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Start Switch for Innovation in "Construction Sequencing": Research Funding

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Abstract: Clusters of knowledge-intensive industries and manufacturing industries form industrial agglomeration in Step I and activate innovation in Step II. Industry clusters are formed by building segments. "Construction sequencing" in the construction industry refers to the process of determining the sequence of segments to optimize a project's resources, budget, and scheduled timeline. The process usually begins by dividing a project into segments. Urban segments consist of public spaces, airports, factories, health, housing, etc. A "segment" is a component of a cluster; the organization of a cluster consists of constructing segments. These segments can be divided into four main categories: human resources, physical infrastructure, institutions, and the living environment. Each segment has a specific function in the process of building a cluster. This study focused on innovation in Step II and extended the Fujita–Thisse model of spatial economics to hypothesize that research expenditure per researcher leads to value being added. The Granger causality was tested for the knowledge and manufacturing industries in nine major countries including China and the U.S. The results showed that the hypothesis was significant in identifying the starting segment of innovation in Step II. Accordingly, it can be concluded that research funding is the start switch that triggers innovation. The policy implication is that activating innovation in cluster policies begins with the establishment of a research fund for researchers in its assigned clusters.

Keywords: construction sequencing; innovation policy; start switch; research funding; sequencing economics; spatial economics

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1. Introduction

According to UNCTAD (2022), the world is at the beginning of a new technological revolution based on Industry 4.0 technologies such as artificial intelligence, robotics, and the Internet of Things. In addition, the impact of and response to the coronavirus outbreak (COVID-19) has accelerated the spread of this digital economy and activated innovation.

Agglomeration can be defined as the spatial concentration of economic activity. Oqubay and Lin (2020) noted that industrialization, supported by the "agglomeration" of industrial hubs, is widely associated with structural transformation and catch-up in developing, emerging, and developed countries. Mayer and Banga (2020) examined whether industrial hubs are effective at activating innovation in developing countries when the digital economy and industrial hubs are complementary. It is necessary to examine how agglomeration relates to innovation activation.

According to Fujita (2003), a cluster is the formation of an agglomeration and the activation of innovation within it. Cluster formation involves an industrial agglomeration step and an innovation activation step. Kanai and Ishida (2000) noted that studying the process of cluster formation is essential for the success of cluster policies. As shown in Figure 1, Kuchiki and Tsuji (2010) divided this process into two steps: Step I is agglomeration, and Step II is innovation.

With respect to Step I (agglomeration), there are three theories: (i) spatial economics, (ii) construction sequencing, and (iii) sequencing economics, as shown in Table 1.

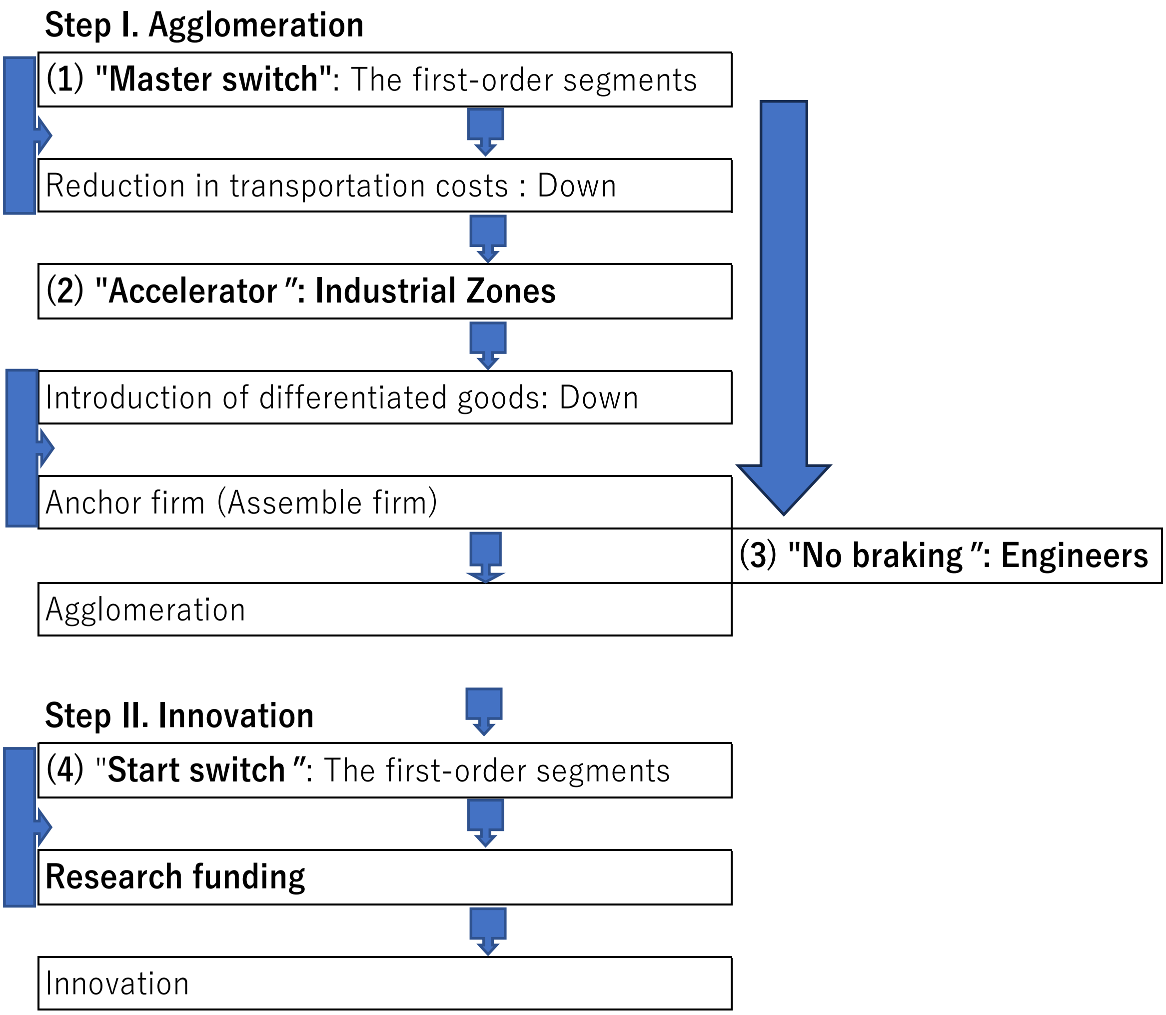

Figure 1. Cluster policy. Source: Author's illustration.

Table 1. Construction sequencing and start segment.

Economics	*(i) Spatial Economics*	*(ii) Construction Sequencing*	*(iii) Sequencing Economics*
	(i) Fujita and Thisse (2003)	Architecture-engineering-construction industry	Kuchiki and Sakai (2023) and this paper
Theory	(i) Theory of location: Agglomeration	(ii) Sequencing: PERT (program evaluation review technique), CPM (critical path method), BIM (building information modeling) etc.	(iii) Theory of sequencing
Charateristics	(i) Breaking conditions from symmetry equlibrium to agglomeration equilibrium	*(ii) construction sequencing*	*(iii) Economies of sequence & Function of segments*
Key factors	Transport costs, the elasticity of substitution between differentiated goods	Segments: public spaces, airports, factories, health, residential, IT OS and data center business, and international opportunities	Function of segments: *(iii) Start switch*, Master switch, Accelerator, No brake

Source: Author's based on A. Kuchiki and H. Sakai.

(i) Spatial economics is a location theory by Fujita et al. (1999). The main factors are the transport costs and the elasticity of substitution between differentiated goods. The theory defines the conditions of breaking away from symmetric equilibrium to agglomeration equilibrium.

(ii) The construction industry is the foundation of our economy and is essential to our daily life. Construction is the biggest industry in the world. As stated in UNHABITAT (2007), urban strategic planning is essentially a dynamic process. Outbuild (2024) noted that in an industry where 72% of firms state that projects are taking longer than expected and 78% of engineering and construction firms believe that project-related risk is increasing, the importance of starting with a first-class construction sequence is evident.

"Construction sequencing" is a method of construction planning, as described by McKinsey & Company (2020). "Construction sequencing" in the construction industry refers to the process of determining the sequence of segments in order to optimize the project's resources, budget, and scheduled timeline (see Brown and Hamilton 2024). The timeline for efficient construction sequencing is as follows: pre-construction planning, creating a breakdown of the work's structure, sequencing based on dependencies, and estimating the durations and lead times (see Outbuild 2024). Ignoring the dependencies may be one of the most common actions and the most damaging to a project (Outbuild 2024).

The process usually begins by dividing a project into "segments". Urban segments consist of public spaces, airports, factories, health, housing, IT OS and data center businesses, and international opportunities (Larsen and Toubro Limited 2024).

Sequencing is a huge factor in many common planning methods including the critical path method (CPM) (see Levy et al. 1963), the program evaluation and review technique (PEPT) (see Danao 2024), and building information modeling (BIM) (see Azhar et al. 2012).

(iii) Sequencing economics is a theory of agglomeration construction that, according to Kuchiki and Sakai (2023), focuses on the process of constructing segments. Sequencing economics in agglomeration-related architectural theory is applied to sequencing agglomeration segments in terms of the "economies of the sequence" and the "function" of the segments. The "economies of the sequence" are defined as the selection and sequencing of any two segments from among the entire group of segments of an industrial agglomeration toward the efficient building of the agglomeration, according to Kuchiki (2021). In statistical analysis, the economy of the sequence from variable X to variable Y is defined as the relationship where X Granger-causes Y.

Agglomerations are organized by building segments. According to Kuchiki (2023), the segments comprise four major categories, namely human resources, physical infrastructure, institutions, and living conditions. Appendices A.1 and A.2 show the segments of the tourism industry and the manufacturing industry.

Kuchiki (2023) found that the formation of industrial agglomeration proceeds through the construction of segments and identified the conditions for a master switch in the case of a manufacturing agglomeration. A segment has the "function" of forming an agglomeration, and one of the master switch segments reduces transportation costs such as highway transportation costs, as shown in Table 2. The functions of segments.

As summarized in Table 1, this study attempts to integrate (ii) "construction sequencing" in the construction industry and (iii) sequencing economics by using (i) the method of Fujita and Thisse (2003).

With respect to Step II, according to Simmie (2008), the concept of innovation can be defined as the introduction of a new or changed product, process, service, or form of organization into the market. According to Kim and Mauborgne (1997, 1999), the definition of innovation used in this study is something that makes "the competition irrelevant by offering fundamentally new and superior buyer value in existing markets and by enabling a quantum leap in buyer value to create new markets". In other words, innovation is the commercialization of new ideas or "value added".

