# Factors Determining Digital Learning Ecosystem Smartness in Schools

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**Abstract.** This paper discusses the factors that determine school's digital learning ecosystem smartness. A dataset was collected from 52 schools in Ghana, Georgia and Estonia. Qualitative school observations and interviews were transformed to the quantitative categories and compound variables using the grid-based approach. We found three distinctive digital learning ecosystem types that described some possible developmental stages in the ecosystem. Discriminant analysis revealed two functions. Most dominant compound variables in the first function were the top-down external provision of digital resources and ICT incentives. The second function characterizes with bottom-up proactiveness of the schools. Path modelling between the compound variables revealed the growing complexity in connectivity among the mediating, transformative and flow components, that determines the smartness of learning ecosystem. Such interconnected components form specific fitness niches which have been co-created in organizations through collective effort, making school ecosystem responsive to the socio-technical regime and externally provided opportunities in the countries.

**Keywords:** digital learning ecosystem, school

## 1 Introduction

Modern schools function as complex learning ecosystems embedded into a wide socio-technical landscape [1]. Various digital assets and transformative processes enable information, data and learning flows through the ecosystem. These learning ecosystems could be described as being digitally in a more or less mature state using the smartness concept. The concept combines systemic and agent-centred dimensions as quality criteria for the maturity of an ecosystem. Giovanella [2] uses the systemic,

[1] Please note that it is assumes that all authors have used the western naming convention, with given names preceding surnames. This determines the structure of the names in the running heads and the author index.

organizational view to smartness in smart city context. It [2] incorporates the bottom-up, participatory, agent-driven self-organization in an ecosystem towards the sustainability of the learning ecosystem to enable common good and high quality of individual's life. Giovanella and associates [3,4,5] defined the multidimensional smartness of a learning ecosystem from the agents' point of view using a bottom-up participatory approach for self-evaluation of the ecosystem. They [3,4,5] assert that smartness does not depend exclusively on ecosystem's ability to run "all gears" in an effective and efficient manner, but rather on its ability to create an environment able to meet individual's basic needs and keep them in a state of "flow" in which their skills are stimulated by adequate challenges, to contribute to the increase of social capital.

In our paper we use smart ecosystem concept [3,4,5] but we narrow it down to smart digital learning ecosystem. The digital maturity of the school as the measure of overall smartness of the learning ecosystems, according to [3,4,5], is still an open issue. We aim to explore digital learning ecosystem smartness and build our research on the theoretical ideas of [3,4,5]. We posit that the smart digital learning ecosystem would evolve dynamically embedded in the external socio-technical landscape through participatory governance of its agents, where the temporally optimal structure and interaction of external and internal assets is achieved that creates challenging learning niches for the self-realization of its agents. Our approach to digital learning ecosystem smartness considers responsiveness of digital learning ecosystems to the future states of the socio-technical landscape, where they are embedded. It assumes that certain transformation components - supporting system responsiveness to future changes - should be at present in the moment of evaluation of the system smartness. Also, the systems should be evaluated as being embedded in the external socio-technical landscape. Evaluation should consider internal and external components, as well as transactional value-making components, that measures proactiveness of the systems to accommodate themselves better to the external landscape.

Secondly, it is an open issue, how to methodologically evaluate the smartness of learning ecosystems. Giovanella and associates [3,4,5] use participatory and bottom-up approaches to support self-evaluation of the stakeholders in the ecosystem. They collected qualitative and quantitative effect data longitudinally. Common approaches for the evaluation of digital maturity [6,7,8,9,10,11,12,13,14] build on self-evaluation practices. In our study we take the post-positivist stance to evaluation. On one hand, we rely on gathering and interpreting qualitative data from schools where different stakeholders' voices are combined by an external evaluator. We assume that such an approach to the evaluation helps to find and explore threats and opportunities in the ecosystem [15]. On the other hand, digital learning ecosystems are complex systems. It needs to explore various components and interrelations among them. For this purpose we transform the qualitative dataset to quantitative binary matrix to analyze the data.

This study aims to identify digital learning ecosystem types, the factors determining these digital learning ecosystems and interaction of the components in them. We will also look at regional digital divide (if there is any) among digital learning ecosystems. Using the data we propose the model of digital smartness of learning ecosystems.

In the following chapters we will first define the principles of digital learning ecosystem that we use to describe ecosystem functioning in this paper. Secondly, we will position our methodological approach in the context of evaluation of ecosystem smartness and digital maturity. Then, we introduce the digital learning context of our study in the sample countries of Ghana, Georgia and Estonia. In the results part we describe the types of digital learning ecosystems, the factors determining ecosystem types and association with regional digital divide. We also explore interconnections among different factors within ecosystem types linking our findings with learning ecosystem smartness. At the end of the paper we will propose the general model of smart digital learning ecosystem based on the findings from this study and discuss the merits and limitations of our empirical evaluation approach.

## 2 Digital Learning Ecosystem

### 2.1 Learning Ecosystem Principles

In our previous research we have defined digital learning ecosystem concept as "an adaptive socio-technical system consisting of mutually interacting digital "species" (tools, services, digital resources) and communities of social agents (such as learners, teachers, support specialists, policymakers), and socio-technically created digital learning services existing in the symbiosis of digital assets and its producers (such as ICT support and training, networks) within a wider socio-technical regime" [17,18].

Our approach is inspired by similar uptake of ecosystem principles for describing information ecosystems as loose, dynamic configuration of different sources, flows, producers, consumers, and sharers of information interacting within a defined community or space [19]. According to Susman-Pena [19] information ecosystems are complex organizations of dynamic social relationships through which information moves and transforms in flows. Through information ecosystems, information appears as a master resource, like energy. Several authors have previously conceptualised also "teaching and learning" as the energy that fuels learning ecosystems and transforms the "information" to "knowledge" [20, 21]. This "knowledge" depicts the general notion of distributed knowledge embedded in relationships, inhering in social practices and the tools and artifacts used in those practices [22]. "Knowledge" in ecosystems denotes all kinds of mutual interactions within the ecosystem that make each organism adaptive to the others in the ecosystem, and the whole ecosystem resilient and responsive to accommodate to the possible changes. The schools as learning ecosystems generally promt such interactions that focus on developing future citizens with the competences that allow them to adapt to the current and possible future states of the world.

