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# PERFORMANCE-DRIVEN EVOLUTIONARY CAPABILITIES IN VIRTUAL PRODUCTION ECOSYSTEMS

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**Abstract:** This paper examines possible aids of performance measurement to the evolution in production ecosystems. A conceptual solution is proposed which derives from the potential of exponential technologies, theory and practice. By adopting an ecosystem approach, a twofold setup of performance has been designed that addresses both the performance of actors and the performance of ecosystem. The proposed mechanism applies Big Data and machine learning. The proof of concept was supported by a prototype of the virtual environment.

**Keywords:** performance measurement, evolution, virtual business ecosystems.

## 1. Introduction

The emerging virtual ecosystems are rapidly revolutionizing the life of human civilization. Probably the most spectacular illustration for this statement is the change in social and political communication, which has been brought about by such Internet platforms, as Facebook, Twitter and YouTube. This megatrend also applies to the area of economy and business, which are being equally affected by the impact of exponential technologies.

The focus in this paper is on the virtual production ecosystems. The problem of interest is to enable the evolutionary capabilities, whether of actors or a whole. The proposed solution applies ecosystemic metaphorizing. It also and learns from cybernetics and theory of control. The analysis of existing Web-based platforms and ecosystems together with the examination of the enabling potential of exponential technologies, were the other sources of inspiration.

The conceptual development presented in this paper considers two ways of adaptation. Firstly, the actors are aided really and virtually with relevant information. Through learning, whether organizational or machine learning, they adapt themselves. Secondly, the virtual domain automatically self-adapts based on ecosystemic learning. Then new decision-making functors are embedded in the virtual agents, who coordinate the collaborative production.

The proposed model of adaptation is based on the performance measurement applied to both, actors as well as the whole ecosystem. To this end a set of measures was proposed including both, the local and overall performance. The latter applies to the entire ecosystem, as well as to its partitions, to enable the discovery of change, trends and correlations.

The notion of performance used herein goes far beyond the common understanding of business performance that solely takes into account the effectiveness and efficiency (effects), by relating outputs and outcomes with inputs (Bititci, 2015). A holistic understanding of performance is proposed which also considers conditioning and causal factors subject to change. These include behaviors, whether of actors, processes or other constituents of the ecosystem, environmental indexes and the relating coefficients. Such approach to performance measurement is necessary not only to ensure the holism of assessment. It also enables regulatory and adaptation mechanism based on machine learning, which is necessary to discover significant interdependencies between factors and effects, as well as changes and trends in the ecosystem and its ambient environment.

The proposed solution was validated using theoretical argumentation and limited proof of concept. The latter has been based on the prototype development of virtual environment.

## 2. Virtual Production Ecosystems

This section outlines an ecosystemic setup for virtual production ecosystems. It is made in accordance with the paradigm of Production Internet (Strzelczak, 2015). It assumes functional scope suggested by a foresight research presented in (Strzelczak, 2017).

Amid the possible archetypes of virtual business environments the following three can be distinguished: system, system of systems and ecosystem (Table 1). The indication of the ecosystemic type is justified by the following features of virtual production environments: (i) large scaling combined with openness and fragmentation; (ii) high complexity: heterogeneity of entities, activities (processes) and resources combined with complex interdependencies and intense connectivity; (iii) coordination and control is basically exerted by small scale bottom-up processes, however, the overall dynamics is influenced by multiple cross-scale linkages of processes at different layers (e.g.: higher-order processes or laws, such as the economic ones, can affect singular transactions). The last feature classifies the power distribution in the virtual business environments as panarchical (Allen, et al., 2014).

The key specificity of ecosystems perspective is in viewing phenomena in interconnected and multilayered reality of interacting actors and their environment, in order to comprehend complexity and avoid oversimplification or unjustified reductionism (Marshall, 2002). Ecosystems can be conceptualized as structured environments governed by general rules.

**Table 1.**
*Archetypes of virtual business environments*

| **Archetype** | **Differentiation** | |
|---|---|---|
| | **Cohesion** | **Share of power** |
| System | coherent structure of interacting, interrelated and interdependent components that form a purposeful and integrated whole | hierarchy |
| System of systems | dedicated community of independent but networked systems that share and pool their objectives, capacities and capabilities, and coordinate to synergize and provide more functionality and performance than acting individually | heterarchy,<br>hierarchy, or<br>hybrid of both |
| Ecosystem | collectivity of entities that interact and exchange with each other and their environment; in order to thrive they swarm, network, compete or collaborate with each other on available resources, evolve and adapt to environment | panarchy |

Source: Own development.