Table 2. Function of segments.

	Function	Segment	Spatial Economics	Sequencing Economics	Location
Step I. Agglomeration	*"Construction sequencing"*				
Urban agglomeration	(1) Master switch	Transport costs	Krugman (1991), Alonso (1964)	Kuchiki and Sakai (2023)	Sapporo, Japan
Manufacturing	(2) Accelerator	Industrial zones	Helpman and Krugman (1985)	Kuchiki (2023)	Industrial hubs, China,
Manufacturing	(3) No braking	Engineers	Helpman and Krugman (1985)	Kuchiki (2024)	Industrial hubs, India
	"Function"	Segment	Spatial economics	Sequencing economics	Location
Step II. Innovation					
Knowledge and manufacturing industry	***(4) "Start switch"***	***"Research funding"***	Fujita and Thisse (2003)	***This paper***	Nations

Source: Author's.

In prior studies, Hernández (2020) analyzed innovation in relation to how it is adopted in clusters and how it can contribute to cluster-level, regional, and "national" development and competitiveness. They discussed important factors that were not considered in Diamond model of Porter (1998) such as the importance of the "multinational activity effect" and the role of the government in regulating regional and international interactions.

University–industry linkages (UILs) and the national innovation system (NIS) play a key role in explaining innovation, according to Hershberg et al. (2007). Brimble and Doner (2007) found few UILs and weak NISs in the case of Thailand, where the Thai industry showed little interest in innovation at that time. Conversely, high-tech zones in China were built in close proximity to universities and public research institutes with the goal of promoting UILs, as shown by Chen and Kenney (2007) and Kuchiki (2021). Wu (2007) analyzed UILs in the context of NISs and found that UILs were exceptionally active in Beijing. However, it was not concluded whether a UIL, an NIS, or any other segment was the starting segment for Step II.

Kanai and Ishida (2000) emphasized the importance of the cumulative process, as it takes time to build any segment of an agglomeration. The Mind Tools Content Team (2024) followed Weiss and Legrand (2011) and described a four-stage innovation process.

The above-mentioned studies can be summarized regarding the purpose of this study as follows. First, these studies explored what determinants were involved in activating innovation in cluster formation and also explored the process of innovation activation. Integrating these ideas, this study focused on the process of segment building for innovation in Step II of the cluster policy, as shown in Figure 2. The process of innovation proceeds through the construction of segments, therefore, an attempt was made to identify a start switch for innovation.

The purpose of this study was to examine whether research expenditure per researcher leads to value being added. For Step II, the innovation process, we conducted an econometric analysis of the knowledge services and knowledge manufacturing industries and the five manufacturing industries in nine countries using data from the WIPO (2002–2019), NSF (2002–2019), and UNESCO (2002–2019). Granger causality tests were conducted between research expenditure per researcher and each of the value added, patents, and papers with lags of one to five years.

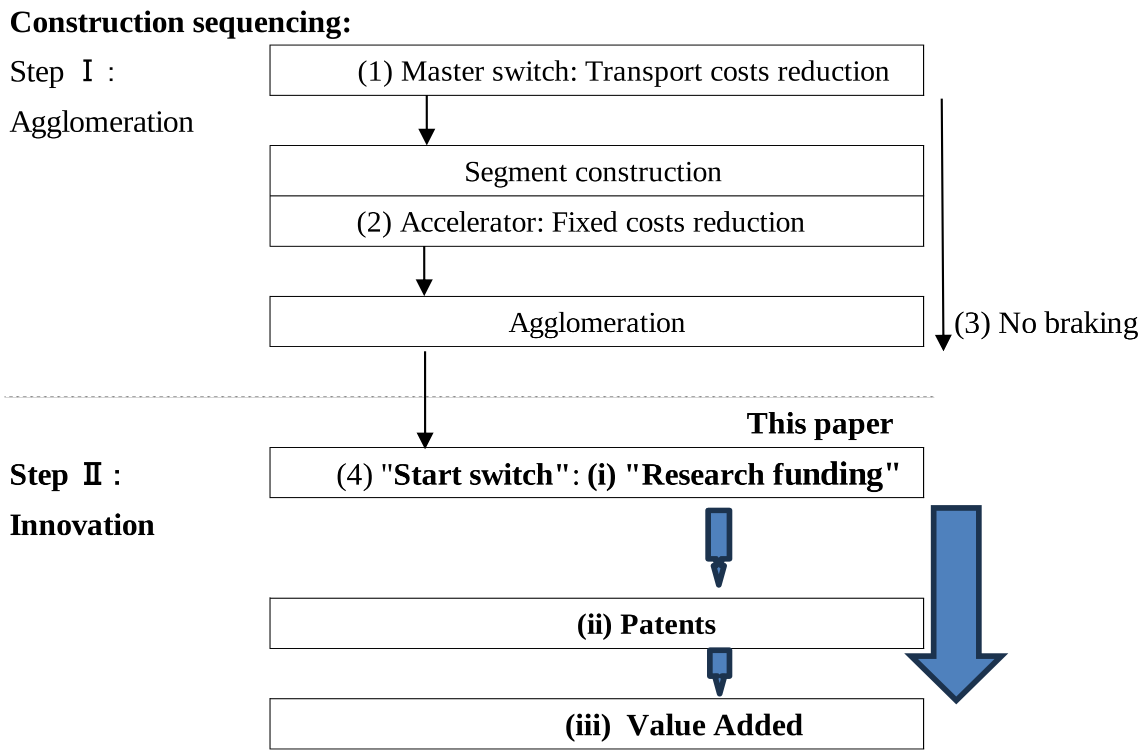

Figure 2. Start switch in construction sequencing. Source: Author's illustration.

Table 3 shows the value added, patents, papers, research expenditure per researcher, and research expenditure per capita data used in this study. This study analyzed the relationship between research expenditure per researcher and the amount of value added created. No relationship was found between research expenditure per head of population and the creation of value added.

The relationship between research expenses per researcher and knowledge/technology services was the same for the first-ranked USA and the ninth-ranked Russia. For research expenses per researcher, those of China, South Korea, Japan, Italy, the UK, and France were around 50% of the first-ranked USA. The countries with knowledge/technology services around 10% of the USA, which was in first place, were Japan, Germany, France, the UK, and South Korea. However, Germany tied with the USA in first place. The country with the largest population (China, 1.4 billion) had 28% of the value added of the USA.

The results of the Granger causality tests indicate that the hypothesis that research expenditure per researcher Granger-causes value added was significant. We also identified the starting segment of innovation activation. Kuchiki and Sakai (2023) and Kuchiki (2023, 2024) linked spatial economics to sequencing economics in Step I (agglomeration), as shown in Table 1. This study concluded that the starting segment of Step II (innovation) is research funding.

The rest of this paper is organized as follows. In Section 2, we derive our hypothesis by introducing the model of Fujita and Thisse (2003). Section 3 explains the data on innovation in nine countries. In Section 4, we perform Granger causality tests and regression analysis to find the starting segment in Step II (innovation). A summary and the conclusions are given in Section 5.

Table 3. Data for analysis.

3.1. Knowledge-intensive industries: Value added (2019)	Unit: Row 1. world ranking; Row 2. US$; Row 3. % of world ranking 1.								
Knowledge/technology manufacturing	China	US	Japan	Germany	Korea	Italy	UK	France	Russia
	1	2	3	4	5	7	8	11	18
	1,981,928	1,301,712	582,386	448,517	248,095	113,710	112,978	98,758	45,893
	100	**66**	**29**	**23**	**13**	**6**	**6**	**5**	**2**
computer	China	US	Korea	Japan	Germany	UK	France	Italy	Russia
electronics, optical instrument	1	2	3	5	6	11	13	15	19
	373,195	310,124	111,575	76,800	39,349	17,968	13,455	8592	5204
	100	**83**	**30**	**21**	**11**	**5**	**4**	**2**	**1**
Knowledge/technology services	US	China	Japan	Germany	France	UK	Korea	Italy	Russia
	1	2	3	4	5	6	8	9	12
	1,034,456	285,503	147,906	145,206	131,487	127,777	93,077	60,483	32,672
	100	**28**	**14**	**14**	**13**	**12**	**9**	**6**	**3**
IT/information services	US	China	Japan	Germany	UK	France	Italy	Korea	Russia
	1	2	3	4	5	6	8	10	16
	655,779	149,643	124,853	104,293	94,448	74,167	37,780	29,830	1514
	100	**23**	**19**	**16**	**14**	**11**	**6**	**5**	**0**
3.2. Knowledge industry: Number of patents (2022)	Unit: Row 1. world ranking; Row 2. number; Row 3. % of world ranking 1.								
semi-conductor/manufacturing	China	Japan	US	Korea	Germany	France	UK	Italy	Russia
	1	2	3	4	5	6	9	14	25
	3045	2641	1541	773	325	122	59	22	5
	100	**87**	**51**	**25**	**11**	**4**	**2**	**1**	**0**
computer technology	China	US	Japan	Korea	Germany	UK	France	Italy	Russia
	1	2	3	4	5	6	7	17	19
	10,657	7631	3342	2306	812	482	427	85	78
	100	**72**	**31**	**22**	**8**	**5**	**4**	**1**	**1**
digital communication technology	China	US	Japan	Korea	Germany	France	UK	Italy	Russia
	1	2	3	4	7	9	10	17	21
	10,596	6143	2736	2327	358	196	164	40	13
	100	**58**	**26**	**22**	**3**	**2**	**2**	**0**	**0**
telecommunication technology	China	US	Japan	Korea	Germany	France	UK	Italy	Russia
	1	2	3	4	6	8	9	13	20
	2109	1344	1050	876	112	89	79	28	10
	100	**64**	**50**	**42**	**5**	**4**	**4**	**1**	**0**