Inspired by biological learning ecosystems we have identified a set of digital learning ecosystem principles (see Figure 1):

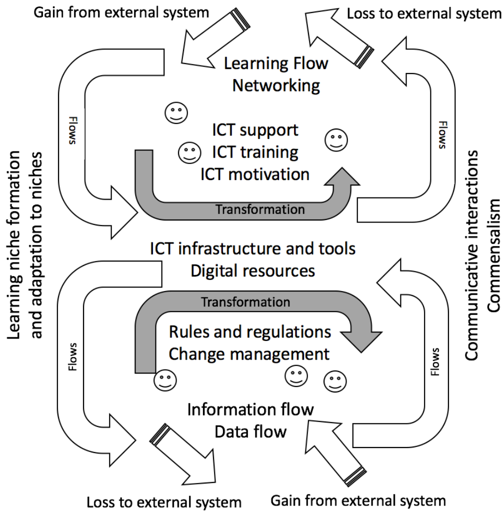


Figure 1. The principles of digital learning ecosystem

i) Learning ecosystem's main goal is to permeate the transformative flows through learning ecosystem. We posit that the flows that should permeate learning ecosystems of digitally enhanced schools are the interconnected learning flow, information flow, and data flow. An example of learning flows are networking and learning activities, where knowledge is constructed individually or collectively from information or data. An example of information flows is an orchestrated administrative information about study management. An example of data flow is grades or other learning and progress measurement data that schools use to evaluate its functioning and project future steps at different levels.

ii) Learning ecosystem should contain different interconnected component types that may act as the mediators or transformers of the flows. Material and digital infrastructure, tools and learning resources mediate as well as transform learning, information and data flows. Active flow-transforming components in the learning ecosystems are rules, change management, incentives, support, and training. In biological ecosystems it is known that at each trophic level about 90 % of energy is lost at metabolistic transformations. This fact is notable also if we are considering potential productivity of learning ecosystems.

Transformative processes play the central role in learning ecosystems because transformation has co-evolving individual and collaborative agency [23]. All human activities (including psychological processes and the self) are instantiations of contributions to collaborative transformative practices that are contingent on both the past and the vision for the future and therefore are profoundly imbued with ideology, ethics, and values. In [23] Stetsenko posits that people together transform their world and are transformed by it in continuous flow of transformative action. This creates the dynamic two-way feedback loop between the inhabitants' well-being in the ecosystem and system's current and future states.

iii) There are different level interactions between the component types in ecosystems, such as commensalism, communicative interactions, as well as interactions between the components and the system level projections such as fitness niches. In ecology Hutchinson [24] defined a niche as a region (n-dimensional hypervolume) in a multi-dimensional space of environmental factors that affect the welfare of species. Learning niches may be conceptualised as abstract range of dimensions in learning ecosystems. They appear as a result of interplay between system components that all together can afford certain type of learning to specific agents in the ecosystem. Any learning niche in social systems may be determined as a set of characteristics that people perceive and actualize as useful for their activities and wellbeing individually or in groups [25]. For example, we can describe a specific "learning at any place and anytime" learning niche that could be promoted by a set of regulative acts favoring Bring Your Own Device (BYOD). It can be mediated by a set of infrastructure components e.g. wifi, charging opportunities or digital services that enable collaboration; and a set of transformative components e.g. innovative teaching approaches that cause a qualitative change in the learning flow. Such learning niches may exist in parallel within dynamically evolving learning ecosystems, and between niches as kind of attraction areas for users [26]. There may be a competition for attention, e.g. teaching ICT for transversal competences, and teaching specific ICT skills for office work. The smartness of learning ecosystem comes from the fitness of specific learning niches to its agents' needs – wheather it can keep them in a state of flow in which their skills are stimulated by adequate challenges, to favor the achievement of self-realization.

### 2.2 Learning Ecosystem as Socio-technical Regime in Socio-technical Landscape

We use concept of responsiveness to define ecosystem smartness and hence describe two kinds of responsiveness: responsiveness of learning ecosystem to external environment and responsiveness of the agents to its niches within a school ecosystem. We refer to the fitness concept from ecology to explain the responsiveness. The fitness is a property developed dynamically in mutual interaction between different system agents and ecosystem appearance levels (within school ecosystems as socio-technical regimes, or at a macro-level that is regional socio-technical landscape). In smart systems the fitness is dynamically created. It describes adaptive response of agents or system's parts to the external environment - an interaction in which both the environment and the agent in interaction will accommodate and change themselves. A mutual responsiveness between ecosystem components and the ecosystem is created by direct and indirect ecosystem-mediated communicative exchanges among counterparts (human agents, digital assets, or services [17,18], their coalitions in using the resources, distributed intelligence and dispersed processes created between networked components in the ecosystem, and adaptive changing of their interactions to appropriately fit to the ecosystem conditions. Bray and associates [27] discuss organizational responsiveness as the ability of an organization to respond in an appropriate manner to mitigate negative threats or capitalize on positive opportunities generated by an organization's environment. Jacobs [28] proposes that responsiveness is a socially constructed attribute referring to the perceptual, reflective and adaptive dimension of an organization. Daft and Weick [29] argued that organizational responsiveness to changes is influenced by fundamental underlying processes involving the recognition and interpretation of those changes.

In this paper we see learning ecosystem smartness rising from responsive processes between ecosystem agents and ecosystem appearance levels in the future-directed ways. Geels [1] distinguished the concepts of socio-technical landscape, socio-technological regimes embedded within that landscape and radical technological niches (innovations) that emerge in it by innovators' actions. Schools as learning ecosystems are socio-technical regimes and must be fit within the regional socio-technical landscape provided by the countries. Technology integration in school has to do with various elements that are interdependent to achieve ICT integration objectives of the bigger socio-technical landscape of national education system. On the other hand, teachers and staff in school are constantly exploring new teaching and learning and information management opportunities enabled by digital technologies that appear as new emerging goals at socio-technical landscape level. They create fitness niches for certain pedagogical goals with innovative technologies, practices and rules that may not be so fit in the current socio-technical landscape provided for schools. When not fitting with the overall school's socio-technical regime, these fitness niches may not be scaled up at the school level. Geels [1] and Perez [30] suggest that such incremental innovations at niche level could sometimes cumulate at regime level and shift the mainstream trajectory how schools' socio-technical regime is shaped, it could even have pressure to reorganize the regional socio-technical landscape. For example, the boom of social software created such a reorganization of teaching at the school ecosystem level. External services provided by the regions are still not coming along with this change, but they are influenced by bottom-up changes. The interrelatedness of technologies with knowledge and experience bases that underlie their development, together with the complementary infrastructures and service networks and accompanying multiple learning processes, provide externalities for all participants and advantages for the society in which they are embedded [30]. Socio-technical regime change may happen by radically shifting assemblies of associations and substitutions, reweaving elements and creating linkages between technical and social elements in order to provide dynamic stability where incremental innovations can still be continued [1].

