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Unraveling Evolutionary Dynamics of Disruptive Innovations: Insights from Multi-Scale Knowledge Networks

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Introduction

Identifying early features of disruptive innovations is crucial for shaping science and technology strategies but remains difficult due to their interdisciplinary nature and weak early signals (Ioannidis, Cristea, & Boyack, 2020). Current methods often rely on retrospective metrics and lack predictive power to guide innovation planning. This study uses time-series network analysis to investigate the micro- and meso-scale evolution of knowledge structures. By revealing sequential patterns and cross-scale linkages, it uncovers the mechanisms driving the early emergence of disruptive innovations, enhancing foresight into their formation and development.

Related research and research gaps

Time-series networks reveal scientific knowledge evolution and disruptive innovation patterns through community dynamics and weak signal detection (Ceria et al., 2022). Multi-layer and motif-based analyses expose interactions across micro- and meso-levels. Yet, research often overlooks cross-scale transitions and multi-level dynamics (Lobbé et al., 2022). This study addresses these gaps by analyzing multi-scale knowledge evolution to identify early drivers of disruptive innovations.

Materials and methods

This study analyzes the evolution of disruptive innovation themes by examining multi-scale knowledge types at micro (nodes, edges, motifs) and meso (thematic communities) levels. Using time-sliced dynamic networks and multi-layer temporal analysis across basic, applied, and industrial research, it constructs knowledge evolution sequences. Techniques like dynamic time warping and anomaly detection identify consistent patterns and mutations in knowledge sequences, revealing the driving mechanisms behind the early emergence and development of disruptive innovation within evolving knowledge networks.

Data Collection and Processing

This study uses scientific papers, patent literature, and product information as carriers to represent scientific, technological, and industrial knowledge content, respectively. At the same time, abstract data is used as the specific data object for constructing the knowledge network. Subsequently, natural language processing techniques are applied to structure the collected text data and extract thematic keywords with entity-concept significance.

Construction of Temporal Knowledge Networks and Knowledge Type Sequences

This study constructs temporal knowledge networks by creating time slices and building thematic keyword co-occurrence networks representing basic research, applied research, and industrial application stages of disruptive innovation. It quantifies nodes, edges, motifs, and community structures within each time slice, using the Fast GN algorithm for community detection and the BEAM method with Orca for motif identification. These analyses generate multivariate time series of 32 knowledge structure types, enabling the study of multi-scale knowledge type evolution sequences and their interactive patterns.

Results and Discussion

This study selects the field of regenerative medicine (stem cells) as the empirical domain for early weak signal identification in the process of structural changes in emerging topic networks. Stem cells are an emerging field of medicine that aims to develop technologies capable of regenerating, repairing, or replacing damaged (diseased) cells, organs, tissues, etc. The current field of leukemia treatment mainly focuses on incremental improvements along existing technological trajectories, exhibiting distinct progressive technological characteristics. This field is selected as the control domain.

Knowledge Type Sequence Evolution Consistency Analysis Based on DTW

This study applies Dynamic Time Warping (DTW) (H. Li et al., 2020) to single-scale knowledge type sequences from scientific, technological, and industrial knowledge networks in SC and LK fields. After z-score normalization, DTW distances are calculated to assess sequence consistency. The resulting DTW distance matrix is visualized as a heatmap (Figure 1), where lighter colors indicate higher similarity and darker colors indicate lower similarity.

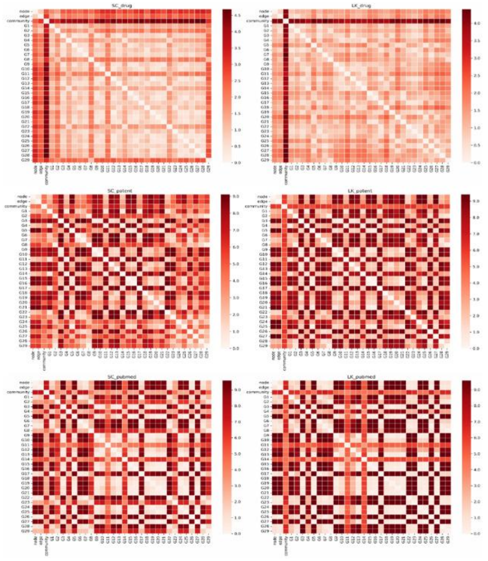

Figure 1. DTW Distance Matrix Heatmap of Knowledge Type Sequences in the Industry-Technological-Scientific Knowledge Network.

Multiscale Knowledge Type Sequence Evolution Consistency Analysis

DTW analysis reveals that scientific and technological knowledge type sequences evolve more consistently within each domain, with the smallest DTW distances observed between these two networks. The SC domain shows slightly higher consistency in technological and industrial knowledge evolution compared to LK. Across both domains, industrial knowledge types exhibit the greatest overall consistency, followed by technological, while scientific knowledge types show the lowest consistency. However, when comparing inconsistency levels, the industrial sector displays the most variation, highlighting distinct evolutionary dynamics and driving mechanisms across science, technology, and industry (Figure 2).

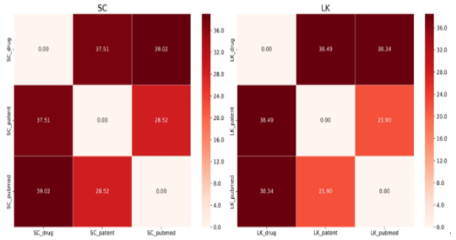

Figure 2. Heatmap of DTW Distances Between Multiscale Knowledge Type Sequences.

Conclusion and policy implications

This study investigates the multi-scale co-evolution of knowledge types in early-stage thematic networks to reveal how disruptive innovation themes emerge and develop. Using temporal network analysis, it constructs micro- and meso-scale knowledge sequences across basic, applied, and industrial research stages. Dynamic Time Warping (DTW) and anomaly detection methods quantify evolutionary consistency and identify mutation timings, showing higher consistency in industrial networks and domain-specific differences between stem cell and leukemia fields.

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