Table 3. *Cont.*

3.3. Knowledge industry: Number of papers (2022)	Unit: world ranking, number, % of world rank 1.								
sciences (total)	China	US	Germany	UK	Japan	Italy	Russia	Korea	France
	1	2	4	5	6	7	8	9	13
	898,949	457,335	113,976	105,584	103,723	90,586	84,252	76,936	65,888
	100	**51**	**13**	**12**	**12**	**10**	**9**	**9**	**7**
computer sciences	China	US	Germany	Japan	UK	Italy	Korea	France	Russia
	1	3	4	5	6	7	8	9	10
	102,524	33,405	11,826	9127	8433	7766	7669	6419	6396
	100	**33**	**12**	**9**	**8**	**8**	**7**	**6**	**6**
3.4. All industies: Research expenses per researcher and research expenses per capita (2021)					Unit: US$.				
per researcher	US	Germany	China	Korea	Japan	Italy	UK	France	Russia
	3	11	18	19	20	21	24	28	60
	484,471	327,722	276,195	256,033	253,151	248,674	239,846	227,542	120,554
	100	**68**	**57**	**53**	**52**	**51**	**50**	**47**	**25**
per capita	US	Korea	Germany	UK	Japan	France	Italy	China	Russia
	4	5	11	16	17	20	29	36	41
	2359	2325	1814	1449	1427	1178	666	466	328
	100	**99**	**77**	**61**	**60**	**50**	**28**	**20**	**14**
3.5. Manufacturing: Value added (2019)	Unit: Row 1. world ranking; Row 2. US$; Row 3. % of world ranking 1.								
automobile/manufacturing	China	US	Japan	Germany	Korea	UK	Italy	France	Russia
	1	2	3	4	6	9	11	14	17
	299,268	149,391	148,741	137,307	29,812	19,392	14,766	12,971	5500
	100	**50**	**50**	**46**	**10**	**6**	**5**	**4**	**2**
machinery	China	US	Japan	Germany	Italy	Korea	UK	France	Russia
	1	2	3	4	5	6	7	10	16
	401,285	166,982	158,186	120,827	42,936	37,447	19,243	13,176	6498
	100	**42**	**39**	**30**	**11**	**9**	**5**	**3**	**2**
chemical	China	US	Japan	Germany	Korea	France	UK	Italy	Russia
	1	2	3	4	5	9	12	13	20
	326,874	208,576	76,153	50,973	30,636	20,046	15,754	12,950	7662
	100	**64**	**23**	**16**	**9**	**6**	**5**	**4**	**2**
electronics	China	Japan	US	Germany	Korea	Italy	France	Russia	UK
	1	2	3	4	5	6	10	11	13
	318,792	71,213	65,004	42,432	26,509	11,800	6668	5894	5552
	100	**22**	**20**	**13**	**8**	**4**	**2**	**2**	**2**
medicine	US	China	Japan	Germany	UK	France	Italy	Korea	Russia
	1	2	3	4	7	8	9	12	19
	182,383	158,924	27,004	24,796	19,137	14,363	10,333	7390	1742
	100	**87**	**15**	**14**	**10**	**8**	**6**	**4**	**1**

Table 3. *Cont.*

3.6. Manufacturing: Number of patents (2022)	Unit: Row 1. world ranking; Row 2. number; Row 3. % of world ranking 1.								
automobile	Japan	China	US	Germany	France	Korea	UK	Italy	Russia
	1	2	3	4	5	7	8	9	21
	800	727	530	425	286	184	133	98	29
	100	**91**	**66**	**53**	**36**	**23**	**17**	**12**	**4**
machinery	Japan	China	US	Germany	Korea	Italy	France	UK	Russia
	1	2	3	4	5	6	9	10	22
	1073	763	522	501	201	101	67	61	12
	100	**71**	**49**	**47**	**19**	**9**	**6**	**6**	**1**
chemical	US	China	Japan	Germany	Korea	France	UK	Italy	Russia
	1	2	3	4	5	6	7	9	23
	1089	963	721	499	375	229	192	102	23
	100	**88**	**66**	**46**	**34**	**21**	**18**	**9**	**2**
electronics	China	US	Japan	Korea	Germany	France	UK	Italy	Russia
	1	2	3	4	5	6	7	10	25
	5997	5539	2355	2095	2000	569	295	174	34
	100	**92**	**39**	**35**	**33**	**9**	**5**	**3**	**1**
medicine	US	China	Korea	Japan	Germany	UK	France	Italy	Russia
	1	2	3	4	5	6	7	8	22
	4759	2446	858	718	405	341	336	295	48
	100	**51**	**18**	**15**	**9**	**7**	**7**	**6**	**1**
3.7. Manufacturing: Number of papers (2022)	Unit: Row 1. world ranking; Row 2. number; Row 3. % of world ranking 1.								
engineering	China	US	Germany	Korea	Japan	Russia	Italy	UK	France
	1	2	4	5	6	7	8	9	12
	228,189	49,437	16,542	15,472	13,324	12,911	12,833	11,860	8669
	100	**22**	**7**	**7**	**6**	**6**	**6**	**5**	**4**
chemical	China	US	Japan	Germany	Russia	Korea	Italy	UK	France
	1	3	4	5	6	7	9	10	11
	72,033	13,693	6927	6453	6040	5611	3813	3613	3504
	100	**19**	**10**	**9**	**8**	**8**	**5**	**5**	**5**
physics	China	Japan	Korea	US	Germany	France	UK	Italy	Russia
	1	2	4	5	6	7	8	10	25
	5997	5539	2355	2095	2000	569	295	174	34
	100	**92**	**39**	**35**	**33**	**9**	**5**	**3**	**1**
biology	US	China	Korea	Japan	Germany	UK	France	Italy	Russia
	1	2	3	4	5	7	8	13	22
	4759	2446	858	718	405	336	295	163	48
	100	**51**	**18**	**15**	**9**	**7**	**6**	**3**	**1**

Source: Author's based on NSF in Appendix B.

2. The Fujita and Thisse Model

2.1. Agglomeration and Innovation (Figure 2)

This study focused on the process of segment construction in cluster formation. We address sequencing economics, which determines the sequence of segment construction. An important concept in sequence economics is the economy of the sequence.

Figure 2 illustrates the process of cluster formation. In this study, the process of cluster formation involves Step I (agglomeration) and Step II (innovation). This study focused on the "process" of segment building to activate innovation (Step II). This concept is defined as the sequencing of segments in the efficient construction of segments that form an agglomeration. In the process of activating Step II (innovation), if the starting segment works, innovation will proceed, and added value will be generated.

Step I, the agglomeration building process, as pointed out by Kuchiki (2023), is as follows. The first step in agglomeration construction is to determine where the agglomerations will be located. Spatial economics determines this location. Table 2 shows an example of spatial economics coupled with sequencing economics, and an example of the sequencing economics of an agglomeration is shown. The organization of an industrial agglomeration consists of segments. Each of these segments has a "function".

As shown in Figure 1 and Table 2, the functions of the segments are (i) the "master switch", (ii) "accelerator", and (iii) "brake". Kuchiki and Sakai (2023) identified the master switch on the basis of the results of Krugman (1991) and Alonso (1964). Kuchiki (2023) and Kuchiki (2024) identified the accelerator and the brake, respectively, by drawing on the work of Helpman and Krugman (1985).

The master switch segment of Step I (agglomeration) in manufacturing is the transport infrastructure, which specifically reduces the "transport costs". For example, ports and roads serve as master switches. The accelerator segment reduces the fixed costs for the tenant firms (i.e., "leased industrial parks"). The brake segment is "the lack of engineers". The agglomeration process is initiated when firms producing differentiated goods with no brakes and a low elasticity of substitution move to an agglomeration region.

In this section, first, the model of spatial economics of Fujita and Thisse (2003) was applied to obtain the master switch that initiates the construction of an industrial agglomeration segment in the knowledge industry. This switch is the construction of segments where the transport costs are below a certain threshold. The knowledge-intensive industries in Table 3 consist of knowledge-intensive manufacturing industries and knowledge-intensive service industries.

Next, we extended the model of Fujita and Thisse (2003) to prove the hypothesis that research expenditure per researcher Granger-causes value added. In this study, we defined a "start switch" as the segment acting as the starting point for the process of innovation, as shown in Figure 2.

In the following sections, an econometric analysis identifies the starting segments that trigger innovation in Step II of the knowledge and manufacturing industries.

2.2. The Model

This section presents the part of the model of Fujita and Thisse (2003) related to the master switch in the first step of agglomeration. The economy consists of two regions, s and t, and three production sectors: the traditional sector (T), the modern sector (M), and the innovation sector (R). In M, the production of any variety requires the use of a "patent" specific to this variety, which has been developed in R.

The number of modern varieties of goods in Region s and Region t is denoted as M_s and M_t, respectively, and is positive at any given time. Consider the case in which a firm producing a variety of goods can freely decide its location at each time, irrespective of the region in which the goods were innovated.

The Cobb–Douglas utility function for all workers is given by

$$u = Q^{\mu}\, T^{1-\mu} / \mu^{\mu}\, (1-\mu)^{1-\mu}, \tag{1}$$

where T is the consumption of homogeneous traditional goods, μ is the share of expenditure of modern varieties, and Q stands for the index of the CES consumption of the modern varieties, which is given by

$$Q = [\int_0^M q(i)^{(\sigma-1)/\sigma}\, \mathrm{d}i]^{\sigma/(\sigma-1)}, \quad (2)$$

where M is the total mass of modern varieties available in the global economy at Time t, σ is the elasticity of substitution between any two varieties, and $q(i)$ is the consumption of Variety i.

Let λ_r be the share of skilled workers in Region r, so that $\lambda_\mathrm{s} \equiv \lambda$ and $\lambda_t \equiv 1 - \lambda$. For the chosen value of the share of skilled workers in a region, λ, V_r $(0;\ \lambda)$ stands for the lifetime indirect utility of a skilled worker in Region r (=s and t), and v_r $(t;\ \lambda)$ is the corresponding instantaneous indirect utility at Time t. This means that

$$V_r\ (0;\ \lambda) = \int_0^\infty \mathrm{e}^{-\gamma \mathrm{t}} \ln[v_r(t;\ \lambda)]\ \mathrm{dt} \quad (3)$$

where $\gamma > 0$ is the subjective discount rate common to all consumers.

Let E_r be the total expenditure in Region r at the time in question and let P_r be the price index of the modern goods in this region. The total demand for Variety i produced in Region r is equal to

$$q_r\ (i) = \mu\ E_r\ p_r\ (i)\ P_r + \mu\ E_s\ [p_r\ (i)\ \Gamma]\ P_s\ \Gamma, \quad (4)$$

where r, s = A, B, and r $\neq$ s, p_r (i) is the price of Variety i in Region r, and Γ accounts for the "iceberg" melting during its transportation. The corresponding profit is

$$\pi_r\ (i) = [p_r\ (i) - 1]\ q_r\ (i). \quad (5)$$

The firms' profits must be identical across regions; thus, $q_s{}^* = q_t{}^*$, where $q_r{}^*$ denotes the equilibrium output of any variety of goods produced in Region r. The equilibrium output of any variety produced in Region r and the equilibrium profit are given by

$$q_r{}^* = \mu\ \rho\ [E_r/(M_r + \varphi\ M_s) + E_{s\,/}(M_s + \varphi\ M_r)],\ \pi_r{}^* = q_r{}^*/(\sigma - 1), \quad (6)$$

where $\varphi \equiv \Gamma^{-(\sigma-1)}$ and M_r represent the number of modern varieties produced in Region r at the time in question. The modern goods are agglomerated in Region s, which has a greater share of the innovation sector.