### 2.3 Systemic Approaches to Measure Schools' Digital Maturity

Smartness is a functional measurable property of the learning ecosystem that helps us define the ecosystem's state regarding to other learning ecosystems in the socio-technical landscape – its digital maturity. In evaluating schools the maturity concept has been used, which relates with relative states of digital innovation in schools. Maturity concept is adopted from natural ecosystems which develop successively from early to mature stages [31, 32]. Thus digital maturity evaluation frameworks suggest some succesive stages of digital innovation to happen in schools. In ecosystemic thinking the succession concept describes suggesstive stages of ecosystems that differ in components, interrelations and entropy. In its early stages the physical structure of ecosystem increases together with entropy (disorderness), which is accompanied by change in input-output relationships. Afterwards the flows and feedback loops in ecosystem increase, the system's internal organization changes towards relatively lower entropy in mature stages, and finally more mature systems accumulate more information that is associated with time lags in the operation of system processes. These principles have not yet been well tied to schools digital maturing stages and succession of stages and will require studies.

Number of frameworks have been developed during last decade to evaluate different aspects of schools' digital maturity: whole-school's use of ICT and digital pedagogical methods [6, 7, 8], leadership and governance for the change practices [9], school's potential in ICT [10], ICT-enabled innovations in different learning settings and implementation strategies [11], and the effectiveness of learning [4,5]. Some tools provide the roadmap to expand further schools' innovative technology-enhanced practices by postulating development stages [12,13,14]. These evaluation frameworks share common educational dimensions that they examine for depicting technology use. They explore existing infrastructure and access to it, pedagogy methods that are enhanced by technology, and change management – that encompasses support and governance from leadership. Many of the frameworks look only internal factors and lack to embed the schools into the regional socio-technical landscape and see the interaction between them. However, some researchers [4,5] also evaluate external components. In our approach we consider important to evaluate schools within external socio-technical landscapes. We also look into what tradeoffs schools are taking to make use of external opportunities or to contribute to the wider socio-technical landscape.

Existing digital maturity tools involve different stakeholders to self-evaluate effectiveness of ecosystem functioning. In our approach we consider important recruiting different stakeholders into evaluation to gain a multi-perspective view what happens in schools. However, for practical reasons we use the external evaluators to collect the qualitative data about the schools.

The digital maturity evaluation tools enable describing the static states of the learning ecosystems at the certain timepoint. The dynamics in ecosystem effectiveness can be seen through the repititive self-evaluation of the stakeholders in different time periods. In our approach we had opportunity to measure the schools only once, thus we could not reveal the dynamic changes of learning ecosystems in time. Yet, our approach focused on certain digital maturity aspecs such as change management and interconnections between internal and external systems that enable depicting some potential of learning ecosystems to plan changes and being responsive.

In order to systemize and analyze the maturity dimensions in schools embedded to the socio-technical landscape of the countries we borrowed the term and definition of the service from ITIL (Information Technology Infrastructure Library) [33] and TMForum (TeleManagement Forum and the Network Management Forum) [34]. We define the service as a flow of logically combined products, e.g. units, inventories, processes, activities. They are kind of species in the learning ecosystem that emerge from the interaction of technical and human components in the socio-technical regime and landscape context. We follow the experience of digital maturity tools that considers that systemic integration of digital learning involves an implementation of change on three dimensions: pedagogical, technological and organizational [35]. In addition, we use a three-layer approach for digital learning services to depict the interaction between external and internal environment that supports the self-realization of the agents in the ecosystem. Three types of digitally enhanced services are distinguished based on: who provides the service; who manages the service; where the service user is situated; where the actual activities for creating, maintaining and using the service takes place; where the rules and regulations for service use is defined. The three types accordingly are: i) external ICT services that exist at regional socio-technical landscape and are provided to schools, ii) internal services that are created and maintained in schools' socio-technical regime, and iii) transactional/trade-off services mediating the interactions between regimes in different schools, as well as between the regional landscape and the socio-technical regimes of schools [36, 37]. In this paper we look how the digitally enhanced services create different types of learning ecosystems, which are at different digital maturity level based on the interactions among different service types.

The analytical approaches for detecting digital maturity have multidimensionally mapped and compared the schools as learning systems, and explored the major factors that distinguish system types. We wanted to take one step further in our analysis and explore the relationshop between different learning ecosystem services. We believe this would enable to describe the learning organizations better using the concepts (such as ecosystem flows, interactions between components and feedback loops, and transformation) from real ecosystems. Ecosystem framework has so far provided a fruitful analogy to see differently the economy, information management and other domains, and could be used to bring a new quality in understanding the smartness of digital learning ecosystems.

# 3 Methodology

## 3.1 Sample and Context Description

52 schools from Ghana Western-Takoradi region (N=17), Georgia (N=30) and Estonia (N=5) were involved into the sample. The schools of the sample were selected using the locational principles - centrally located city schools, schools from city suburbs and, urban area schools across the countries. The countries represent digitally developing (Ghana) and relatively more developed socio-technical regimes (Georgia, Estonia).

## 3.2 Estonia

Estonia has highly developed ICT society, most of the households have computers and Internet connection, many people and students own smartphones with Internet connection. The public initiatives in the fields of ICT in education started with Estonian Tiger Leap organization initiated at 1997. It provided infrastructure support for schools, and created nationwide training network for teachers digital competences, as well as the digital repositories for teachers. The ICT competences were defined in national curriculum around 2000. Currently Estonia is following ISTE standard of ICT competences for students, teachers and school administrators. By 1998 all schools were online provided with Internet connection by Ministry of Education. By 2015 most of the schools were equipped with wifi connection for students provided by combined efforts of regional municipalities and schools themselves. Wifi connections in schools are still not sufficient to provide simultaneuous internet access to evey student, and schools are lacking resources to renew infrastructure. In the beginning of 2000 most of the schools had one or two computer-classes that is still the case. Starting from 2005 a nationwide project has managed to equip most of the classrooms with computers and data projectors. Currently most of the schools also hold few mobile classes (laptops or tablets) that may be used in the classrooms. Many schools use Bring Your Own Device (BYOD) policy. Few schools require tablets or laptops throughout all the studies. Schools have proactively gained access to digital infrastructure, tools and software by participating in the competitions held by government funded Tiger Leap and National Information Technology Foundation for Education. In 2008 the burst of social media has changed teachers' agency in developing digital learning activities for students. Every teacher is required to teach digital competences embedded in their subject lessons. Additionally some informatics courses are provided at grades 5 and 9, and robotics and programming lessons are taught as hobby education. From 2017 Estonia is digitalizing all textbooks. The digital resource cloud eKoolikott has been initiated by the ministry, and several publishers also provide digital textbooks. The eDiary environments are widely used by schools. One of the five strategic priorities of the Estonian education strategy, known as the Lifelong Learning Strategy 2020, is digital focus in lifelong learning. From 2017 digital maturity of schools has been monitored with DigitalMirror software, that is to provide change management support for regional educational policymakers and schools.

