Towards knowledge ecosystems: Modelling knowledge dynamics in environmental systems

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Abstract

In order to understand basic mechanisms of so-called Knowledge Ecosystems, the paper presents a study for modelling the emergence and diffusion of knowledge in regards to environmental conditions. The text gives an outline for the description of Knowledge Ecosystems by integrating 1) models for environmental dynamics based on resources and attractiveness, and 2) models for knowledge dynamics based on the behaviors and processes of knowledge agents (innovators) and agencies. As key methods, the work employs Cellular Automata for the modelling of knowledge environments, as well as agent models for the simulation of knowledge agents (innovators). The paper presents preliminary results of the ongoing study, including a first version of both scopes integrated into one descriptive system.

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1. Introduction

In the context of post-industrial Knowledge Society and Knowledge Economy, it has been understood that knowledge work is significantly influenced by environmental determinants. Despite controversial disputes about the term ‘Knowledge work’, we may use it here to describe work processes based on intellectual training, creative research and innovation, all of which have become central to social welfare and value creation in highly developed economies. The setting of such activities certainly reduces itself not reduced to natural, physical and spatial

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environment, but includes socio-cultural and technological ambience too. These complex environmental systems are conditioning the creation, dissemination, and application of ideas and innovations to a large extent. On this background, the notion of Knowledge Ecosystems has become a key term to describe environments that trigger intellectual interaction and innovative production. The term indicates a dynamic relationship between knowledge work and environmental conditions, hinting at cross-scale processes between diverse agents and agencies. These actors benefit from, and contribute to, synergetic networks which continuously transform and develop the resource ‘knowledge’. The best-known ecosystem is certainly the Silicon Valley, whose actors themselves have repeatedly stressed its eco-systemic qualities.

2. State of research

Interdependences of knowledge work and environment have been observed on small-scale as well as in large-scale. On small scale, factors of socio-spatial environment like affordance, group cohesion, and personal control strongly influence knowledge work. On the large-scale level of cities and regions in turn it is the technological, cultural, and geographical environment that impacts the emergence of creative milieus, the diffusion of innovation, or the transfer of knowledge and skills. It has been recognized that highly influential micro-to-macro dynamics take place: from small-scale innovation activities (e.g. Garage start-ups like Google or Facebook), as well as from single institutions (e.g. Bauhaus, Stanford University, Bell Labs) massive global disruptions can emerge. Vice versa it is understood that influential macro-to-micro dynamics exist that determine the knowledge work-performance of individual actors and agencies to large extent e.g. socio-economic conditions, public opinion, or real estate development.

Intensified globalization, technological advances, as well as quickly shifting economies have made the successful establishment and maintenance of knowledge work environments an important issue. Well-functioning ecosystems have been recognised as fundamental conditioners of successful knowledge processes, which in turn lead to innovation, economic growth, and social stability. Research institutions, industries and policy makers thus strive hard to facilitate knowledge ecosystems, and to provide conditions appropriate for innovation, research, and creativity. On the application level, however, little evidence is given how such knowledge environments can be purposefully engineered. The majority of existing research is descriptive and statistical in nature, based on methodologies of social sciences. There is few theory in support of practical planning and development. The lack of applicable knowledge hints to deficits in fundamental research. Apart from a number of pioneering studies (mostly in social sciences, e.g.) descriptions, methods and models barely exist that provide a reliable basis for research on knowledge environments and their systemic principles. Due to their inherent complexity and dynamics, we are still far from understanding how knowledge ecosystems emerge, function, and persist. The lack in scientific fundamentals, in turn, can be explained by a fragmented approach which views the various levels of knowledge ecosystems from micro to macro scale in separated manner (Vertical Disintegration). Similarly, comprehensive studies are rarely undertaken that horizontally connect involved fields and disciplines (Horizontal Disintegration). As ecosystems, by nature, are integrated vertically and horizontally, such a fragmented scope overlooks key aspects of eco-systems, before all the dynamic exchange and flow of knowledge between a multiple actors and levels.

