Here, basic design characteristics are not reduced to such items as mass, center of mass co-ordinates, aerodynamic surfaces, central tensor of inertia, but also include manufacturability, maintenability, serviceability, etc.

The design proposal ought to contain some technical and technico-economical justification of selected structures, their comparative estimation with taking into account product's structural and maintenance characteristics («Design for Maintenance»).

A preliminary project supposes information search and retrieval concerning available prototypes and analogous systems (phase 5).

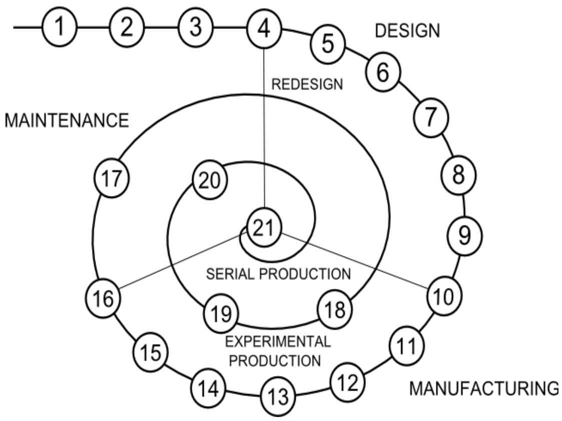

Figure 7. Product lifecycle representation

Phase 1. Formulation of product function;
Phase 2. Evaluation of product scales and product's prices;
Phase 3. Product specification;
Phase 4. Specification analysis and formation of design proposal;
Phase 5. Preliminary project;
Phase 6. Basic project;
Phase 7. Detailed project;
Phase 8. Development of static mockup;
Phase 9. Generation of structural-technological solutions for manufacturing;
Phase 10. Manufacturing pre-planning;
Phase 11. Development of assembly technology;
Phase 12. Design of technological equipment;
Phase 13. Production management design;
Phase 14. Manufacturing of technological equipment, fixtures and tools;
Phase 15. Equipment spatial allocation;
Phase 16. Elaboration of development batch;
Phase 17. Model (ground) tests;
Phase 18. Production management;
Phase 19. Serial production;
Phase 20. Product's maintenance;
Phase 21. Product's disposal

The phase of basic project supposes the justification of conceptual design solutions and specification of basic production indices (phase 6). Here, necessary data arc collected and calculations are made to specify the main product parameters, dimensions and form features. Various types of design analysis are executed: mass analysis, aerodynamic analysis including lift distribution, aerofoil design, aerodynamic performance estimation and confirmation. The construction layout and aerodynamic surfaces may be corrected many times to attain required aircraft properties. As a result, a detailed project is performed to obtain a final structure (phase 7). Here, a working documentation is made such as parts drawings, assembly drawings with appropriate technical solutions and technical requirements. The results of aerodynamic tests permit to fix aircraft form and to perform final strength analysis. Here, given temperatures and efforts on aerodynamic surfaces, so as fight accelerations, on vary possible a materials and reinforcement mode for load-carrying constructions. One specifies all the dimensions and the forms of reinforcement elements, the skin thickness ensuring a necessary strength. The data and knowledge on mechanical loads are widely used to verify forms and dimensions. Here, we deal with an overall construction except some parts such as engine, control system with devices and drives, or transportable parts obtained through plants cooperation. As a result of detailed design, we get final technical solutions with all product parameters and specifications for manufacturing. Then a static mockup (phase 8) is built. The participation of technologists is required to generate complex structural-technological solutions (phase 9) and organize manufacturing pre-planning (phase 10).

The next phases of technological support are assembly technology development (phase 11), technological equipment design (phase 12), and production management design (phase 13). Now, if the production technical-economical indices are satisfactory, then we proceed to manufacturing of technological equipment; fixtures and tools (phase 14), their spatial allocation (phase l5), elaboration and assembly of product's development batch (phase 16).

Because the processes of conceptual design and the enabling production technology and production management have rather approximate than precise nature, it is natural to expect that product's technical-economical indices and performances differ from specifications and requirements. Their correspondence to these preliminary requirements is specified through model (ground) tests (17) in the framework of exploitation sector.

Basing on results of the model tests a comparison with initial specifications is made, and some new local specifications are formulated to correct both the product structure and the production technology and management (18). These steps 3–18 may be repeated on each new spire of lifecycle’s diagram (redesign and production modification) until product's performances begin to correspond to general specifications. Later on, a commercialization stage opens with the start of serial production (phase 19), followed by product's usage and maintenance (phase 20) and its disposal (phase 21) due to obsolescence with taking into consideration economic and ecological restrictions.

Such a representation of product's lifecycle by logarithmic spiral simplifies the analysis of concurrent engineering problems and the development and adaptation of appropriate AI methods and tools. The number of spires of life-cycle diagram depend on the level of informational/intelligent support and may be interpreted as a degree of simultaneous engineering.

Uncertain and imprecise knowledge on products' structure and its manufacturing technology, imperfect design and simulation models necessitate a repeated passing of production stages followed by exploitation tests in order to verify how initial specifications are satisfied. According the estimates of Russian experts in aerospace technology [17], the duration of first life-cycle's spire until first exploitation tests is 15% and the cost of this first spire establishes 25% of the integral duration and cost respectively to compare with the whole product' refinement phase until meeting initial specifications/requirements.

V. Conclusion

The new approach to EE centered on various lifecycle models has been proposed. On the one hand, it provides a theoretical background for implementing various lifecycle ontologies to develop advanced knowledge-based PLM systems. On the other hand, a system of lifecycle ontologies seems to be a necessary tool for mutual understanding and join work of all enterprise actors - both human and artificial agents. Here, the main difficulties consist in different ways of information granulation along the whole lifecycle. Lifecycle Ontologies has been considered as a core of EE. Granular lifecycle meta-ontology and upper ontology are of special concern. Both abstract and visualized lifecycle representations have been constructed; they encompass circular, sequential and spiral models. The emphasis has been made on spiral representations with using the Archimedean and logarithmic spirals.

Our future work will be focused on specifying basic indices for granular ontologies and developing an ontological sub-system for intelligent PLM-system.

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