Production ecosystem is a collectivity of individuals and organizations related by exchanges, cooperation and competition. The key actors are customers, producers, suppliers, forwarders and creditors. The environmental components include economy, society, state (rules of law, government agencies, and so on) and natural environment. The virtual domain of production ecosystems provides resources and capabilities that govern and facilitate operations within the real domain, including such functionalities as: processing of demand, matchmaking of contractors and brokerage, coordination and control of operations. By applying ecosystemic metaphorizing and deriving from (Strzelczak, 2018), the following constituents of virtual production ecosystems have been distinguished:

- Micro-components: real actors (individuals; firms; Things: products, materials, resources, devices, etc.; flows); virtual actors (Web-services, software agents, smart contracts, decision making functors; APIs; data & knowledge bases; digital twins of: work flows, demand flows, cash flows, data and knowledge flows, credit action);
- Microsystems: networking of micro-components, whether temporary or lasting, related to: demands and offerings; products, technologies and processes; firms and resources;
- Mesosystem: partitioning of ecosystems and interdependencies (correlations, causal dependencies, control loops, etc.) between micro-components (considering decision making functors), microsystems and partitions; in this context, the indexing of performance, homeostasis and trends are included in the domain representation;
- Exosystem: links between the contexts in which the micro-components do not have any active role and the contexts in which they are actively participating;
- Macro-environment (macrosystemic conditioning): social and economic conditioning (consumer behavior, overall credit action, business climate, economic institutions and paradigms); legal factors (business, commercial and tax law, etc.); political conditioning (political climate, political risks), ecological conditioning (pollution, availability and depletion of natural resources); also rules of internal governance.

The appropriate conceptualization of mesosystem is critically important for discovery of behavioral patterns and correlations in the ecosystem. Apart of real actors and "real" clusters (i.e. those related to the real objects), behavior- and performance-based partitioning of ecosystems provides another opportunity to distinguish constituents subject to important interdependencies. Basically, partitioning can be supported by the common methods of pattern recognition. This is because measuring the behavior and performance in partitions, takes place in metric spaces (an approach of that kind is presented in section 5).

Measuring a relative change, regardless of the considered factor, behavior, effect or performance measured, can be done by adapting the modified Lilien index (Ansari, et al., 2014), according to the following formula:

$$\Delta_V^{pt} = \sqrt{\sum_{i=1}^{N} \overleftrightarrow{V}_{pt} \left[ \ln \Delta V_{ipt} - \ln \Delta V_{pt} \right]^2} \tag{1}$$

where:

V – variable (observable),
i – index of object (alternatively – partition),
p – index of partition (alternatively – whole),
t – time unit,
Δ – operator of change,
↔ – operator of averaging.

The relative change can be referred to: (i) objects (actors, etc.); in such case the measure of object is compared against the change in host partition; (ii) partitions: in such case the measure of partition is compared against the change in the entire ecosystem. To measure the relative change over time (time-phased change), formula (1) can be adapted as follows:

$$\Delta_V^{pt} = \sqrt{\sum_{i=1}^{N} \overleftrightarrow{V}_{p<t,t+\delta t>} \left[ \ln \Delta V_{ip<t,t+\delta t>} - \ln \Delta V_{p<t,t+\delta t>} \right]^2} \tag{2}$$

where $\delta t$ is the time-phasing (backward of forward offset).

The above conceptualization provides a basis to facilitate identification of causal factors, conditioning factors, as well as effects and interdependencies. It can also help to design the mechanisms of evolutionary capabilities, and the aids to self-made evolution of actors.

## 3. Ecosystemic Performance

This section outlines a set of measures that altogether can comprehensively represent the performance in the virtual production ecosystem and its environment. The structure of metrics is consistent with the ecosystemic layout of virtual production ecosystems. The choice of measures meets the expected functional requirements of evolutionary support, the expected range of interdependencies between factors, effects, behaviors and performances, as well as probable mechanisms of evolutionary support. The latter incorporate (Strzelczak, and Marciniak, 2018): self-made adaptation of firms and individuals through own learning, self-adaptation of virtual agents and Cyber-Physical Systems (CPS) through machine learning, as well as automated adaptation of virtual agents aided by evolutionary services.