**Horizontal disintegration:** Integrative notions of environments are few in the context of knowledge research. Vice versa few comprehensive notions of knowledge have been created in the context of environmental studies. The combination of the two domains remains a widely undiscovered field, despite knowledge-based discourses have emerged in social geography, in urban and spatial studies, as well as in media and systems engineering. Also in knowledge and innovation management, environmental and spatial aspect have come into focus, but did not find yet much response.

**Vertical disintegration:** Notably, before-mentioned discourses unfold most prominently on abstract and large-scale perspective. Before all, valid concepts have been developed on the level of regional, urban, or cluster development. Disconnected from them are, however, eminent theories in microsociology, organizational and environmental psychology, design science, as well as workplace design, showing how knowledge work depends on small and micro scale environmental determinants. Conceptually unlinked to the ‘meta-levels’ yet, they
nonetheless catalyze and fertilize core qualities of the large-scale environment. These cross-scale processes of knowledge diffusion, spillover, and amplification have been realized as being decisive for the overall knowledge performance, but their functioning is still unclear. There is a significant lack of vertical integration i.e. of multi- and cross-scale models that give inference how processes of knowledge work connect from micro- to macro-levels, how accumulation and amplification effects lead to certain milieus, and how micro-impulses may trigger the dynamics of the larger system.

Desiderata: A comprehensive description of knowledge environments is the prerequisite for the understanding and facilitation of well-working knowledge ecosystems. Knowledge as well as environment must be understood as highly dynamic, complex systems that are interwoven and mutually influencing. Following research desiderata can be outlined thereupon: 1) a systematic, systems-based description of knowledge environments (‘ecosystems’); 2) a horizontal integration of models for knowledge processes and environmental systems; 3) an understanding of cross-scale dynamics and processes in knowledge ecosystems (vertical integration); 4) applicable tools for modeling and conditioning of knowledge ecosystems.

This research paper thus attempts to extends previous approaches in knowledge mapping and social geography and positions itself as a new interdisciplinary approach transcending the limits of social sciences by integrating additional modelling and design points of view.

3. Objectives

The work presented here is to investigate the functional nature of knowledge ecosystems, and to create an understanding of their functional processes. Part of an ongoing research cooperation between TU Dresden, TU Wroclaw and Toyohashi University of Technology, the study asks how Knowledge Ecosystems emerge, function, and persist; in the long run it shall give insights on the possibility of predicting knowledge dynamics e.g. innovation emergence in regards to environment. It is hoped that thus a path can be broken towards the purposeful facilitation of ambiances and milieus in support of knowledge work. For this aim, we want to establish systematic descriptions to explain the interrelations of knowledge and environment. The core concept is to integrate models of knowledge processes and environmental dynamics within a comprehensive conceptual framework, and to investigate how micro-processes on small scale determine the overall nature of a Knowledge Ecosystems on macro scale. Taking knowledge processes as the starting point, and not only as a result or outcome of knowledge environments, two approaches are to be unified within one framework:

- Modelling the dynamics of environmental systems in regards to knowledge processes, based on resources, attractiveness and affordances;
- Modelling the dynamics of knowledge processes in regards to environment, based on social dynamics of knowledge work and knowledge workers.

4. Preliminary results

4.1. Modelling environmental dynamics

A first general set of investigations addressed the modelling of parameters of knowledge environments. A resource-based approach was taken, for such ‘biotopes’ may be described, before all, on the basis of availability of
knowledge-work related resources (e.g. human resources, intellectual production, financial means, values). Relevant
data can be drawn from geographical information systems, social and population statistics, scientific rankings and
surveys, among others. Two core concepts to be employed in this respect are \textit{affordance} and \textit{attractiveness}. The first
one indicates the potential to leverage knowledge work upon the levels of scientific production, intellectual
enrichment and creative fertilization that exist within certain environments. Upon such factors, the second concept
derives values of attractiveness which – as will be shown in 4.2. – stimulate activity and movement of knowledge
workers, innovators, or creative teams. In other words: knowledge diffusion. With such properties conventional
descriptions of environment (geographical maps; plans of buildings, cities, and regions; technological
infrastructures) can be further qualified by layers of knowledge dynamics.