### 3.3 Ghana

Computers and the Internet in Ghana start late back in the 1990s. However the formal national ICT agenda was developed in 2003 [38, 39, 40]. The agenda called on ICT for Accelerated Development (ICT4AD). In the policy 14 key areas were identified as the pillars for nation's digital transformation. The education sector was cited as one of the key pillars [41]. Consequently, an ICT in Education Policy was officially published in 2008 [41]. Its content was influenced by the 2007 New Education Reform (NER). According to policy ICT was introduced in schools; ICT tools and resources were supplied to schools; and teachers were trained [42, 43]. At the national level ICT in Education collaborating unit exist to collaborate with regional and district education offices on ICT in schools. At the Regional and District Education Offices an officer in charge of ICT coordination is expected to be a post.

As required by policy ICT is taught in schools as a subject and in addition it is expected to be integrated into all other subjects. Schools have been supplied with laptops and teachers were trained. At the terminal point of the pre-high school education, students pass examination to test their ICT competence. National

Inspectorate Division supervises instructional delivery in schools and compliance to the national curriculum. At the regional and district education offices, circuit supervisors (CS) play the role of school inspectors. Added to the management structure school heads take the school-based supervisory roles in conformity with the rules and regulation of Ghana Education Service (GES). District education offices build up data about schools and transmit to the EMIS unit of the national office of Ministry of Education/Ghana Education Service. Practically, educational delivery in Ghana tends to assume top-down approach and seems to leave little or no room for bottom-up approach. By and large the policy of ICT in education in schools is being pursued in both endowed and less endowed schools to the best of schools' condition.

### 3.4 Georgia

Georgia launched the first school computerization program in 2005. Since then number of governmental programs has been realized to enhance learning and teaching process with technology.

Schools have been equipped with desktop computers that until now are kept in a separate computer lab where students and teachers have limited access to technology. The student computer ratio is 30:1. Due to the lack of technology and the space limitation the technology is mainly used for ICT lessons. Teachers can use computer labs for subject-specific lessons only if the labs are not occupied with ICT lessons. In addition to government provided technology the schools obtain laptops. Laptop computers and projectors mostly are the awards that schools get after participation in different contests organized either by the Ministry of Education and Science of Georgia, or different companies. Laptops are mainly used for subject teaching in the classroom, but again due to the limited number teachers have to sign up in advance to be able to use in their classrooms.

In 2011 Georgia began ambitious program to grant all the first graders netbook computers on their first day at school. By 2017 all the students from 1st to 7th grade possess government granted netbooks. Classroom management software – Mythware – is installed in the netbooks to enable teachers to manage class virtually. However the system works with intranet as primary schools usually do not have Internet connection.

All the schools in Georgia are connected to the Internet. Internet connection is usually wired to computer labs, teachers common office area and administrative offices. National Center for Teacher Professional Development offers free ICT trainings for the teachers of public schools. The trainings differ by complexity level starting from basic ICT skills to methodologies of using ICT for enhancing teaching and learning process.

New edition of National Curriculum of Georgia has been approved recently. According to the curriculum ICT is taught as a separate subject in all 1st, 5th and 6th grades of Georgia. Also, curriculum defines ICT to be a cross-curricular discipline through 1st to 12th grade through all subject groups.

### 3.5 Instrument

We collected qualitative data through semi-structured interviews of the teahers, ICT managers and school principals from Georgia (total number of interviews=62; School principals=15, teachers=42, ICT managers=5 out of which 2 are full-time ICT managers, and 3 ICT managers who served as teachers at the same time.), Ghana (total N=51; school principals=17, teachers=17, ICT managers=17) and Estonia (N=5, mapping was done by educational technologists working in these schools). In addition we made observations of lessons and schools digital settings in the corresponding schools to triangulate the data from the interviews. The qualitative data was later quantified.

We developed the grid of digitally enhanced services in schools [36] based on the qualitative data and identified 3 educational dimensions following the international experience of similar frameworks: Infrastructure, learning facilitation and change management. In addition our matrix contains three types of services: internal, external and transactional, to depict the interplay of external and internal factors. Total 191 statements were allocated to the educational dimensions across 3 types and 3 dimensions of services [44].

We mapped the schools on the grid using the binary system. 0 value indicated that service did not exist in the school and 1 showed existance of the service. Grid of services helped us to explore how schools make use of resources at hand to create digitally enhanced learning ecosystems that is responsive to external environment and agent's needs within the ecosystem.

### 3.6 Data Analysis

Data from observation grid analysis [36] was transformed to 13 compound variables describing the following dimensions: a) Mediating components: ICT infrastructure, Digital resources, Mobile teaching tools, Computer class; b) Transformation components: ICT rules, ICT change management, ICT incentives, ICT support, ICT training; c) Flow components: Digital learning, Networking, Digital information management, Data analytics. Note that the separation of components to mediating, transforming and flow type of components in this article is an ecosystemic modelling attempt. The authors support the idea that in a way each of those components has a role in transformation processes.

Hierarchical Cluster analysis with Ward method was composed with 13 compound variables. ANOVA identified 3 significantly different clusters of digital learning ecosystems among schools. Chi square analysis was used to find the country-based distribution of digital learning ecosystem types. We also computed compound variables for internal, transactional and external dimensions of each compound variable. Discriminant analysis was run with these variables to identify more precisely the internal, transactional and external factors determining school distribution to three distinctive learning ecosystem clusters. Path analysis of clustered learning ecosystems with linear regression model was conducted separately for each cluster using the initial 13 compound variables. This approach was taken to keep the path model simpler.

# 4 Results

## 4.1 Digital Learning Ecosystem Types

Hierarchical Cluster analysis with Ward method predicted 3 distinctive clusters among schools based on all digital learning ecosystem components. The followup K-means analysis was conducted searching for 3 clusters of digital learning ecosystem types. The cases were divided between 3 types as follows:, Cluster 1 – 27 cases, Cluster 2 – 12 cases and Cluster 3 - 13 cases. ANOVA results showed that these clusters were significantly ($p<0.05$) different in 12 components, and did not differ in one component - Computer classes. After 7 iterations the final cluster centres were identified (Fig. 2).