The complete set of key performance indicators (KPIs) for virtual production ecosystems is summarized in Table 2. The choice of KPIs can be justified as follows. Metrics of actors' (local) performance reflect the attractiveness of actors in the eyes of potential contractors, i.e. as credible and attractive suppliers, or clients. Such KPIs include common measures of delivery performance and credibility measures. The choice of the latter was largely inspired by the practices of the Social Credit System in China (Lin, 2012).

**Table 2.**
*KPIs for virtual production ecosystems*

| Range | Aspect | Measure |
|---|---|---|
| Local performance | Credibility and performance of contractor | OTIF (on-time-in-full)<br>Quality (quality ratios)<br>Speed (customer lead-time CLT)<br>Stockouts (%)<br>Credit behavior (timely bill payment, timely credit repayment) |
| | Operational behavior and performance | Liquidity: manufacturing lead-time, throughput, work-in-progress<br>Circulation: stock rotation, capacity turnover, cash-to-cash<br>Local congestion (overload): lead-time extension rate, overload<br>Variability of lead-times, throughputs, work-in-progress, loads |
| Homeostatic performance | Change, homeostasis and variability | Relative change of flows (slowdown, speed-up)<br>Phased change of flows (offset)<br>Microsystemic congestion (overload)<br>Variability, turbulences, and disruptions (assessed and represented according to the current partitioning) |
| | Propagation of change and variability | Relative change (amplification, attenuation) and phased change of: congestion, variability, turbulences, and disruptions (assessed and represented according to current partitioning) |
| Overall behavior and performance | Efficiency of resources | Overall utilization of resources<br>Overall turnover of resources |
| | Pareto-efficiency | Price of anarchy in relation to efficiency |
| Environmental performance | Ecological | E.g. ecological tariffs & taxes, intensity ratios of waste & pollution, etc. |
| | Economical | E.g. consumer indexes, indexes of credit action, price indexes, etc. |
| | Social | E.g. indexes of trust |

Source: Own development.

Another consideration is the impact of dynamic network behavior as well as performance of actors on the overall performance. In this regard, the insights from the theory of queueing networks have been taken into account (Little, 2011; Kingman, 1961). As homeostasis is an important condition for the efficiency and effectiveness of operations in production ecosystems, relevant performance indicators have been considered, including direct metrics of phenomena, as well as those that measure change or propagation of particular effects within the ecosystem (Strzelczak, and Marciniak, 2018).

As for overall behavior and performance two aspects were taken into account, including the resource efficiency and the price of anarchy. The latter considers the Pareto optimum and evaluates how efficiency degrades due to the selfish behavior of interacting actors (Koutsoupias, and Papadimitriou, 2009). Measures of environmental conditions were only selectively indicated in Table 2 (rows in grey). Also the metrics of network topology are not presented in Table 2, because the theoretical basis for their effective use is still not sufficient.

The above setup of performance measurement together with the partitioning mechanism presented in section 2, provide a robust and viable basis for the evolutionary support in virtual production ecosystems.

## 4. Evolutionary Capabilities

This section describes the mechanism of evolutionary capabilities of virtual production ecosystems. The proposed solution considers a wider context of the entire virtual domain in the production ecosystem (Strzelczak, and Marciniak, 2018). Following the discussion in previous sections, three modes of evolutionary capabilities were proposed:

- Self-adaptation of firms and individuals: based on learning and facilitated by the supplied information on: own behavior and performance, microsystemic performance, propagation of variability and change, homeostatic performance and change, overall behavior and performance, trends and environmental performance; this support augments the reality visible to actors and includes relevant query services; the responsibility for self-made adaptation rests with the firms and individuals;
- Self-adaptation of virtual agents and Cyber-Physical Systems: it is driven by their own learning (machine learning) and facilitated by aids of augmented reality (as above);
- Automated adaptation of virtual actors (software agents): by embedding new decision-making functors that are provided to them.

The last mode requires the use of ecosystem-wide intelligence, which is expected to discover trends and invisible patterns of change, as well as relate decision-making rules embedded in the agents (in their functors) with overall efficiency. To this end the measures of overall performance proposed in Table 2 may be applied.

The overall view of the proposed mechanism is exhibited in Fig.1. Agents measuring performance within the operational services, whether local or microsystemic, report to the services of homeostatic analytics. For this purpose, they receive the information on the state of matters from the actors. Local performance is also reported to the brokerage services, to aid their decision making capabilities, which rely on the locally oriented analytics or machine learning. The environmental performance is reported directly to the services of homeostatic analytics. Therefore, partitioning of the ecosystem is enabled, which provides the basis for a continuous process of indexing partitions by performance. The homeostatic performance is reported to the brokerage services, to aid their decision making capabilities. The services of evolutionary support perpetually receive the layout of overall performance. Being equipped with a base of functors, as well as a twofold representation of the entire ecosystem (performance by functors and trends), the evolutionary services are capable to operate the ecosystem-wide intelligence. Basically, the machine learning can be used for this purpose.