Turning to the innovation sector, when the knowledge capital in Region r is K_r, and the share of skilled workers in Region r is λ_r, the number of patents developed per unit of time in Region r is

$$n_r = K_r\ \lambda_r.$$

The equation of motion for the number of patents/varieties per unit of time in the economy is

$$\mathrm{D}M = n_s + n_t = M\{\lambda\ [\lambda + \eta(1 - \lambda)]^{1/\beta} + (1 - \lambda)(1 - \lambda + \eta\ \lambda)^{1/\beta}\},$$

where DM = d$M(t)$/dt, t is time, and

$$\mathrm{g}\ (\lambda) = \lambda\ [\lambda + \eta\ (1 - \lambda)]^{1/\beta} + (1 - \lambda)(1 + \eta\ \lambda)^{1/\beta},$$

where η $(0 \leqq \eta \leqq 1)$ expresses the intensity of knowledge spillovers between the two regions. The growth rate of the number of patents/varieties (DM/M) in the global economy is given by

$$\mathrm{D}M/M = \mathrm{g}\ (\lambda),$$

where the distribution of skilled workers is λ. Here, g (λ) is symmetric about 1/2, so that

$$g(0) = g(1) = 1.$$

The condition of breaking from symmetric equilibrium at $\lambda = 1/2$ to agglomeration equilibrium for an agglomeration policy is given by

$$\mathrm{d}\,[V_1\,(0;\lambda) - V_2\,(0;\lambda)]/\mathrm{d}\lambda > 0.$$

When the transport costs of the modern goods, Γ, are low, the equation is

$$\Gamma \leqq C \equiv [(\sigma + \mu)/(\sigma - \mu)]^{-(\sigma-1)}. \quad (7)$$

Then, in the core–periphery structure, the whole innovation sector begins to agglomerate in the core region. "Breaking conditions" are the conditions that trigger the transition from symmetric equilibrium to agglomeration equilibrium in knowledge-based industries. The master switch of industrial agglomeration is the construction of segments that satisfy the breaking conditions. The segments in this model are those that reduce the transport costs in a broad sense.

In this study, we introduced the following two assumptions. First, Fujita and Thisse (2003) assumed that human capital h (j) is the number of papers read by an individual and that the knowledge capital Kr available in Region r depends on human capital. In this study, we assumed that the number of papers depends on the research expenditure.

Assumption 1. *h (j) = f (research expenditure per researcher).*

Second, Fujita and Thisse (2003) assumed that the number of patents M equals the number of varieties. Patents lead to new varieties of products, and varieties generate added value. This is the process of innovation. In this study, we assumed that the value added depends on the number of patents.

Assumption 2. *Value added* = g(M).

By integrating these two assumptions, we obtained the following causal sequence: *research expenditure per researcher*, papers, patents, varieties, and *value added*. Therefore, the following hypothesis holds.

Hypothesis 1. *Research expenditure per researcher causes value added.*

Section 3 describes the data used in the econometric analysis of this study. Section 4 tests the Granger causality of the hypothesis presented here.

2.3. The Case of the Taiwan Semiconductor Manufacturing Company (TSMC)

In this subsection, Equation (8) is obtained via Equation (7). This equation is used to define the master switch in building an agglomeration. In this subsection, we study the case of a semiconductor agglomeration formed by Taiwan's TSMC, which built a factory in Kumamoto Prefecture.

In Step I of the industrial agglomeration shown in Figure 1, the master switch was to use subsidies to attract TSMC to Kumamoto Prefecture. As a result of the master switch being pushed, the semiconductor agglomeration in Kumamoto Prefecture started to form clusters. This is explained below.

Note that the hypothesis presented in the previous subsection of this article is the hypothesis regarding the starting switch of Step II following Step I (agglomeration). The following subsections test this hypothesis.

In this subsection, Equation (8) is also proposed for the master switch of agglomeration as a valid suggestion for the cluster policy. In other words, it has implications regarding what the policy should be for the threshold of transport costs in a broad sense, which should be lowered. The following equation was obtained by the partial differentiation of C in Equation (7) via σ.

$$\partial C/\partial\sigma = 2\,(\sigma - 1)\,\mu\,(\sigma - \mu)^{-2}\,[(\sigma + \mu)/(\sigma - \mu)]^{-\sigma} > 0, \quad \text{since } \sigma > 1 \text{ and } 0 < \mu < 1. \tag{8}$$

This equation shows that the smaller the σ, the smaller the C. In other words, as a breaking condition for the start of a knowledge industry-related agglomeration, agglomeration does not begin unless the reduction in its transport costs is greater than the threshold C in the case of heterogeneous goods and services in knowledge-intensive industries with a lower elasticity of substitution.

TSMC created a dedicated IC semiconductor foundry business model when it was founded in 1987. In 2023, TSMC served 528 customers and manufactured 11,895 products for various applications covering a variety of end markets including high-performance computing, smartphones, the Internet of Things (IoT), automotive, and digital consumer electronics (TSMC 2024).

TSMC is capable of producing two nano-semiconductors. These products have a very low elasticity of substitution σ. Theoretically, the breaking condition from symmetric equilibrium to agglomeration equilibrium cannot be established unless the transport costs in a broad sense are very low.

TSMC decided to expand its plant to Kumamoto Prefecture in Japan on 14 October 2021 (Nikkei 2024). At that time, Japan's Ministry of Economy, Trade, and Industry decided to provide JPY 476 billion (USD 3 billion; USD 1 = JPY 155) in subsidies for the first plant to manufacture 12 nano-semiconductors (Ohta 2021).

Subsequently, TSMC decided to expand to a second plant, and METI announced more subsidies. The subsidy for the second plant, which produces semiconductors of 6 nanometers with high product differentiation (i.e., a smaller σ should be increased to up to JPY 732 billion (USD 4.72 billion), thereby lowering the threshold of transport costs). It can be interpreted that the "subsidy" broadly contributed to the reduction in transport costs.

Fifty-six companies announced their intention to establish or expand operations in Kumamoto by February 2024 (Ministry of Economy, Trade, and Industry 2023). The effect of TSMC has led to a semiconductor-related industrial agglomeration around Kumamoto Prefecture. The agglomeration includes major Japanese semiconductor companies such as the Ebara Corporation, Renesas Electronics, Tokyo Electron Kyushu, Mitsubishi Electric, and Fujifilm. New buildings, expansions, and new factories were constructed not only in Kumamoto Prefecture, but also throughout Kyushu Island including Rohm Semiconductor in Fukuoka Prefecture and Japan Semiconductor in Ohita Prefecture (Kumamoto Prefecture 2024).

3. Materials

In this section, we aim to understand the results for the nine countries for which data were analyzed. These data cover knowledge-intensive industries and five types of manufacturing. The situation in the nine countries was outlined in terms of value added, patents, the number of publications, research expenditure per researcher, and research expenditure per capita. The nine countries were chosen because, with the exception of Russia, their policies have had a significant impact on research expenditure and value added per researcher as well as their high world rankings. In particular, we tried to identify the underlying preconditions that indicate that research expenditure per capita Granger-causes value added.

Table 3 shows that for both the added value of knowledge and technology services and for knowledge and technology manufacturing in knowledge-intensive industries, there were only eight countries with a value added of more than 5% of that of the country that ranked first, taking the value added of the country that ranked first as 100%. One country whose value added was below 3% of that of the country in first place was Russia. Table 3 shows that in the four manufacturing sectors, with the exception of electronics, the top seven countries had a value added of more than 5% of that of the top-ranked country, taking the value added of the country that ranked first as 100%. In addition, Russia was the only country where the value added was below 2% of that of the country in first place. In other words, the top eight countries in the knowledge-intensive and manufacturing industries occupied the top positions in the global value-added ranking.

This study therefore analyzed nine countries including the top eight countries for knowledge-intensive industries, and Russia, as a country below the threshold of the global value-added rankings.

The relationship between research expenditure per researcher and the value added of knowledge/technology services was the same for the USA, which was in first place, with Russia in ninth place. In terms of research expenditure per researcher, China, South Korea, Japan, Italy, the UK, and France had around 50% of that of the USA. Countries with knowledge/technology services around 10% of that of the USA were Japan, Germany, France, the UK, and South Korea. Germany tied with the USA in first place. In China, which has a population of 1.4 billion, the value added was 28% of that of the USA.

The statistics of value added in the knowledge-intensive industries and the manufacturing industries were obtained from the NSF (U.S. National Science Foundation). Knowledge-intensive industries were divided into (i) knowledge/technology-intensive manufacturing and (ii) knowledge/technology-intensive services. According to the definition of the OECD, knowledge/technology-intensive manufacturing includes computer electronics and optical equipment, aerospace, pharmaceuticals, weapons and arms, automotive, medical equipment, mechanical equipment, chemical, electrical equipment, and rail and transportation equipment, whereas knowledge/technology-intensive services include the IT and information-related service industry, scientific research and development services, and the software publishing industry.

Statistics on patents were obtained from the WIPO (2002–2019), statistics on papers were from the NSF (2002–2019), and statistics on the total research expenditure for each country were from UNESCO (2002–2019) (UNESCO Institute of Statistics). The total research expenditure for each country was divided by the number of full-time equivalent researchers; the number of researchers was obtained from ISCO (International Standard Classification of Occupations) 88 Major Category 2, namely “professionals” who are actually engaged in research and development.

This section presents the rankings for value added, patents, publications, and research expenditure per researcher. These rankings are not related to the results of the hypothesis tested in the next section. However, in the UK and Russia, the results for the manufacturing industries are likely to be related to the low rankings of value added, patents, and research expenditure per researcher.

Hernández (2020) explains clusters as follows. Porter’s diamond model stands out for its approach to the competitiveness of a nation, given that it limits the capacity to innovate the national or territorial scope. According to the diamond model, clusters play a very noteworthy role in national or territorial competitiveness. Accordingly, this study used country-level data that were available.

3.1. Ranking of Knowledge-Intensive Industries in Terms of Value Added

This section examines the world’s major countries in terms of their knowledge-intensive industries in terms of value added.

In the knowledge/technology-intensive manufacturing industry, China ranked first and the USA ranked second. In knowledge/technology-intensive manufacturing, the USA accounted for two-thirds of China’s value added. In third place was Japan, followed by Germany, and Korea. In sixth place and below were Italy, the UK, and France, with about 5%; Russia followed with 2%.