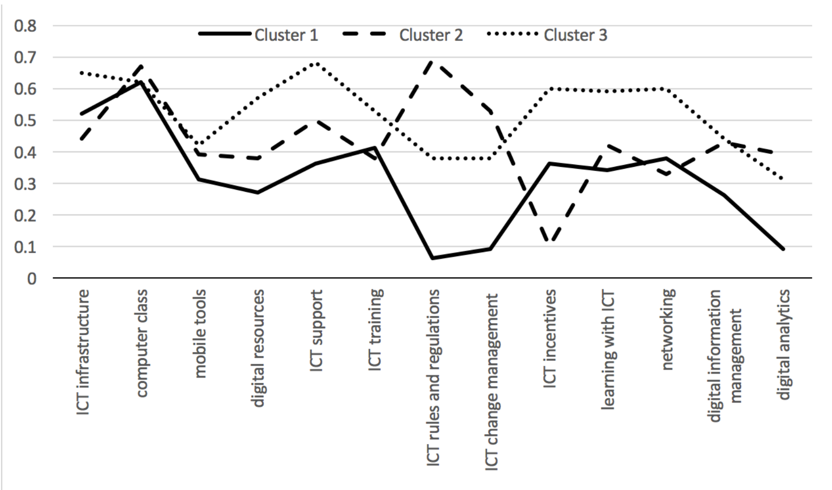


**Fig.2.** Digital learning ecosystem types: Cluster 1 – low level of digital learning, networking and information flows is accompanied by lowest performed ICT transformation processes, especially at regulative and change management aspects; Cluster 2 – Higher application of digital transformation processes especially at regulative and change management aspects, but low level ecosystem flows of learning with ICT and networking, higher focus on digital data flows; Cluster 3 – learning with ICT and networking flows are achieved at higher level using higher level of Digital resources provision, ICT training and ICT support as transformation processes.

In the schools of Cluster 1 (N=27) the ICT infrastructure was at medium level, but the digital resources and mobile digital tools were seldom sufficiently available. ICT rules and ICT change management were almost missing in these schools, while ICT incentives, ICT training and support were at medium level. Digital information management, learning with ICT, networking and digital analytics were at lowest level among the three clusters. Based on our qualitative findings from Georgia and Ghana [45,46] we can summarize that ICT is mostly used to maintain digital information flows for school administration in this cluster.

Fig. 2 indicated, that in Cluster 2 (N=12) the components of ICT infrastructure and digital resources were of medium availability, while ICT rules and ICT change management were the most used transformative components if compared to lower level of ICT training and support, and rare ICT incentives. The flow components - learning with ICT, networking, digital information management, and digital data analytics - appeared at medium level. We could summarize that in this cluster the externally provided formal rules have been applied at school level without causing actual learning ecosystem transformation towards digital one.

Cluster 3 had the highest availability of infrastructure and digital learning resources among the three clusters. Schools belonging to Cluster 3 (N=13) were characterized with higher level of some flow components - ICT learning, networking, digital information sharing, which associated with higher level of some transformation components: ICT support, ICT training, and ICT incentives. In these schools ICT management, ICT rules, and digital analytics were present at above the average level. We could assume that in these shools the digital learning ecosystem was empowered by the increased knowledge-related transformative components (training, support) and learning and networking flows themselves.

From our model we can assume that the 3rd cluster represents the smartest ecosystem of our sample. The ultimate goal of technology provision to the education is supporting the learning of digital era. The learning part of the ecosystem is depicted in flow components in our model. It includes: digital information and analytics, learning with ICT and networking. Fig.2 shows that we can achieve higher flow with certain higher mediator and transformative components if applied together. Division of transformative components has occurred among clusters. ICT rules and change management, which emphasize top-down organization of the environment, are clearly leading in the 2nd cluster. The 3rd cluster shows the highest indication of transformative components such as: ICT support and incentives, ICT trainings. From our definition the smart ecosystem embraces the notion of bottom-up and participatory agent-driven organization. We can conclude that 3rd cluster represents how the ecosystem provides the agents with adequate support for self-realization. As a result we have the highest indicator of the flow components in this cluster: digital learning and networking. In the same cluster the mediator components like digital infrastructure and digital resources are higher. However, we may not say that ICT rules and ICT change management are unimportant. In our sample schools we observed that particularly whole-school inclusive change management is not yet very well applied.

### 4.2 Factors Determining the Digital Learning Ecosystem Types

Discriminant analysis with compound variables for internal, external, and transactional dimensions of each variable group revealed two functions that differentiated digital learning ecosystems of schools at the highest significance level and could be used for measuring digital divide among schools' digital learning ecosystems (see Figure 3). The first function depicted 80.4% of the variance and the second function 19.6%.

**Table 1.** Structure matrix of discriminant analysis

| | Function 1 | Function 2 |
|---|---|---|
| ICT rules internal | -.269* | .258* |
| ICT change-management transactional | -.174* | .117 |
| Digital resources and services external | .125* | .102 |
| ICT incentives external | .122* | .082 |
| Digital information transactional | -.119* | .010 |
| ICT infrastructure external | .113* | .052 |
| Data analytics internal | -.095* | .091 |
| ICT rules external | -.083* | .008 |
| ICT support transactional | .029* | -.022 |
| Networking external | .024* | .015 |
| Computer class internal | -.012* | -.008 |
| Digital learning transactional | .041 | .498* |
| Digital learning internal | -.058 | .250* |
| Digital resources and services internal | -.023 | .237* |
| ICT support internal | -.035 | .233* |
| ICT incentives internal | .014 | .210* |
| ICT infrastructure transactional | -.011 | .189* |
| Digital resources and services transactional | -.127 | .177* |
| ICT training internal | -.030 | .152* |
| Networking internal | .013 | .150* |
| Digital information internal | -.054 | .115* |
| ICT change-management internal | -.027 | .112* |
| Digital information external | .085 | .105* |
| ICT infrastructure internal | .011 | .104* |
| Mobile tools internal | -.046 | .090* |
| Mobile tools transactional | .006 | .067* |
| ICT training transactional | -.032 | .065* |
| Digital learning external | .036 | .065* |
| ICT training external | .044 | .049* |
| ICT support external | .001 | .034* |
| Data analytics external | -.018 | .032* |
| Mobile tools external | -.006 | -.025* |

Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions
Variables ordered by absolute size of correlation within function.
*. Largest absolute correlation between each variable and any discriminant function

The Wilks' Lambda test indicated that the model is a good fit for both functions DF1 ($\lambda$=.002, $\chi 2$= 214.632, df = 64, p=0.001), DF2 ($\lambda$=.080, $\chi 2$= 84.697, df = 31, p=0.001). The group centroids for the Cluster 1 was (F1= -12.099, F2-.759), for Cluster 2 (F1=4.296, F2= -2.360) and for Cluster 3 (F1=2.246, F2=5.601). From the classification results, 100% of the original grouped cases were correctly classified. The corresponding equation of the functions were:

DF1 = 2.096 (ICT infrastructure external) + 2.077 (Digital resources and services external) - 0.565 (ICT change management transactional) -16.730 (ICT rules internal) + 7.262 (ICT incentives external) + 1.183 (Digital information transactional). DF2 = -5.532 (ICT infrastructure transactional) + 1.407 (Digital resources and services internal) – 1.243 (Digital resouces and services transactional) + 1.056 (ICT support internal) + 1.600 (ICT training internal) - 0.077 (ICT change management internal) + 3.009 (Digital learning internal) + 9.533 (Digital learning transactional) + 2.648 (Digital information internal) + 0.792 (Networking internal).