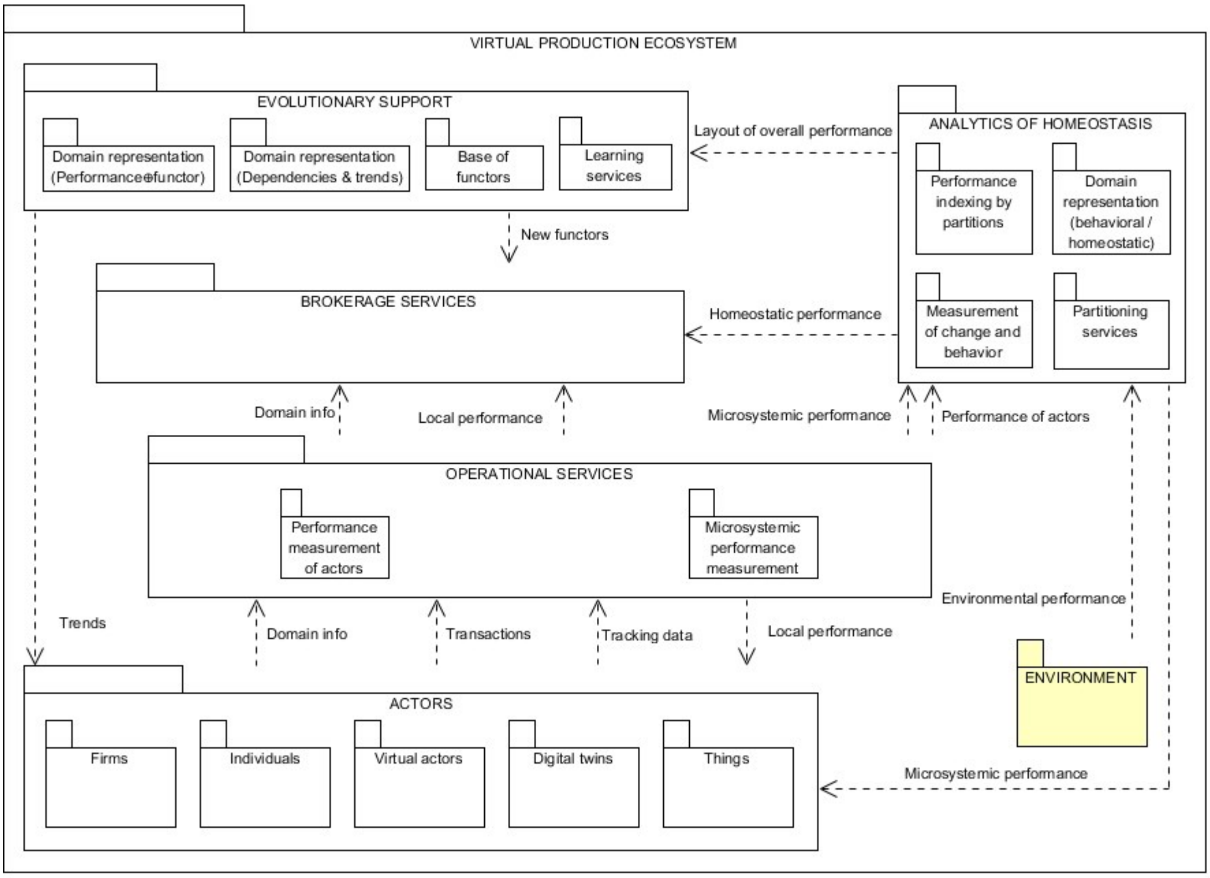

**Figure 1.** Mechanism of evolutionary capabilities in virtual production ecosystems (ideation).Source: Own development.

By interpreting the performance measures as rewards, reinforcement learning is enabled, including deep generative models (Kingma, et al., 2014). In all cases the design of changes to the control rules can be implemented following the transformational approach to ontological representation (Strzelczak, 2015). Depending on the applicability, a semi-supervised or unsupervised mode of learning may be used. Data mining and advanced analytics can also aid the self-made adaptation of real actors, by equipping them with relevant query services.