Similarly, for computer technology and optical instruments, China was in first place, with the USA in second place, accounting for 83% of China’s value added. In computer technology, in third place and below, Korea, Japan, and Germany had around 25% of

China's total value added; in sixth place and below, the UK and France had around 5% of China's total value added.

In knowledge/technology-intensive services, the first and second positions of the USA and China were reversed. The USA was in first place, with a higher ratio than the other countries, while China was in second place. China's value added was 28% of the USA's value added, followed by Japan, Germany, France, and the UK, which accounted for around 13% of the USA's value added. South Korea and Italy followed with 9% and 6%, respectively, and Russia had 3%.

The same ranking applied to the IT information service sector up to fourth place. The USA ranked first, with a higher share than the other countries, followed by China in second place. The ratio of China's value added to that of the USA was 23%, followed by Japan in third place and Germany in fourth place with 19% and 16%, respectively. Italy and South Korea (seventh and eighth) followed with 6% and 5%, respectively. As for Russia, the above-mentioned industries accounted for 1–3% of the value added of the top-ranking country.

3.2. Ranking of the Number of Patents Acquired

Next, we examined the ranking for the number of patents acquired by the knowledge-intensive industry. "Semiconductor manufacturing" was selected as representative of the knowledge/technology-intensive manufacturing sector. In addition, "computer technology" was taken to represent computer technology and optical instruments. "Digital communication technology" represents the knowledge and technology service industries, and "telecommunication" represents the IT information service industry.

(i) Semiconductor manufacturing

China ranked first in the number of patents for semiconductor manufacturing, with Japan in second place. The ratio of the number of patents in Japan to those in China was 87%, and the proportions for the USA (third), Korea (fourth), and Germany (fifth) to the number of patents in China were 50%, 25%, and 11%, respectively. Other countries included France in ninth place with 4%, and Italy in fourteenth place with 1%.

(ii) Computer technology

For the number of patents related to computer technology, China ranked first, followed by the USA. The ratio of the number of patents in the USA to those in China was 72%, while the ratios for Japan and South Korea compared with China were 31% and 22%, respectively. Germany ranked fifth, the UK ranked sixth, and France ranked seventh, with 8%, 5%, and 4% compared with the number of patents in China, respectively. Italy and Russia were last at 1%.

(iii) Digital communication technology

China ranked first in the number of patents in digital communication technology, followed by the USA. The ratio of the number of U.S. patents to the number of Chinese patents was 58%; the ratios of Japan and Korea compared with the number of Chinese patents were 26% and 22%, respectively; those for Germany, France, and the UK were 3%, 2%, and 2%, respectively, and the ratios of Germany and the UK relative to China were 3% and 2%, respectively.

(iv) Telecommunication

For the number of telecommunication patents, China ranked first, followed by the USA. The ratio of U.S. patents to Chinese patents was 64%, the ratios of Japan and Korea compared with China were 50% and 42%, respectively, and the ratios of Germany, France, and the UK were 5%, 2%, and 2%, respectively.

In summary, China ranked first in all industries, with the USA, Japan, and South Korea occupying the second, third, and fourth places, respectively. In Germany, France, and the UK, the number of patents acquired by the knowledge industry was less than 10% of the number acquired by China across the four industries, with the exception of semiconductors in Germany. Italy and Russia had less than 1% of the number of patents acquired by China.

3.3. Number of Papers (2022) and Research Expenditure per Researcher and per Capita (2021)

Data on the number of papers on computer science were analyzed.

(i) Number of computer science papers

China ranked first in the number of computer science papers, while the USA ranked second. The ratio of U.S. papers to Chinese papers was 33%, while the ratios of Germany (third) and Japan (fourth) were 12% and 9%, respectively. The ratios of the other countries (the UK, Italy, Korea, France, and Russia) were 6–8%.

(ii) Research expenditure per researcher and research expenditure per capita

In terms of research expenditure per capita, the USA ranked first and Korea second; these countries had the same level of research expenditure per capita. Germany ranked third, the UK fourth, Japan fifth, and France sixth, with ratios of 77%, 61%, 60%, and 50%, respectively, compared with the USA's per capita research expenditure. Italy, China, and Russia's percentages of the USA's per capita research expenditure were much lower at 28%, 20%, and 14%, respectively.

In terms of research expenditure per researcher, the USA was number one, with Germany in second place at two-thirds of the USA's research expenditure per researcher. Among the other countries, China had 57% of the USA's research expenditure, and France had 47%. Other countries (South Korea, Japan, Italy, and the UK) had about half of the USA's research expenditure, while Russia had a quarter of the USA's research expenditure.

The following section presents the results of an analysis of the research expenditure per researcher.

3.4. Ranking of Manufacturing Industries in Terms of Value Added

The following is an overview of the situation in the world's major countries in terms of value added. Five manufacturing industries were addressed: automotive, machinery, chemical, electronics, and pharmaceuticals.

In the automotive, machinery, chemical, and electrical machinery industries, China, the USA, Japan, Germany, and South Korea ranked first through to fifth, with the exception of the machinery industry, where Italy ranked fifth. China ranked first in value added for all industries, except for pharmaceuticals. Except for Japan, which ranked second in value added in the electronics industry, the USA, Japan, and Germany ranked second, third, and fourth, respectively, for the other three industries. The value added of the manufacturing industries in the UK, Italy, and France was approximately 5% or less of the value added of China, which ranked first for all industries. Russia's value added was about 1–2% of that of China.

In the pharmaceutical industry, the USA ranked first and China second, while the value added for Japan, Germany, the UK, and France was about 10% of that of the USA. The value added of Italy and South Korea was about 5% of that of USA, and that of Russia was 1% of that of the USA.

3.5. Ranking of Manufacturing Industries in Terms of Patents

In the five manufacturing industries, Japan, China, the USA, Germany, and Korea ranked first through to fifth, except for the automotive industry, where France ranked fifth. Japan ranked first in terms of the number of patents in the automotive and machinery industries, while China ranked first in the electrical industry. China also ranked second in four other industries. The USA ranked first in the number of patents in the chemical and pharmaceutical industries, second in the electrical industry, and third in the automotive and machinery industries. Germany ranked fourth in the number of patents, except for those in the electrical industry and the pharmaceutical industry. Korea ranked sixth in the number of patents in the automotive industry, fifth for those in the mechanical and chemical industries, fourth for those in the electrical industry, and second in the pharmaceutical industry. France, Italy, and the UK had around 10% of the number of patents in the manufacturing industry compared with the country ranking first for each industry. Russia had about 1–4% of the number of patents compared with the country ranked first for all industries.

3.6. Ranking of Manufacturing Industries in Terms of Papers

Regarding the number of papers, data on the number of papers in the fields of engineering, chemistry, and physics were available. For engineering, chemistry, and physics, China ranked first. The USA ranked second in engineering and chemistry, with 22% and 19% of China's share, respectively. In engineering and chemistry, Germany, Korea, Japan, Russia, Italy, the UK, and France had less than 10% compared with China's papers. Regarding the number of papers on physics, China remained in first place, but Japan was in second place, with 92% compared with China's papers. The number of papers in Korea, the USA, and Germany was about one-third of that of China, while France, the UK, Italy, and Russia had less than 10%.

4. Econometric Analysis: Research Funding

This section examines whether the starting segment of Step II is research funding. The nine countries included in the following analysis were China, Italy, the UK, the USA, Japan, Russia, France, Germany, and Korea. Granger causality tests were conducted between research expenditure per researcher and each of the value added, patents, and papers with lags of one to five years. The process of innovation is described as research expenses, papers, patents, and value added. The hypothesis is that innovation proceeds in the order of research expenses, papers, patents, and value added. The alternative variable for innovation is value added. This research assumed that innovation equaled value added in the econometric analysis.

The industries analyzed were (K1) knowledge/technology-intensive manufacturing; (K2) computers, electronics, and optical instruments; (K3) knowledge/technology-intensive services; and (K4) IT and information services, according to the NSF's value-added classification. In addition, according to the WIPO's classification of the number of international patent applications, the industries corresponding to each of the four were (K1) semiconductor technology, (K2) computer technology, (K3) digital communication technology, and (K4) telecommunications technology.

In the NSF classification of the number of scientific papers, the computer science sector corresponded to the computer, electronic, and optical instruments industry in the value-added classification; for per capita research expenditure, the average of all industries was used for further analysis.

The conversions among value added, patents, and papers used in this study were as follows. In terms of value added, the knowledge-intensive industries were classified into the following categories: (K1) knowledge/technology-intensive manufacturing, (K2) computers and electronics, (K3) knowledge/technology-intensive services, and (K4) IT information. These were converted to patents related to (K1) semiconductors, (K2) computers, (K3) digital communication technology, and (K4) telecommunication technology.

Next, in terms of value added, manufacturing industries were classified into the following categories: (M1) automobiles, (M2) machinery, (M3) chemicals, (M4) electronics, and (M5) medicine. These were converted into automobiles, machinery, chemicals, electronics, and medicine, respectively, in terms of patents, and into engineering (M1 and M2), chemistry (M3), physics (M4), and biology (M5) in terms of papers. The data are presented in Appendices B.1 and B.2.

In this section, Tables 4–7 show the results of regression analyses and Granger causality tests from all countries from 2002 to 2019, with the exception of the UK, which was analyzed from 2002 to 2017.

4.1. Linear Regression: Knowledge-Intensive Industries

Table 4 shows the results of three linear regressions of the knowledge industry. First, linear regression analysis was conducted with research expenditure as the independent variable and value added as the dependent variable. Second, regression analysis was conducted with research expenditure as the independent variable and papers as the dependent variable. Third, a regression analysis was conducted with research expenses as the independent variable and patents as the dependent variable.

Table 4. Regression analysis on knowledge-intensive industries.