In order to provide a dynamic field description for the backdrop of knowledge work, we have devised various
Cellular Automata (CA)\textsuperscript{36}. Based on hypotheses on the epidemic spread of intellectual matter (meme theory\textsuperscript{37}), the
aim was to provide a first glimpse on the evolution of knowledge environments by modelling key features like
‘enrichment’ or ‘ground fertilization’. Importantly, there are no actors, or agents, involved in this description:
knowledge is seen as an environmental condition, as an embedded resource or quality.

\textbf{4.1.1. Integrating knowledge resources}

A first subset of investigations tackled the question of how to embed the resource knowledge in environmental
descriptions. Starting from the occurrence of a meme (it may be a creative idea, a scientific concept, or a
technological innovation) and attributing certain qualities to it (graphically represented by intensity of shade), we
assumed that memes continuously decay until being completely diffused, or dissolved within the environment\textsuperscript{36}. Eventually becoming unrecognizable, the still form a fond for later emerging new memes. Fig. 2 and 3 show
schematic patterns for such meme evolution in a CA space, and how their interferences may lead to a certain
environmental enrichment resp. and ground fertilization.

More complex patterns emerge when sets of memes of different quality and number are being introduced in
periodical occurrence, which more realistically resembles natural cycles of innovation breakthrough. In Fig. 4 the
evolutionary steps of meme sets are indicated, as well as the number of new memes introduced after a certain
number of iterative steps of the original set (+n). Fig. 5 shows the effect that memes of different quality have within
the system, Fig. 6 brings patterns of CA environments with higher numbers of cells (400, 1600). Here, we have
introduced various cycles, qualities and numbers of memes – a set of properties that can be used already to
distinctively describe and profile specific places (e.g. buildings, campuses, city quarters, regions).

![Fig. 2: Occurrence and gradual dissolution of a new meme (above: 14 steps), and of two memes (below: 8 steps)](image-url)
Fig. 3: Occurrence, dissolution, and interference of ten memes of 100% quality (above), 50% quality (below).

Fig. 4: Multiple sets of memes sets: ten memes of 100% quality added in step 7 and 11

Fig. 5: One meme of 50% quality introduced after 5 steps (top); two memes of 50% quality introduced after every 10 steps (bottom)
In the test modelling represented in figures 2-6, the threshold of number of meme as well as the the timing of introduction of new memes is to follow temporal parameters of intellectual productivity thus allowing clear distinction of specific environments (e.g. mean patent registrations, scientific publications, or number of VC funded start up companies over fix periods of time in a defined area). The models already indicates that number and frequency of meme introduction, as well as speed of meme decay will impact on the quality of knowledge diffusion, without yet modelling the effects in detail. It can be hypothesized that for instance the rapid emergence of new memes in short time may either lead to environmental saturation and stagnation, or potentially trigger an escalation of knowledge production. This is a major aspect for further research, calling for appropriate hypotheses and models.

4.1.2. Calibrating models to specific environment

In a second subset of investigations, we tackled the question of how to appropriate the environmental modelling to local specifics. We informed the cells of the CA by two site-specific features: centrality (abbreviated as “Centre”) and infrastructural occupation (“Road”). Thus the combinatory set of centre / non-centre and road / not-road can be derived which qualifies existing environmental descriptions in terms of attractiveness to knowledge processes (Fig. 8). Centre is defined as preferable to non-centre for its affordance of services, supplies, connectivity etc., while road is disabled for the settling (or embedding) of knowledge resources in the same cell, as we assume that a highly defined functional places give little support for creative knowledge generation, exchange, and interaction. Thus not-road cells are left as potential knowledge bases, from which only centre or non-centre cells may host knowledge resources, with the former having higher levels of attractiveness than the latter. The term ‘cell attractiveness’ stands for the suitability of a cell for knowledge activities, and is operationalized in relational terms: For potential knowledge-hosting environments values “1” / “2” were attributed according to the proximity of a cell to the centre of the model area (Fig. 7).