Altogether, the above proposed aids to evolutionary capabilities in virtual production ecosystems are sound and viable. Especially, the mechanism of facilitating the self-adaptation of real actors by information provisions provides an important advantage in comparison to the current situation of actors.

## 5. Validation

A primary validation of the proposed solution was carried out through a theoretical discussion, which is included in previous sections. In order to justify the concept, three inputs were considered: (i) insights into existing theories along with research evidence (ecosystemic approach, cybernetics, network dynamics); (ii) reflections on enabling technologies; (iii) observations from the developments of virtual platforms and Web-based ecosystems.

Another way to validate the solution was to implement a prototype virtual environment. To this end, existing pattern recognition tools were adapted. As graphical representation is typically used during pattern recognition, an appropriate method to map the original domain representation into the graphical one has also been developed, including the mapping of individual items to their partitions. This allows indexing of ecosystem performance in accordance with the identified partitions by aggregating local performance indicators. Then, machine learning can be applied to discover significant interdependencies between factors and effects, as well as changes and trends in the ecosystem and its ambient environment. Finally, an inverse mapping can be applied to identify entities within individual partitions.

The prototype software has been implemented as an overlay for the previously developed multi-agent environment of Production Internet, which includes operational and brokerage functionalities and is consistant with the architecture shown in Fig. 1 (Strzelczak, 2017). Distributed ontology was assumed as the basic means to represent resource and processual entities. To this end, the TRANSFORMERS ontology for manufacturing and logistics has been adopted, which was previously developed at Warsaw University of Technology in OWL (Strzelczak, 2015). The functional layout of the prototype is shown in Fig. 2 as a UML sequence diagram. Life-lines correspond to the subsequent representations of the domain.

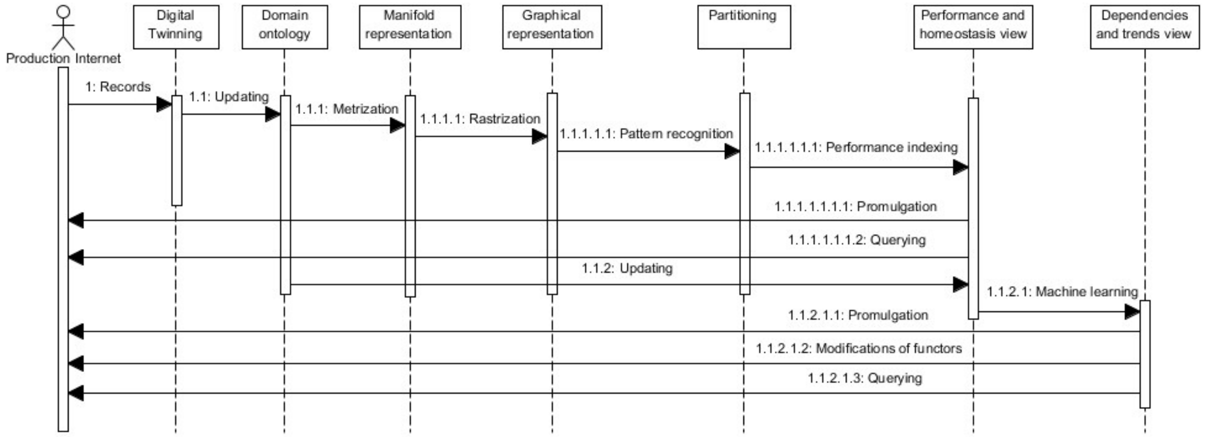

**Figure 2.** Functional layout of prototyping. Source: Own development.

To map the original domain representation into graphical, the following approaches and measures were taken into account:

- Use of angular coordinates (GPS coordinates) to map physical location of entities to manifolds (metric spaces), then to raster graphics or alternatively to a representation based on GIS; such mappings can secure the isomorphism (or even homeomorphism) of the two representations that can be all regarded as spatiotemporal mereologies or mereotopologies, depending on the circumstances; mappings of physical locations can be subjected to the homotopic transformations (e.g. replacing distances by the time lengths of particular flows) to obtain alternative representations of the domain;
- Handling the granularity of original representation and imaging the production ecosystem in a twofold way:
  - Low resolution of pixels or voxels corresponds to low granularity of viewing the ecosystem and phenomena; it is assumed that colors, saturation and elevation (i.e. the z coordinate in GIS imaging) represent particular performances;
  - Lower levels of instancing entities (products, resources, processes/activities), i.e. lower levels of aggregation, correspond to greater granularity;

  Again, the isomorphism or homeomorphism of dual representations can be secured by corresponding mappings.