		China	US	Russia	Germany	France	Korea	Japan	UK	Italy
		p-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value
research expenses [RE] → Value added [VA]	knowledge manufacturing	1.7×10^{10} ***	8.56×10^{12} ***	0.0119 *	0.000000312 ***	0.000128 ***	1.50×10^{11} ***	RE ->Pt->VA	-	-
	knowledge services	0.00000000115 ***	1.08×10^{9} ***	0.000128 ***	1.60×10^{12} ***	0.0119 *	1.92×10^{10} ***	RE ->Pt->VA	0.000055 ***	-
	computer	0.00000000274 ***	1.34×10^{11} ***	-	0.00705 **	-	5.91×10^{13} ***	0.00173 **	-	-
	ITS	0.00000000265 ***	2.07×10^{9} ***	0.000353 ***	6.18×10^{13} ***	0.00000946 ***	3.55×10^{10} ***	-	0.0162 *	-
Research expense → paper	computer	0.000103 ***	0.00015 ***	0.00004868 ***	0.00000061810 ***	0.00004868 ***	0.00521 **	0.0000161 ***	0.0464 *	-
research expenses → patent	knowledge manufacturing	0.000016921 ***	0.000506 ***	-	0.0219 *	-	1.80×10^{7} ***	1.18×10^{6} ***	-	-
	knowledge services	0.0000000798 ***	-	-	0.000000381 ***	-	0.00763 **	0.0031 **	-	-
	computer	0.00006495 ***	0.00003581 ***	0.00529 **	-	0.00529 **	1.69×10^{8} ***	2.34×10^{11} ***	0.0381 *	-
	ITS	5.81×10^{10} ***	0.000019855 ***	-	-	-	4.98×10^{10} ***	7.63×10^{10} ***	0.0382 *	0.0136 *
patent [Pt] → VA	knowledge manufacturing	0.000000017 ***	0.00481 **	0.000274 ***	0.00895 **	0.01009 *	0.000000086 ***	0.00878 **	-	0.0275 *
	knowledge services	1.04×10^{11} ***	-	0.01009 *	8.00×10^{8} ***	0.000274 ***	0.00364 **	0.0331 *	0.000497 ***	-
	computer	0.0000000185 ***	0.00021 ***	-	-	-	0.000000225 ***	0.000951 ***	-	0.025 *
	ITS	1.82×10^{13} ***	0.000000616 ***	-	-	-	0.0000000145 ***	-	-	-

Note 1: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05. Note 2: RE = Research expenses, Pt = Patents, VA = Value added. Source: Author's calculation.

As shown in Table 4, an additional regression analysis was conducted with patents as the independent variable, and value added as the dependent variable.

In particular, in the first regression analysis with research expenditure as the independent variable and value added as the dependent variable, the countries for which research expenditure was not significant for the knowledge/technology-intensive manufacturing and service industries were the UK and Italy. For all of the other seven countries, the regression of research expenditure on value added was significant. Notably, for Japan's knowledge/technology-intensive services and knowledge/technology-intensive manufacturing industries, the third and fourth regression analyses showed that the research expenditure regressed significantly with regard to patents, and patents regressed significantly with regard to value added. In other words, the research expenditure indirectly significantly regressed with regard to the value added. Therefore, the UK and Italy remain countries where research expenditure did not significantly regress on the value added.

4.2. Granger Causality Test: Knowledge-Intensive Industries

The Granger causality test allowed us to examine whether the findings regarding the "economies of sequences" were significant or not. Consider the two variables x and y. Model 1 is an autoregressive model of y, and Model 2 is an autoregressive model of x and y. Granger causality holds if the value of the prediction error of Model 2 is smaller than that of Model 1. Suppose that the lags of x and y are n (n = 1, 2, 3, 4, or 5, in our models) and e_i (i = 1, 2) is an error term.

Model 1: $y(t) = b_{11}y(t-1) + \ldots + b_{1n}y(t-n) + e_1$,

Model 2: $y(t) = b_{21}y(t-1) + \ldots + b_{2n}y(t-n) + c_{21}x(t-1) + \ldots + c_{2n}x(t-n) + e_2$.

In the case where all values of c_{2i} are 0, x does not Granger-cause y. We applied the F-test to find the causal relationships between research expenses per researcher and value added.

Time-series analyses assume stationary stochastic processes, while drift is an intercept component in a time series. On the other hand, ordinary least square estimations with a drift term (constant term) are non-stationary stochastic processes. It is generally accepted that equations without a drift term should be used for stationary stochastic processes. Thus, Model 1 and Model 2 were adopted without a drift term once it was confirmed that equations with a drift term provided results for non-stationary stochastic processes (see Kuchiki 2021 for details).

As shown in Table 5, we tested three types of Granger causality for each of the nine countries in the regression analysis in Table 4. In each case, we tested the Granger causality for all lags from one to five years. First, we tested whether the research expenditure per researcher Granger-caused value added. Second, we tested whether research expenditure per researcher Granger-caused papers. Third, we examined whether research expenditure per researcher Granger-caused patents. Regarding the first Granger causality tests for the knowledge/technology-intensive manufacturing and services industries, the countries in which research expenditure per researcher Granger-caused value added were, in order, China, the USA, Russia, Italy, and the UK. Thus, Italy and the UK showed significant Granger causality between research expenditure and value added with a time lag, although research expenditure did not significantly regress on value added, as seen in Table 4.

Table 5. Granger causality on knowledge-intensive industries.

		1. China		2. US		3. Russia		4. Italy		5. UK		France		Germany		Korea		Japan	
		Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value
research	knowledge manufacturing	3	0.0003	5	0.0091	5	0.0426	5	0.0014	4	0.0635			4	0.0030				
expenses	knowledge services	3	0.0028	1	0.0254	2	0.0538	1	0.0076	2	0.0016	1	0.0295						
→ VA	computer	3	0.0046			5	0.0112	1	0.0513	5	0.0139								
	ITS	3	0.0046					1	0.0243	5	0.0205								
research																			
expense → paper	computer	3	0.0046	3	0.0213			2	0.0003			1	0.0015	1	0.0143	1	0.0012	1	0.0152
research	knowledge manufacturing			4	0.0254	1	0.0460	1	0.0360	4	0.0058							5	0.0007
expenses	knowledge services					1	0.0177	1	0.0133	3	0.0329			1	0.0489			1	0.0429
→ patent	computer	3	0.0003	2	0.0177			3	0.0024	1	0.0107	3	0.0105						
	ITS	1	0.0127					5	0.0003	1	0.0367			4	0.0229	5	0.0223	4	0.0229

Source: Author's calculation.

4.3. Regression Analysis and Granger Causality Tests: Manufacturing Industries

Table 6 presents the regression analysis results for research expenditure per researcher, the number of papers, the number of patents, and value added for the five manufacturing industries in the nine countries. The countries where research expenditure per researcher significantly regressed on value added in at least four of the five industries were China, Germany, the USA, and Korea. The countries where research expenditure per researcher did not significantly regress on the number of patents were France, Japan, Italy, Russia, and the UK.

Next, Table 7 presents the results of the Granger causality tests for the five manufacturing industries. The results show that, with the exception of Russia and the UK, the Granger causality of research expenditure per researcher regarding value added was significant for the following seven countries: China, Germany, the USA, France, Japan, Italy, and Korea. The following three reasons can be suggested. First, the Granger causality of research expenditure per capita regarding value added was significant in at least four out of the five manufacturing industries for five countries. Second, in the case of Korea, research expenditure per researcher in the pharmaceutical industry significantly Granger-caused the number of papers, and the number of papers in the pharmaceutical industry significantly Granger-caused the number of patents in the pharmaceutical industry, as shown in Table 7. For the chemical industry, research expenditure per researcher significantly Granger-caused the number of patents, and the number of patents significantly Granger-caused the value added. Third, in the case of Japan, research expenditure per researcher significantly Granger-caused the number of patents, and the number of patents significantly Granger-caused the value added for the electrical and machinery industries, as shown in Table 7. Thus, the Granger causality was significant for research expenditure per researcher regarding the value added for the seven countries.

4.4. Research Funding as a Starting Segment

Table 8 shows the two results of the Granger causality tests and regression analyses in Tables 4–7. First, the countries where research expenditure per researcher significantly Granger-caused the value added of the knowledge/technology-intensive manufacturing and knowledge/technology-intensive services industries were China, the USA, Russia, Italy, and the UK. The countries where research expenditure per researcher was shown to be significant in a linear regression analysis on the value added of the knowledge/technology-intensive manufacturing and knowledge/technology-intensive service industries were Germany, France, Korea, and Japan. In short, the Granger causality of research expenditure per researcher regarding value added was significant for five countries, and the regression was significant for four countries.

Second, in the five manufacturing industries, the countries where research expenditure per researcher Granger-caused value added were China, Germany, the USA, France, Japan, Italy, and Korea.

The conclusion from the first and second results together is that research funding is the starting point for generating and creating value added, and that an increase in research expenditure per researcher leads to an increase in value added. The starting segment in the second stage of innovation is therefore the construction of a “research fund”.

Table 6. Regression analysis on manufacturing industries.

		China	Germany	US	Korea	France	Japan	Italy	Russia	UK
		***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**	***p*-Value**
research expenses → VA	automobile	1.61 × 10^{9} ***	0.00000169 ***				0.04323 *	1.73 × 10^{12} ***	0.000131 ***	
	chemical	8.31 × 10^{12} ***	0.0000271 ***	6.79 × 10^{10} ***	0.00000011758 ***	0.00149 **				
	electrocnics	2.58 × 10^{10} ***	0.00551 **	0.000000148 ***	4.50 × 10^{10} ***	0.0175 *				0.0068 **
	machinery	1.42 × 10^{11} ***	0.00000743 ***	0.000000066 ***	2.83 × 10^{11} ***		0.00185 **			
	medicine	0.0000000473 ***	0.001835 **	9.02 × 10^{10} ***	4.29 × 10^{8} ***					
research expense → paper	automobile	0.00000000924 ***	1.99 × 10^{11} ***	0.0000871 ***	5.83 × 10^{11} ***	1.91 × 10^{5} ***	0.0129 *		0.00184 **	0.000147 ***
	chemical	0.0000000132 ***	3.26 × 10^{10} ***	0.000868 ***	3.39 × 10^{10} ***	0.00158 **				0.0151 *
	electrocnics	0.0000000561 ***			0.00951 **		0.000772 ***		0.000754 ***	
	machinery	0.00000000924 ***	1.99 × 10^{11} ***	0.0000871 ***	3.49 × 10^{11} ***	1.91 × 10ˆ05 ***	0.0274 *		0.00184 **	0.000147 ***
	medicine	0.00000000924 ***	0.000000152 ***	0.00171 **	9.79 × 109 ***	0.000763 ***	0.000224 ***		0.0000436 ***	
research expenses → patent	automobile	0.0000000157 ***	0.000689 ***		5.71 × 10^{8} ***	0.0000261 ***	0.00000000136 ***		0.00000245 ***	
	chemical	0.00001817 ***	0.00443 **	0.014 *	3.49 × 10^{11} ***	2.65 × 10^{5} ***	0.00000000152 ***			
	electrocnics	0.000001463 ***	0.0000010531 ***	0.0000962 ***	2.01 × 10^{11} ***	2.65 × 10^{6} ***	7.38 × 10^{10} ***		0.000193 ***	0.0000698 ***
	machinery	0.00003405 ***	0.000229 ***		6.99 × 10^{10} ***		2.01 × 10^{11} ***			0.0368 *
	medicine	0.0000261 ***	4.04 × 10^{6} ***	0.0106 *	6.84 × 10^{10} ***	0.00429 **			0.00215 **	
patent → VA	automobile	1.7 × 10^{13} ***	0.00951 **			0.0261 *	0.0209 *		0.000182 ***	
	chemical	0.000000204 ***	0.000381 ***	0.0096 **	0.0000000658 ***	0.00411 **	0.0224 *	0.041 *	0.041 *	0.0000568 ***
	electrocnics	6.31 × 10^{11} ***	0.00102 **		5.53 × 10^{10} ***					0.00129 **
	machinery	0.000000347 ***	0.00000725 ***	0.020193 *	0.0000000102 ***	0.0174 *	0.00693 **	0.000384 ***		
	medicine	6.5 × 10^{11} ***			0.00000919 ***				0.000358 ***	0.0424 *
paper → VA	automobile	2.19 × 10^{10} ***	0.00000127 ***			0.03717 *				
	chemical	2.29 × 10^{11} ***	0.000162 ***	0.000331 ***	0.0000000226 ***	1.33 × 10^{5} ***			0.00035 ***	
	electrocnics	2.06 × 10^{13} ***	0.000277 ***		0.00326 **	0.005891 **		0.000374 ***		
	machinery	3.02 × 10^{12} ***	0.0000807 ***	0.0000221 ***	1.25 × 10^{10} ***		0.005101 **	0.0082 **	0.0112 *	
	medicine	1.69 × 10^{14} ***	0.000126 ***	0.0156 *	0.0000395 ***			0.0231 *		