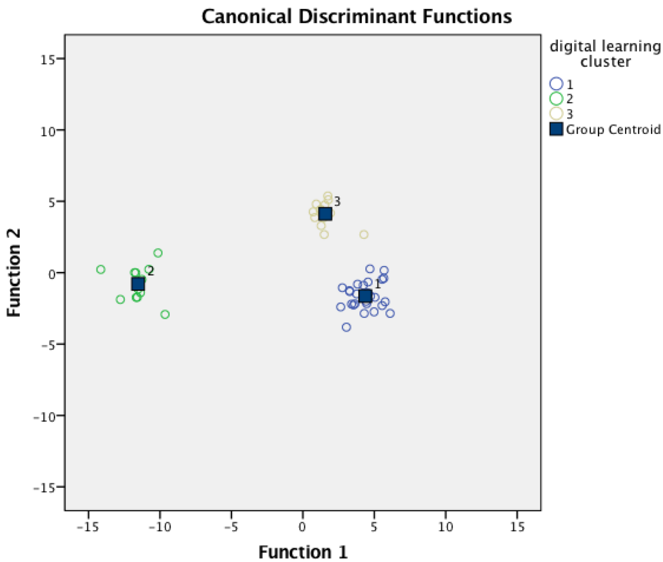


**Fig. 3.** Canonical discriminant analysis of the distribution of schools around the three cluster centres depicting different learning ecosystem types.

These findings can be interpreted as follows: digital maturity of learning ecosystems expresses itself as the appropriate orchestration of digital learning resources, transformative components (ICT training, support, incentives, rules) and digital learning and networking activities. Most dominant compound variables in the first function indicate towards the top-down external provision of digital resources and services and infrastructure and ICT incentives, but missing internal ICT rules. The second function relates with the bottom-up pro-activeness of schools in gaining digital learning resources and infrastructure, applied ICT rules, collective engagement in providing internally and change management, ICT support, incentives and training, and the evidences of internal flows of learning, networking, and digital information.

### 4.3 Learning Ecosystem Types and Digital Divide

Taking the ecosystems approach assumes that there might be different stages in the ecosystem transformation that may be successive if studied in longer time frame. Our instrument observed schools as digital learning ecosystems with wide scale of characteristics common for evaluating digital maturity of schools, thus we may associate the three clusters of schools with specific maturity stages of digital learning ecosystems. This enables the comparison of schools for detecting digital divide among schools in the region or across regions. Digital divide among schools in the country has been previously explored in our studies among the schools in Ghana, where training for teachers' digital literacy and digital technology usage were the differentiating factors of digital divide [46]; while in the schools of Georgia ICT change management component distinguished some schools from the others [45]. In this study we wanted additionally to explore if digital divide among schools' measured with digital learning ecosystems approach appears both within regions and across regions (being evident in developing countries).

We found that three different digital learning ecosystem types were represented in each country, except in Estonia where the sample of cases was small. We may tentatively assume that such digital learning ecosystem types may be representative to successive transformational changes among schools in the digitalization path and could be used for identifying schools that are digitally divided and less/more digitally mature in comparison with their regional schools.

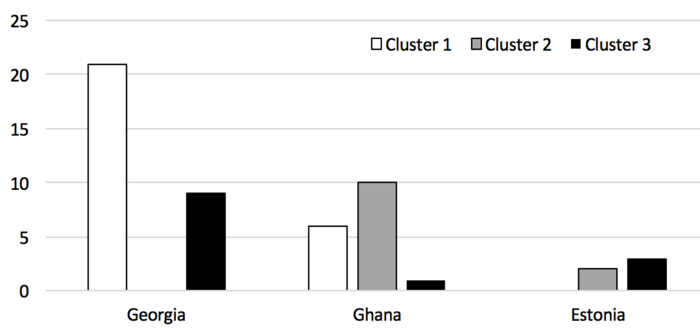


**Fig 4**. Digital divide among schools in developing and developed countries

On the other hand, it came out that the learning ecosystem types were not country specific. We performed Chi square analysis to see if some of the learning ecosystem types occur more in the developing countries Ghana and Georgia, indicating the digital divide among countries' digital learning ecosystem maturity. The Chi square analysis showed that some digital learning ecosystem types were significantly country-specific $X^2$=27.582, df= 4, p<0.001 (see Figure 4). Ghanian schools belonged more than expected to Cluster 2 (Std. residual 3.1), Georgian schools to Cluster 1 (Std. residual 1.4), and Estonian schools to Cluster 3 (Std. residual 1.6). We can assume that these identified functions describe some general tendencies across countries as the schools develop in a less or more digitally mature socio-technical landscape.

### 4.4 Digital Learning Ecosystem Smartness

Path modeling between the compound variables within three ecosystem types (see Fig 5-7) revealed the growing complexity in connectivity between the mediating and transformative components of digital learning ecosystems, and flow components that determines learning ecosystem smartness. Such interconnected components form specific fitness niches which have been co-created in organizations through collective efforts, making the ecosystem responsive to the socio-technical regime and externally provided opportunities in the countries.

Fig. 5 depicts the Path model in Cluster 1. It visualizes that strongest paths were around digital information management in schools rather than around digital learning activities. In this cluster the application of rules and regulations and ICT change management was applied at low level, but it appeared that the rules and regulations were associated with digital data management. Also ICT training and ICT incentives were bi-directionally related indicating that ICT training was prompted by school with some motivation means. We know from our qualitative findings from Georgia and Ghana [45,46], that many school headmasters saw the main role of ICT in schools in managing information flows and the teachers were passive in using ICT in lessons, although they had had ICT trainings.