Based on the above approaches, an overall list of mappings was elaborated, which should be considered in the prototype environment (Table 3). However, in order to limit the development efforts, an alternative approach to graphical domain mapping was also used. Social Network Analysis tool was adopted as a mean to map the network ecosystem representation to the graphical one. It was NetworkX, which is a Python package capable to operate up to three-dimensional spaces. The interface between the ontological representation of production ecosystem and NetworkX has been developed accordingly.

**Table 3.**
*Correspondences between original and graphical representations*

| Original representation | Mapping | Graphical representation |
|---|---|---|
| Micro-components | Bucketing/Mereological summation | Pixels/Voxels & Partitions |
| Location (distance) | Metrization by GPS coordinates | Manifolds (Metric space) |
| Time spread | Metrization by time distances (cycles) | Manifolds |
| Granularity/Aggregation | Bucketing/Mereological summation/Rasterization | Resolution |
| Local performance | Bucketing/Weighted averaging or summation | Pixels/Voxels by Colors/Saturation |
| Homeostatic performance | Bucketing/Weighted averaging or summation | Pixels/Voxels by Elevation |
| Overall behavior and performance | Bucketing/Weighted averaging or summation | Pixels/Voxels by Colors/Saturation/Elevation |

Source: Own development.

For partitioning the production ecosystem based on using a graphical representation, the Vision Builder package was adopted, which is capable to recognize objects and borders, i.e. mereology of scenes. The software operates various graphical formats, including jpg. Then the perpetual indexing of performance and change could be implemented to support the machine learning.

To mine the graphical representation of production ecosystem, two alternative approaches were used. Multilayered neural networks were applied as a basic mean for the machine learning to explore the domain, based on its metric representation. For this purpose, a proprietary package for computing neural networks has been implemented, which was previously developed at Warsaw University of Technology.

Additionally, an alternative approach to the ecosystem-wide intelligence was verified, which is based on the adaptation and extension of the calculus of scenes. It consists in implementation of hybrid comparisons that merge the qualitative and quantitative representations.

Apart of advanced analytics, the use of graphical domain representation enables visualizations and animations of production ecosystems, which can be accessed through the human interfaces. This functionality can aid the learning and self-adaptation of actors.

The prototype platform was validated by running its functions concurrently (as overlays) with the basic brokerage and operative functionalities of the virtual production ecosystem. The performed runs considered only computer simulations – virtual actors were used as dummies for real actors. Gamifications involving real actors have not been applied. Therefore, self-adaptation of real actors was not considered. Also local learning of virtual actors was not included.

The following types of runs have been used to validate the concept: (i) demand shocks; (ii) availability shocks; (iii) variability shocks; (iv) steady growth of variability; (v) exponential growth of variability. The last three types of change were considered both locally (in regions) and in the whole ecosystem. The impacts of structural changes within the production ecosystems, like the environmental conditioning, have not been tested. As expected, the introduced changes were causing modifications of decision making functors, whether by adjustments of parameters or profound structural modifications of the functors.

Although the developed prototype is rather primitive, it could be effectively used for functional validation of the proposed solution.

## 6. Summary and Future Work

This paper proposes a mechanism of evolutionary capabilities for the virtual production ecosystems. The approach is based on the use of performance measurement to facilitate the regulatory functions. It derives from relevant theories and best practices, and leverages on the up to date technologies.

The novelty of the proposed solution is manifold:

- it applies a comprehensive novel model of the evolutionary capabilities for virtual production ecosystems, which takes into account both real and virtual actors, as well as the whole;
- it is based on an extended notion of performance that apart of effectiveness and efficiency considers behavioral aspects and conditioning factors;
- it applies a set of homeostatic and ecosystemic performance measures to support the ecosystemic intelligence;
- actors are offered augmented reality so that they can learn and adapt on their own;
- it implements an automated adaptation of virtual actors based on machine learning.

A similar approach was not yet presented in the accessible literature nor is it used by any known software development.

The proposed evolutionary mechanism is sound and viable, because it relies on solid theoretical foundations and synthesizes the existing knowledge and practice. Apart of an argumentation the proof of concept was supported by the use of a prototype software development. As the approach relies mostly on theoretical justification and limited prototyping, it requires further validation.

The further work should investigate the full-blown functionalities of virtual production ecosystem. It should also explore important exploitation aspects, such as interoperability, security and scalability. Such aspects were not considered herein, however expectedly they may bring about significant development and practice challenges.

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