Table 6. *Cont.*

		China	Germany	US	Korea	France	Japan	Italy	Russia	UK
		p-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value	*p*-Value
paper → patent	automobile	5.01×10^{11} ***	0.000197 ***	0.0293 *	0.00000000479 ***	8.98×10^{11} ***	0.0442 *	0.00000618 ***	0.0309 *	0.00492 **
	chemical	0.00000000647 ***	0.00862 **		8.89×10^{11} ***	0.0138 *		0.00303 **		
	electrocnics	0.00000000040 ***	0.00331 **		0.0265 *		5.88×10^{5} ***	0.0018 **		0.0404 *
	machinery	0.0000000500 ***	0.000152 ***		4.78×10^{11} ***			0.000173 ***		0.0324 *
	medicine	0.00000000188 ***	0.000161 ***	0.00000124 ***	4.55×10^{11} ***	0.00396 **		0.0250 *		

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05. Source: Author's calculation.

Table 7. Granger causality on manufacturing industries.

		1. China		2. Germany		3. US		4. France		5. Japan		6. Italy		7. Korea		Russia		UK	
		Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value	Time Lag	*p*-Value
research expenses → VA	automobile	1	0.0005782	1	0.0003931	3	0.02033	5	0.004196	3	0.002152	5	0.001305			5	0.01123		
	chemical	1	0.002759			2	0.03582	1	0.007459	2	0.02098	1	0.01026	RE->Pt->VA		RE->Pr->VA		4	0.0104
	electrocnics	1	0.02399	2	0.03627	1	0.00283	5	0.04121	RE->Pt->VA		5	0.01163	1	0.03791				
	machinery	3	0.007767	1	0.006289	2	0.05986			RE->Pt->VA		5	7.135×10^{5} ***	1	0.04528	RE->Pr->VA			
	medicine	1	0.004031	1	0.03299	1	0.036	4	0.05973	5	0.0005573	1	0.002347	RE->Pr->VA					
research expense → paper	automobile	4	0.0003871	2	0.007884			1	0.004823			1	0.0505	2	0.002166	5	0.02677	5	0.01668
	chemical			5	0.04862	2	0.001778	4	0.004839	5	0.003421			3	0.04339	1	0.003932		
	electrocnics			4	0.04884			3	0.007929										
	machinery	4	0.0003871	2	0.007884			1	0.004823			1	0.0505	2	0.002166	5	0.02677	5	0.01668
	medicine			5	0.003375							5	0.5054	1	0.004201				
research expenses → patent	automobile							2	0.007197	1	0.007088	1	0.02797					3	0.04176
	chemical							1	0.0103	3	3.898×10^{6} ***	3	0.0324	5	0.03486			2	0.05074
	electrocnics	4	0.02162	1	0.02915			5	0.01908	1	0.05371	1	0.007952			1	0.006342		
	machinery			1	0.01026					2	0.000188	4	0.03953	4	0.00702				
	medicine							2	0.00945			2	0.02193						

Table 7. *Cont.*

		1. China		**2. Germany**		**3. US**		**4. France**		**5. Japan**		**6. Italy**		**7. Korea**		**Russia**		**UK**	
		Time Lag	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**	**Time Lag**	***p*-Value**
patent $\rightarrow$ VA	automobile	5	0.007519															1	0.03643
	chemical					4	0.02923			5	0.006903	1	0.02506	5	0.01342	2	0.03777	1	0.03595
	electrocnics	1	0.03054	4	0.01941	1	0.02141	2	0.02057	3	0.01933							5	0.01725
	machinery			2	0.01931					3	0.002327							3	0.01199
	medicine	2	0.05268	2	0.001904					5	0.04556	3	0.03667					1	0.007831
paper $\rightarrow$ VA	automobile	3	2.026×10^5 ***			5	0.000272	1	0.05596	5	0.04938					2	0.007205	1	0.03325
	chemical	2	0.01808	1	0.003124	4	0.05314	1	0.0008412			2	0.003245			3	0.007512		
	electrocnics	1	0.0007995	1	1.301×10^5 ***			4	0.00627			1	0.02881			2	0.001018		
	machinery	2	0.0006962			1	0.01777			1	0.005931					3	0.004204	4	0.05634
	medicine	2	5.518×10^5 ***	1	0.001744	5	0.7632			2	0.05489			4	0.0002894				
paper $\rightarrow$ patent	automobile					1	0.04935	1	0.003534	2	0.006062			1	0.01137			2	0.02453
	chemical					1	0.01655	4	0.001901			1	0.002241	2	0.01692	3	0.002075	1	0.001396
	electrocnics	3	0.0005932			1	0.01139	1	0.03994	1	0.0425	1	0.002947						
	machinery							3	0.04288	1	0.04987			1	0.000234			5	0.05209
	medicine					1	0.04715	5	0.0151	1	0.0274			3	0.01562	1	0.05257		

Note: RE = Research expenses, Pt = Patents, VA = Value added. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05. Source: Author's calculation.

Table 8. Summary.

	1. China		2. US		3. Russia		4. Italy		5. UK			Germany	France	Korea	Japan
	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value		*p*-value	*p*-value	*p*-value	*p*-value
knowledge manufacturing	3	0.0003343 ***	5	0.00913 **	5	0.04261 *	5	0.00143 **	4	0.0635		0.000000312 ***	0.000128 ***	1.50×10^{11} ***	RE->Pt->VA
knowledge services	3	0.002839 *	1	0.02544 *	2	0.0538	1	0.007579 **	2	0.001634 **		1.60×10^{12} ***	0.0119 *	1.92×10^{10} ***	RE->Pt->VA
	1. China		2. Germany		3. US		4. France		5. Japan		6. Italy		7. Korea		
	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	Time lag	*p*-value	
automobile	1	0.0005782 ***	1	0.0003931 ***	3	0.02033 *	5	0.004196 **	3	0.002152 **	5	0.001305 **			
chemical	1	0.002759 **			2	0.03582 *	1	0.007459 **	2	0.02098 *	1	0.01026 *		RE->Pt->VA	
electronics	1	0.02399 *	2	0.03627 *	1	0.00283 **	5	0.04121 *		RE->Pt->VA	5	0.01163 *	1	0.04	
machinery	3	0.007767 **	1	0.006289 **	2	0.0599				RE->Pt->VA	5	0.00007135 ***	1	0.05	
medicine	1	0.004031 **	1	0.03299 *	1	0.036 *	4	0.05973 *	5	0.0005573 ***	1	0.002347 **		RE->Pr->VA	

Note 1: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05. Note 2: RE = Research expenses, Pt = Patents, VA = Value added. Source: Author's.

5. Summary and Conclusions

This study concerned innovation, which is Step II in cluster policy. Granger causality tests were conducted between research expenditure per researcher and each of the value added, patents, and papers for the knowledge/technology-intensive industries and the manufacturing industries in nine countries with lags of one to five years.

The hypothesis that research expenditure per researcher Granger-caused value added is significant, as shown by the results summarized in Table 8. Consequently, this study identified research funds as the initial segment for Step II. The conclusion is that the starting segment of innovation is the construction of a research fund.

This implication is critical for cluster policy. The outcome of research depends, in part, on funding, and one cannot initiate research activities without funding. The policy implication is that innovation begins with the establishment of research funds for researchers.

The amount of funding is a major determinant of research outcomes. According to Honjyo (2024), research related to the Nobel Prize in Medicinal Physiology will become increasingly expensive, making it difficult to collect funding. There were 26 Japanese Nobel laureates as of 2024, and many of them have relocated to the USA to improve their research environment, especially to raise funds for their research. Notably, the winner of the Nobel Prize in Physics, S. Manabe, changed his nationality to American.

This study contributes to the development of specific guidelines for cluster policies. First, we divided a cluster policy into two steps, namely agglomeration and innovation, and further divided the determinants, such as elements of Porter's diamond model, into segments for the step of innovation. Second, we sequenced these segments into the process of efficient construction by economies of sequences. It is important to note that the finalization of agglomeration is not automatically the starting segment that activates innovation. Step II (innovation) does not begin without building the starting segment of innovation, even after agglomeration is established. In order to initialize innovation, a research fund must be set up as the starting segment. Thus, the need to implement many policies at the same time is eliminated, and the feasibility of the policy's implementation is increased.

The contributions of this study are as follows. There are three theories of agglomeration: (i) spatial economics, (ii) construction sequencing in the industry, and (iii) sequencing economics. In this study, we linked construction sequencing in industries to sequencing economics, as shown in Table 1. Construction sequencing and start segment. We also integrated sequencing economics for cluster policy with the theory of Fujita and Thisse (2003), as shown in Figure 1. This study identified research funding as the starting segment of innovation.

However, there are many remaining issues. First, it is essential to re-examine our conclusions by examining other data and other methods such as causal inference tools, Bayesian causality, and behavioral economics. For example, causal inference tools would ensure that the observed outcomes were a direct result of the intervention and were not confounded by other variables. Bayesian causality provides a probabilistic framework for understanding how rational agents should update their beliefs and make decisions under uncertainty. Behavioral economics provides a theoretical foundation for understanding decision making.

