Capability Compression and Combinatorial Creativity: How Software-Defined Manufacturing Bypasses the Network Dependence of Complex Innovation

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Abstract: Complex innovation concentrates in large, well-connected cities because the non-fungible capabilities it requires are geographically distributed and costly to access [1, 2]. Regions that lack these specific capabilities must either accumulate them locally over long periods or rely on intercity network links — creating a connectivity dependence that constrains where complex goods can be produced [3, 4]. We argue that general-purpose manufacturing platforms disrupt this connectivity dependence through capability compression — embedding multiple, previously distributed non-fungible capabilities into a single, small-footprint tool. Specifically, we examine a digitally programmable pulsed-laser nanomanufacturing system that synthesizes functional materials directly from molecular precursors at ambient conditions. One desktop-scale platform produces nonequilibrium metals, photonic structures, micro-batteries, and catalyst nanoparticles — products whose conventional fabrication requires separate cleanrooms, foundries, and specialized facilities concentrated in a handful of global hubs. An integrated uncertainty-aware machine learning framework predicts material outcomes from precursor-pulse inputs, compressing not only physical infrastructure but also the tacit process knowledge normally locked within networks of specialized engineers — adding a software complexity dimension that makes the compressed capabilities transmissible and updatable [5]. This dual compression — of physical infrastructure and non-fungible know-how into software — lowers the activation cost of recombinant search in the product space, yielding combinatorial creativity: the number of novel capability-product experiments a local actor can execute per unit time and capital. By expanding combinatorial creativity, capability compression enables deep-tech startups and university laboratories in emerging innovation ecosystems to explore complex product categories without legacy infrastructure or sequential

capability accumulation. We derive three testable predictions: (i) adopting regions will exhibit positive innovation scaling residuals unexplained by population or connectivity, entering complex technology classes faster than relatedness density predicts; (ii) the product space will develop new short-range links between previously distant technological clusters; (iii) a region's entry rate into novel patent subclasses will scale with the platform's ML-navigable chemical programmability. We discuss implications for distributed manufacturing policy and non-sequential industrialization pathways.

THEORETICAL FRAMEWORK: In the combinatorial model of economic complexity, a product is present in a location only if all required capabilities are simultaneously available [3, 6]. Because productive knowledge is non-fungible — a surgeon's expertise cannot substitute for a pianist's — regions diversify by accumulating specific capabilities that complete new product combinations [4]. This creates path dependence: regions enter products related to their existing portfolio, a regularity known as the principle of relatedness [7]. Capability compression disrupts this path dependence not by violating the principle of relatedness but by changing the input: a single platform simultaneously provides capabilities that previously required separate, geographically distant infrastructure. The platform thus locally densifies the product space, making previously unrelated products suddenly share a common capability requirement. Recent work extending complexity to software further shows that digital capabilities — transmissible and updatable — form an independent complexity dimension [5]. Our ML framework inherits this property: when the model updates, every deployed platform updates, making capability compression scalable in a way that physical infrastructure accumulation is not.

MECHANISM: The platform is a pulsed-laser system operating on molecular precursors in solution at ambient conditions. By varying pulse energy, duration, wavelength, and repetition rate, the same photon source performs distinct manufacturing modalities — subtractive processing, material synthesis, nanoscale assembly, and in-situ characterization — without hardware reconfiguration [8]. This programmability is the physical root of capability compression: the manufacturing modality is encoded in the pulse program, not in the hardware. An uncertainty-aware ML descriptor framework maps the high-dimensional precursor-pulse parameter space to material outcomes (phase, composition, defect structure), replacing the trial-and-error heuristics of specialized process engineers with a codified, transferable software layer. Together, the programmable hardware and the ML layer compress what was a distributed, multi-facility, multi-expert capability stack into a single local node.

TESTABLE PREDICTIONS: We operationalize our three predictions using patent data (NBER/CPC technology classes) and GitHub-derived software complexity indicators. (i) Scaling residuals. We will estimate urban innovation scaling regressions following Liang et al. [2], adding a binary treatment variable for platform adoption. Adopting regions should exhibit positive residuals — innovating beyond what their population, connectivity, and existing relatedness density predict. (ii) Product space topology. We will measure proximity between technology classes before and after platform deployment [9]. New short-range links should emerge between previously distant clusters (e.g., metals ↔ photonics, catalysis ↔ energy storage), as shown schematically in Figure 1. (iii) Creativity-programmability scaling. We will measure the velocity of entry into novel patent subclasses (new CPC codes per year) and regress it against the platform's chemical programmability — the dimensionality of precursor families it can process. A positive, significant relationship would confirm that combinatorial creativity scales with the platform's capability fluidity.