<table>
<thead>
<tr>
<th>Cell attractiveness</th>
<th>possibility to settle a cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>centre = 2</td>
<td>2</td>
</tr>
<tr>
<td>non-centre = 1</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 7: cell attractiveness matrix.

Fig. 8 shows a schematic application of this value matrix to the city of Wroclaw. By combining attractiveness-values with the feature of decaying, or fading knowledge (as described in 4.1.) another environmental characteristics can be derived, ‘Knowledge absorptivity’. Here, the fade-out of knowledge within an enriched or ‘pollinated’ cell can be correlated to the same cells potential of absorption, which may be taken as an additional ingredient of a cell’s attractiveness. Generally, in detailed development of the attractiveness feature, nearly any measurable factor can be made into a variable of a cell’s attractiveness and help to calibrate the environmental model successively to real-world situations. Upon first estimation, variables like cell capacity (amount of knowledge embedded within a cell), cell absorptivity (speed of knowledge-take-up until maximum capacity is reached), and multiple-tier topographies (attractiveness ranking, not merely the 0-1 possible-impossible distinction) provide good environmental descriptions of attractiveness and affordance in regards to knowledge work.
Fig. 8 (left) Types of cells with different quality and attractiveness; Fig. 9 (right) Mapping of Wroclaw (Source: K. Lewacki)

Fig. 9 shows an in-detail interpretation of the features given above applied to the city of Wroclaw. Wroclaw was chosen as test case for we had access to rich geographic and real-estate information on the one hand, and for Wroclaw being a major science and technology hub in the Lower Silesia region. The mapping is based on an extended set of attractiveness parameters, including real-estate information. The represented areas are urban plots which are either in the state of decline or already past that state, i.e. degraded or abandoned, which raises their attractiveness for example for creative start-up activities given they are in central location. In sum, the attractiveness and absorptivity measures as given by the CA models, as well as their translations onto real-world locations, provides a satisfactory basis for the dynamic description of knowledge environments – on generic as well as on site-specific level.

4.2. Dynamics of knowledge actors (innovators agents movement)

A second general set of investigations attempted to model specific knowledge processes (innovation, replication, diffusion), yet without explicit reference to specific environment. Arguably, knowledge processes cannot be separated from the actions of agents and agencies. Thus the description of knowledge dynamics will be about human and social actors resp. activities: these are the ‘species’ inhabiting ‘knowledge biotopes’ as described above. A previous sample-study has sketched the path of innovative agencies within a three-dimensional environment (space-organization-value) which in itself had been composed by a subset of parametric micro-environments. Although this ‘Creative City Matrix’ was devised to provide an environmental description for the multitude of potential knowledge-work sites, it also helped to track the evolutionary path of actors and agencies (e.g. innovative companies) in their attempt to increase value resp. to move to places of a higher attractivness (Fig. 10).

Fig. 10 (left) Evolutionary path of a company; Fig. 11 (right) Parameters for knowledge agent

On that basis, we have developed parametric models that describe knowledge dynamics (specifically: innovations) by the behaviour of agents (innovators) and their inherent resources. Fig. 11 presents a parameter set
for the simulation of knowledge agents, comprising the number of involved agents, the number of innovations, and their initial energy (representing the founding capital of the agent). Also specified are the costs of movement (while the direction of movement was random), profit from an agent’s activity, and the minimum energy necessary to replicate and diffuse, for which continuous movement is requisite. With this set of parameters knowledge agents can navigate within any given environment (see 4.1.) while taking into consideration environmental factors of attractiveness, absorptivity, or others. This setup takes reference to Game of Life concepts as it includes a number of competing agents trying to negotiate their activities, resources, and expenditures. Still embryonic though, first inferences can be drawn as regards innovators’ number and resources, their activities and amount of innovations created.