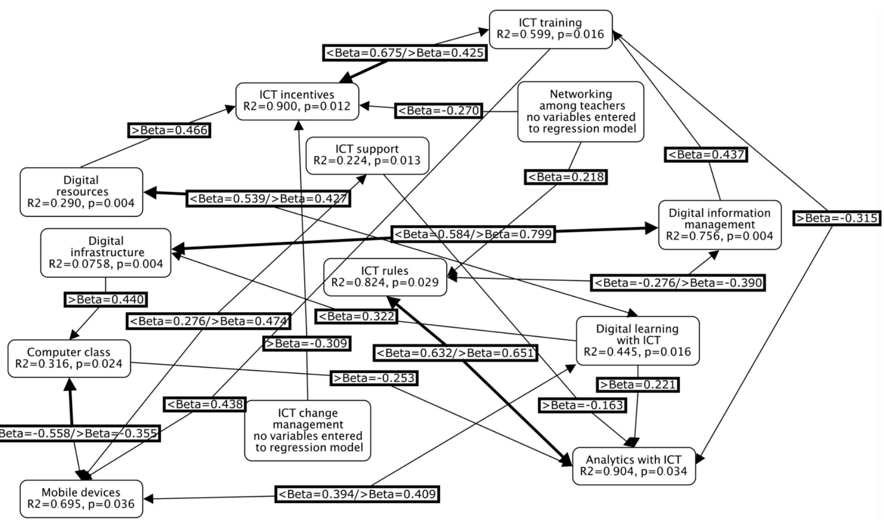


**Fig. 5**. A Path model of digital learning ecosystem components' interrelations in Cluster 1

The Path model of Cluster 2 (Fig. 6) demonstrated the computer-class centred learning niche where the main transformative component was ICT training that built on digital information management, it had impact on and was influenced by digital learning and ICT infrastructure. Digital resources of schools were dependent on learning with ICT, we could see in our interviews in Ghana [46] and Georgia [45] that it were the active teachers that found, shared and developed new digital resources. Interestingly, ICT rules were excluded from this regression model although in this cluster the rules and regulations were formally at place in schools. We found in the interviews that the formally existing ICT rules, regulations, visions and agendas were not known by the teachers in these schools. The schools generally had authoritive leadership that did not include teachers' agency [45,46]. Figure 6 indicates that ICT change management had no connections with other components except negative two-way dependencies with mobile ICT devices, showing that mobile teaching niche was discouraged. We know from our qualitative analyses in Ghanaian and Georgian schools that mobile devices were missing or dysfunctional.

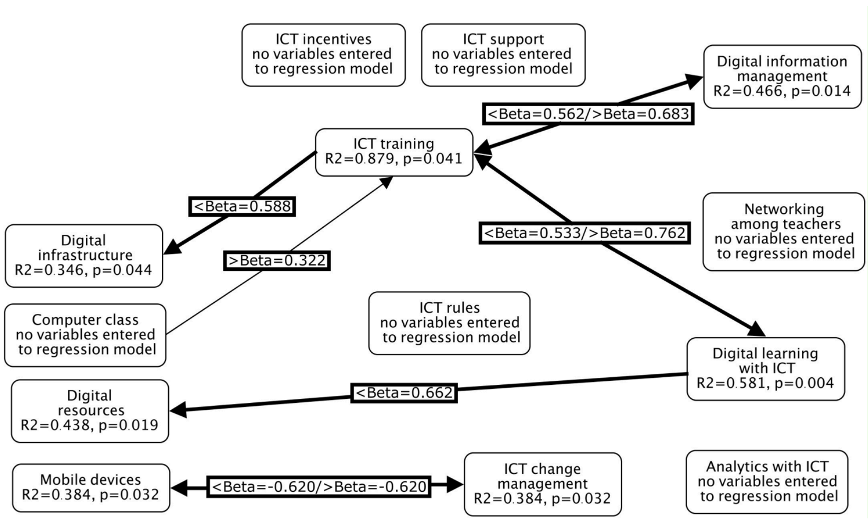


**Fig. 6**. A Path model of digital learning ecosystem components' interrelations in Cluster 2

Figure 7 from Cluster 3 reveals the most complex connectivity among the components. In this cluster the ICT rules and regulations and change management were applied at the moderate level. But different to other clusters, they were connected over digital data analytics with digital learning with ICT, also change management had input from Digital information management and ICT training. We found in qualitative analysis that in the schools of this cluster there was a collective decision-making process applied that involved different stakeholders [45]. We may depict the path model of cluster 3 as the learning ecosystem with the emerging connectedness of different mediating, transforming and flow components. Notable is the mutual antagonism of computer class teaching and mobile tools teaching.

Our approach to see schools as the digital learning ecosystems was not based on dynamic or longitudinal datasets. We may not claim, that the depicted digital learning ecosystem types represent certain successive states in ecosystem development towards digital maturity. We may conclude that schools in our sample seemed to follow authoritive top down model where ICT management for school administration was in forefront, and the collective and bottom up powered change management model that used different transformation means and inputs from learning-, data-, and information flows for planning the digital change. In all the path models digital learning resources appeared to be the most influential among the mediation components of learning ecosystems.

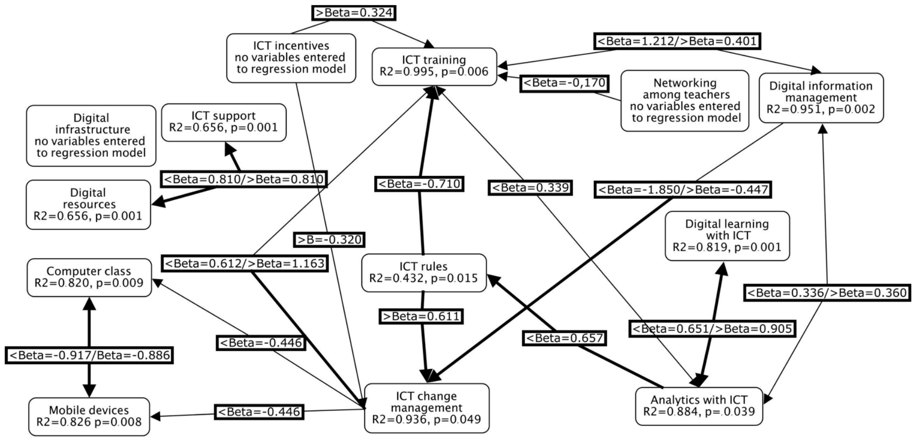


**Fig. 7**. A Path model of digital learning ecosystem components' interrelations in Cluster 3

# 5 Discussion

The goal of this paper was to study the digital learning ecosystem types in schools, the factors defining the types of the ecosystem and interaction of the components in the ecosystems. We refer to the following open issues in the paper: digital maturity as the measure of overall smartness of learning ecosystem; and the methodology of studying digital maturity and smart ecosystem.

We narrowed down Giovannella's [2,3,4,5] definition of smart ecosystem to the smart digital learning ecosystem concept. Giovannela emphasizes bottom-up, participatory, agent-driven self-organization approach of smartness taking into consideration external and internal factors of the ecosystem [3,4,5]. Building on this concept our study additionally highlights the responsiveness of digital learning ecosystems to the socio-technical landscape, where they are embedded, and connectedness of the components within the ecosystem. Our model takes the following assumptions into the consideration while evaluatng the smartness of digital learning ecosystem: certain transformation components are in place that support system's responsiveness to future changes; the learning ecosystems are embedded in the external socio-technical landscape; and the system involves transactional components, besides external and internal factors. Transactional components measure proactiveness of the systems to accommodate themselves better to the external landscape.