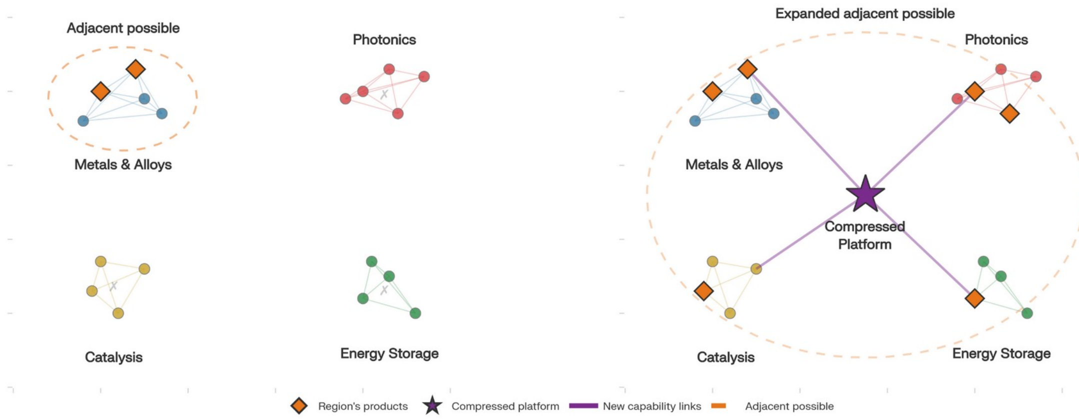

Figure 1. Schematic of capability compression in the product space, left panel without compression and right panel with a compressed manufacturing platform.

REFERENCES

1. Balland, P.-A., Jara-Figueroa, C., Petralia, S.G., Steijn, M.P.A., Rigby, D.L., and Hidalgo, C.A. "Complex Economic Activities Concentrate in Large Cities." *Nature Human Behaviour*, vol. 4, 2020, pp. 248–254.

2. Liang, Xiaofan, Hidalgo, César A., Balland, Pierre-Alexandre, Zheng, Siqi, and Wang, Jianghao. "Intercity Connectivity and Urban Innovation." *Computers, Environment and Urban Systems*, vol. 109, 2024, article 102092.

3. Hidalgo, César A. "Economic Complexity Theory and Applications." *Nature Reviews Physics*, vol. 3, no. 2, 2021, pp. 92–113.

4. Hidalgo, César A. "Knowledge Is Non-Fungible." *Routledge International Handbook of Complexity Economics*, edited by Ping Chen, Wolfram Elsner, and Andreas Pyka, Routledge, 2024.

5. Juhász, Sándor, Wachs, Johannes, Kaminski, Jermain, and Hidalgo, César A. "The Software Complexity of Nations." *Research Policy*, vol. 55, no. 3, 2026, article 105422.

6. Hidalgo, César A., and Hausmann, Ricardo. "The Building Blocks of Economic Complexity." *Proceedings of the National Academy of Sciences*, vol. 106, no. 26, 2009, pp. 10570–10575.

7. Hidalgo, César A., Balland, P.-A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., Glaeser, E., He, C., Kogler, D.F., Morrison, A., Neffke, F., Rigby, D., Stern, S., Zheng, S., and Zhu, S. "The Principle of Relatedness." *Unifying Themes in Complex Systems IX (ICCS 2018)*, Springer Proceedings in Complexity, 2018, pp. 451–457.

8. Park, Huijae, et al. “Laser-Based Selective Material Processing for Next-Generation Additive Manufacturing.” *Advanced Materials*, vol. 36, no. 34, 2024, article 2307586.

9. Hidalgo, César A., Klinger, B., Barabási, A.-L., and Hausmann, R. “The Product Space Conditions the Development of Nations.” *Science*, vol. 317, no. 5837, 2007, pp. 482–487.