4.3. Dynamic interaction of knowledge environment and actors

In order to model a complete ‘ecosystem’, we have integrated the two aspects – environmental dynamics (4.1.) and knowledge dynamics (4.2.) – within one descriptive framework. A first unified rendition is shown in Fig. 12 – a CA environment in which knowledge agents move according to attractiveness and resourcefulness of the environments as well as of the agents themselves. In contrast to the agent-free environmental schemes of section 4.1., the agents (here codified by arrows and, if promoted, by cars) ‘pollinate’ the cells of the environmental automaton upon their movement. They potentially settle in them if environmental attractiveness is high. The agent’s successful settlement within a cell can be called incubation, representing the situation where an innovative agent (i.e. a creative company or individual or a group) is looking for a physical place in which to locate their potential. This process requires a constant analysis of the territory in which the agents navigate in order to assess whether their settlement has highest chances in terms of resources, attractiveness etc. By employing multiple agents, the competition and pressure on the cells can be still increased. In such case, global environmental parameter (population of the area, number of university graduates, technological supply, etc.) generate a specified number of agents (ideas) who look for locations (cells) where they can evolve (incubate) into new knowledge (innovation). Thus, in reference to input-throughput-output processes of living systems, we have modelled the innovation agents’ decision-making in dependence on the knowledge-resource topology of their environment. In order to act and decide, the agents were supplied initial information concerning the examined area, especially the area’s attractiveness (codified by the map colouring). If the area was of high attractiveness, the cell got occupied by moving agents and subjected to the process of innovation (cells marked white). An example of an advanced stage of the simulation (tick/iteration 81) is shown on fig. 12 where agents innovate several cells: If they do find a cell meeting their demands, they change the cell type and increase the global value of a system; after some time a new agent appears on this cell (representing the aging of innovation, when an innovation ceases to be innovative; rendering the phenomenon of new innovations pushing out existing ones) and becomes a lower-level innovator. If attractive places were not encountered after repeated movement, the innovation agents disappear. In order to clarify the mechanism, the system counted at each iteration the number of cells that reach or exceed a certain level of attractiveness. If a threshold was met, it generated a car symbol (‘2nd generation agent’). Finally, the ‘innovated’ cells were set to ‘fade away’, i.e. lose its innovated status in the case they would not be occupied by an agent after a certain number of iterations. Fig. 13 illustrates the evolution of agents from the onset (iteration 0), and an in-progress view (it. 35).

As a first preliminary conclusion of this unified model, the important notion was derived that environmental knowledge dynamics may be modelled indeed as a scenario of artificial life on the one hand, which is to balance resource availability and population development, but also as a game situation where actors have to optimize their strategies and behaviours (movement, settlement) in accordance with their social and geographical environmental.
5. Scientific impact and practical implications

The research project has introduced knowledge-based models to environmental sciences, as well as environment-based models to knowledge studies. It wants to deliver insights how innovations and ideas emerge and proliferate, and describe patterns for the occurrence of knowledge in given environments. The goal is to outline probabilities for the emergence of innovation for specific spaces, areas, or regions, based on a limited set of data about that environment and the innovators behaviour. In the long run, the forecasting of innovation activities for places, regions, cities may be expected. The project is to support innovation policy-making by way of supplying a reliable environmental or ‘ecosystems’ perspective on innovation and knowledge. With the establishment of a unified model and subsequent discovery of effective knowledge dynamics in respect to environment, knowledge ecosystems may not only be described but potentially conditioned and ‘designed’ to a certain extent. By lining out key triggers of knowledge growth, and discovering effective cross-scale paths of ideation and innovation, clues and means may be provided how work environments have to be conditioned on small scale as well as on large scale. Forthcoming results may be of importance to the theory and practice of management, education, and R&D.

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6. References