Distinctive to the previous researches on smart ecosystem and digital maturity tools, we use qualitative data collected by the external evaluaters to develop the instrument for the study. Qualitative data gave us a better opportunity to see the threats and opportunities in the digital school ecosystems [15]. The data was then quantified that enabled us to explore the interplay of the school regims and external socio-technical landscape and develop the model of smart digital learning ecosystem.
Based on the findings from the study we suggest to model the learning ecosystem with 3 types of the components: mediator, transformative and flow components (see fig. 8). The school as learning ecosystem is embedded in socio-technical landscape. Socio-technical landscape imposes a set of rules that enable and constrain activities within communities [1]. Ecosystem functioning is dependent on these enablers and deterrents. External enablers (provided from the socio-technical landscape), as well as interaction of agents with mediating and transformative components of the ecosystem, mediate transformation processes in schools. This connectedness creates the learning flow in the ecosystem. The flow then transforms back socio-technical landscape.

Mediator components mediate school's transformation to digitally matured environment. We use dashed line (see fig. 8) to illustrate the probability of internally mediated and externally provided mediating components. The mediating components trigger transformative components in the learning ecosystem. The direction of the arrows as well as dashed line pattern describes that transformative processes might be imposed by the rules of socio-technical landscape (e.g. centrally provided teacher trainings, national ICT incentives and etc.) or internally mediated by agents (e.g., school ICT agenda, locally organized teacher professional development trainings). The dashed line also represents that there's no clear line between mediator and transformative components, as some transformative components might be mediators at certain point.

Results achieved through mediator and transformative components are then depicted in flow components of the model that is the ultimate goal for smart ecosystem's functioning. Learning, data and information flows go back to socio-technical landscape as an incremental innovations or niches described by Geels [1]. Flows also go through the loop of school learning ecosystem bringing new mediating and transformative components to the ecosystem and therefore contributing to ecosystem transformation.

Connectedness of mediator, transformative and flow components in the ecosystem supports creation of learning niches. Learning niches enable schools to be responsive to the socio-technical landscape they are embeded in, as well as to agents' needs in the learning ecosystem. In other words, responsivness describes adaptive response of agents or system's parts to the external environment, and vice versa the environment's change to fit to the ecosystem condition. We have two-way feedback loop between the agents and ecosystem's state. Agents transform ecosystem and are transformed by it in a continuous flow [23].

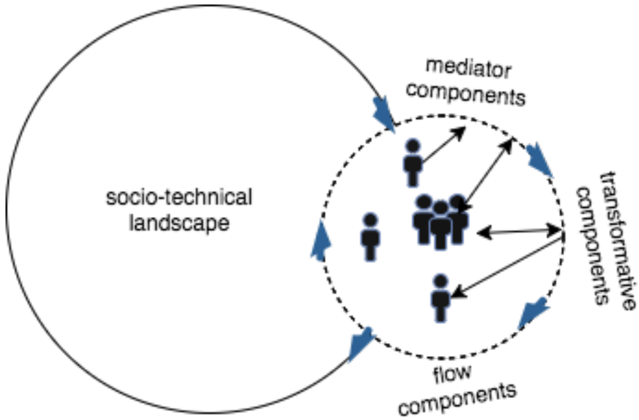


**Fig 8**. Smart learning ecosystem model

Responsiveness of ecosystem to socio-technical landscape and agents' needs within the ecosystem defines its smartness. Based on this assumption we propose to discuss the smartness of learning ecosystem with three indicators:

a) Intensity of flow component within the ecosystem. Higher the flow component is the smarter the ecosystem becomes. We base this assumption on the results presented in 4.1. Higher level of mediator and transformative components result in a reletively higher level of flow component in schools. The flow of learning, information and data component is an ultimate goal for ecosystems functioning.

b) Connectivity of the mediator, transformative and flow components among each other and to the agents. Connectivity enables creation of learning niches that support agents' individual needs. Therefore, connectivity of the components define ecosystem's responsivenes to the agents' needs. Complex connectivity among the components and agents activate more learning niches in the ecosystem, making it more responsive. This notion is based on the results presented in 4.4.

c) Ecosystems' responsiveness to a regional socio-technical landscape where it is embedded. Socio-technical landscape provides the set of rules that enables or deters certain activties in socio-technical regimes. On the other hand the incremental changes and innovations evolving on the socio-technical regime level transfers back to the landscape. In 4.3 we present how ecosystem type was related to the country profiles. Subchapter 4.2 described the interplay of external and internal factors to represent the idea of ecosystem responsivenes to the socio-technological lanscape.

Our model defines and compares the ecosystems of different digital maturity, the factors that contribute to the smartness of the digital learning ecosystem and the strongest path of the connection among those components within each type of ecosystem. We hope the model will support designing the smart digital learning ecosystem process. It will provide the ecosystem designers with a set of indicators (or "services" in our model) that will contribute to put the structures and respective processes into the place.

We acknowledge that there are some limitations to this study that needs further exploration. We name responsiveness as the key factor for smart learning ecosystems.

Responsivness to socio-technical landscape encompasses its future-orientedness not only determination of the fit to current state of landscape or ecosystem itself. However, our dataset do not support exploration of emergent changes in digital learning ecosystems and regional socio-technical landscapes. With the dataset from three countries we could monitor some maturity stages of learning ecosystems, and relate them with top-down and bottom up processes in ecosystems that are embedded to socio-technical landscapes of regions and generally with the notion of digital divide of schools in regions. Secondly, we quantified our qualitative observations from the schools to model the interactions between the components in the ecosystem. It reduced the actual richness of context in digital learning ecosystems. Third, we made some assumptions about the services related to the learning, data, and information flows in order to model smart learning ecosystem. But it was out of the scope of this paper to measure the flows itself with quantitative means. And last, our data collection method limits us to assess the effectiveness of the ecosystem and process outcomes, as opposed to the participatory self-evaluation approach of the stakeholders in the ecosystem. Our instrument of grid of services describes the existence of certain services in the ecosystem with a binary scale. Therefore, it provides the static description of the temporal structure of the ecosystem.

## 6 Conclusions

This study explored the types of the digital learning ecosystem and the factors that contribute to schools' evolvment as smart ecosystems. We understand smartness as a qualitative functional property of learning ecosystem that describes its states of digital maturity. The study was inspired by Giovannella's [2,3,4,5] definition of smart ecosystems. Buidling on this theory of smart ecosystem, as well as the results from this study we proposed the model (see fig. 8) of smart learning ecosystem. We described the model with mediator, transformative and flow components to illustrate schools's responsiveness to a bigger socio-technical landscape and agents' individual needs within the ecosystem. Based on the results from the schools of three countries we conclude that ecosystems responsivness to the external environment and stakeholders' needs within the organization contributes to the smartness of the learning ecosystem that can be related to its digital maturity state. The model can contribute to the design of the smart digital learning environment.

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