Second, although "research funding" was identified as the starting segment, the existence of "human resources for researchers" was assumed. Although the data on research expenses were based on expenses per researcher and the factor of human resources was considered, it is necessary to further analyze the relationship between the human resources of researchers and research funding. Third, one study showed that university–industry–government links are effective in stimulating innovation. It is also essential to analyze the conclusions of this article regarding research expenditure. In addition, there are many other issues to be considered such as the identification of segments for cluster formation and their sequencing in the construction process.

Fourth, as stated above regarding the actions of Japanese Nobel laureates, outside of the USA, research funding per capita is low, and obtaining research funding is the first major obstacle for researchers in various research efforts. In this sense, it is essential to recognize that funding is the starting segment of research. For example, Nobel laureate Yamanaka (2024) also identified research funding activities in Japan as an important issue in his IPS cell research. However, further empirical research is needed on this point.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The following publicly available datasets were analyzed in this study: World Intellectual Property Organization (WIPO 2002–2019) (available online at https://www.wipo.int/patentscope/en/data/forms/products.jsp, accessed on 26 April 2024), the National Science Foundation (NSF 2002–2019) (available online at https://www.nsf.gov/statistics/, accessed on 26 April 2024) and UNESCO (2002–2019) (UNESCO Institute of Statistics) (https://uis.unesco.org/, accessed on 26 April 2024).

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Appendix A

Appendix A.1. The Segments of a Tourism Agglomeration in Osaka

Category	Segment
Infrastructure	**1. Kansai International Airport:** **Low-cost carriers** Railway Port Communication, Electricity, Water
Human resources	Population Unskilled labor Engineers Managers
Institutions	Laws and regulations Land ownership
Living conditions	**2. Entertainment: Universal Studio Japan** Hospitals and schools
Living conditions: Cultural aspects	Dynasty: Heian Dynasty Food: Octopus dumplings Music: Kawachi folk song History: Osaka Castle Texitle: Senshu Towel Painting: the Korin school Nakamurahochu Resort: Kyoto, Kobe Alcholic beverage: Local sake Akishika

Source: Author's Illustration based on Kuchiki (2020).

Appendix A.2. The Segments of a Manufacturing Industry Agglomeration

Category	Segment
Infrastructure	**Transport: 1. Port, Highways, Railway, Airport** **1. Industrial zone** Electricity Water Communication
Human resources	**2. Unskilled labor** Engineers Managers
Institutions	**3. Deregulation** **3. Preferential treatments (tax incentives, etc.)** **3. One-stop services** Laws and regulations
Living conditions	Housing International schools Hospitals Entertainment & shopping

Source: Author's Illustration based on Kuchiki (2020).

Appendix B. Data Sources for Table 3

Patents: World Intellectual Property Organization (WIPO 2002–2019); available online at https://www.wipo.int/patentscope/en/data/forms/products.jsp (accessed on 26 April 2024);

Value-added: National Science Foundation (NSF 2002–2019); available online at https://www.nsf.gov/statistics/ (accessed on 26 April 2024);

Number of published science and engineering articles: National Science Foundation (NSF 2002–2019); available online at http://www.nsf.gov/statistics/ (accessed on 26 April 2024);

Research expenses: UNESCO (2002–2019) (UNESCO Institute of Statistics); available at https://uis.unesco.org/ (accessed on 26 April 2024);

Material: Global Note; https://www.globalnote.jp/post-17789.html (accessed on 2 May 2024).

Samples of these data are shown in Appendices B.1 and B.2.

Appendix B.1. Data of Main Countries: Knowledge Industries

	China					US				
		Manufacturing		Service			Manufacturing		Service	
Year	re	pt	va	pt	va	re	pt	va	pt	va
2002	58,839	7	203,326	44	19,857	58,839	7	203,326	1655	300,333
2003	65,749	16	244,588	52	20,286	65,749	16	244,588	1567	312,111
2004	75,031	18	275,052	91	23,378	75,031	18	275,052	1412	340,318
2005	76,833	22	323,745	132	29,921	76,833	22	323,745	1581	360,619
2006	85,391	33	391,773	288	37,831	85,391	33	391,773	1792	384,845
2007	86,448	50	497,876	427	50,613	86,448	50	497,876	2097	405,546
2008	90,888	93	643,951	499	66,448	90,888	93	643,951	2180	451,098
2009	159,202	103	688,103	623	79,820	159,202	103	688,103	1453	465,210
2010	174,634	122	852,641	615	94,812	174,634	122	852,641	1162	508,349
2011	186,388	308	1,033,982	810	122,088	186,388	308	1,033,982	1014	562,385
2012	205,220	554	1,148,147	1043	150,561	205,220	554	1,148,147	1038	589,059
2013	217,178	609	1,283,720	843	174,833	217,178	609	1,283,720	1337	632,570
2014	226,412	757	1,397,329	996	205,027	226,412	757	1,397,329	1397	675,251
2015	225,475	844	1,460,433	1093	215,576	225,475	844	1,460,433	1195	734,204
2016	231,550	1053	1,514,143	1369	215,915	231,550	1053	1,514,143	1226	789,795
2017	241,078	1057	1,702,829	1630	243,712	241,078	1057	1,702,829	1319	847,116
2018	248,868	1426	1,937,445	1993	288,090	248,868	1426	1,937,445	1441	940,907
2019	249,066	2060	1,981,928	1854	285,503	249,066	2060	1,981,928	1333	1,034,456

	Russia					Italy				
		Manufacturing		Service		Manufacturing			Service	
Year	re	pt	va	pt	va	re	pt	va	pt	va
2002	29,658	4	22,362	15	5475	248,420	12	74,413	13	33,066
2003	35,394	6	26,002	8	6895	250,990	17	88,214	13	40,211
2004	35,580	5	37,228	13	8978	247,710	13	101,182	13	44,437
2005	39,081	9	47,419	16	10,938	220,673	9	101,347	13	45,911
2006	49,351	10	59,821	12	14,662	230,886	21	108,612	15	48,350
2007	56,585	10	79,587	21	18,924	241,215	25	125,988	13	55,535
2008	66,612	6	104,859	9	25,576	252,185	24	134,670	13	60,984
2009	78,335	10	66,800	10	21,233	243,992	34	109,634	13	58,795
2010	74,825	10	83,694	10	28,360	244,914	31	114,957	13	57,301
2011	73,890	13	108,645	18	37,365	245,670	29	123,018	16	60,468
2012	80,598	17	118,015	20	41,991	247,346	34	111,185	16	55,354
2013	87,145	19	124,589	22	48,530	244,851	40	115,973	14	57,863
2014	90,627	18	111,060	31	44,012	249,278	28	115,650	16	58,832
2015	86,286	9	61,512	22	27,083	238,546	32	104,291	16	50,733
2016	90,830	2	60,373	16	24,617	247,586	22	110,645	14	52,970
2017	102,793	12	69,912	20	29,621	245,951	18	117,112	15	56,813
2018	103,200	6	73,316	25	30,774	243,441	30	125,224	12	59,600
2019	114,013	13	78,565	13	32,672	241,240	26	113,710	14	60,483

Note 1: re: research expenditures per researcher, pr: papers, pt: patents, va: value added. Note 2: Program R 4.3.3. is used for Granger causality test. source: Appendix B.

Appendix B.2. Data of Main Countries: Manufacturing Industries

	China															
		Automobile			Chemistry			Electronics			Machinery			Medicine		
Year	re	pr	pt	va	pr	pt	va	pr	pt	va	pr	pt	va	pr	pt	va
2002	58,839	20,188	22	5695	8,427	11	36,714	9651	44	27,719	20,188	11	33,564	4939	154	14,497
2003	65,749	22,897	28	6001	9,452	25	43,679	11,183	83	32,094	22,897	12	41,002	6405	83	16,186
2004	75,031	32,328	24	6189	12,304	29	56,156	14,185	64	36,381	32,328	13	46,834	7991	121	16,141
2005	76,833	46,084	34	7341	15,361	24	62,765	18,731	107	46,107	46,084	20	59,684	10,792	132	19,658
2006	85,391	54,332	49	7749	17,496	39	74,288	22,142	176	57,244	54,332	28	75,317	13,597	171	22,349
2007	86,448	58,085	79	9815	20,295	65	100,067	23,530	201	74,419	58,085	54	100,212	16,259	169	28,052
2008	90,888	65,792	109	13,392	21,163	110	120,194	26,429	323	102,628	65,792	72	144,758	18,597	238	37,488
2009	159,202	75,839	113	14,427	23,653	81	127,064	27,841	368	113,041	75,839	95	150,615	21,202	220	41,334
2010	174,634	82,537	135	17,594	23,613	103	163,643	30,222	485	133,301	82,537	93	186,474	22,725	254	47,335
2011	186,388	94,564	229	21,187	26,914	180	214,757	31,686	743	157,116	94,564	132	231,110	25,862	329	58,692
2012	205,220	87,752	261	25,071	29,197	231	221,443	33,860	1056	174,714	87,752	217	254,584	28,992	414	73,290
2013	217,178	96,347	305	27,759	32,438	211	242,156	37,497	1265	196,140	96,347	226	280,127	33,943	411	84,314
2014	226,412	101,202	289	34,107	37,288	269	250,309	40,457	1395	214,155	101,202	238	292,900	38,387	479	95,166
2015	225,475	109,652	368	36,230	40,449	230	256,040	42,152	1577	225,875	109,652	252	297,394	42,579	502	106,325
2016	231,550	116,023	351	37,089	41,604	291	246,983	42,202	1900	236,717	116,023	342	304,797	45,802	707	116,085
2017	241,078	124,888	372	41,092	43,428	418	273,074	49,105	2328	266,149	124,888	343	344,290	46,204	919	133,259
2018	248,868	142,832	457	44,959	48,912	556	325,928	55,110	2972	297,886	142,832	560	391,636	52,618	1017	153,450
2019	249,066	162,746	557	46,628	54,517	676	326,874	63,921	3031	318,792	162,746	746	401,285	63,007	1233	158,924

	US															
		Automobile			Chemistry			Electronics			Machinery			Medicine		
Year	re	pr	pt	va	pr	va	re	pr	pt	va	pr	pt	va	pr	pt	va
2002	271,089	38,525	520	126,710	14,098	110,416	271,089	28,125	1488	43690	38524.61	596	99,340	53,624	2646	97,432
2003	266,650	42,144	513	134,318	13,530	110,060	266,650	30,363	1526	45545	42144.05	632	98,027	54,912	2725	100,571
2004	285,183	48,874	540	130,398	12,939	121,101	285,183	29,314	1484	42063	48873.55	612	105,023	58,238	2743	105,686
2005	309,764	55,197	570	127,477	12,432	119,214	309,764	36,575	1723	43212	55197.17	730	115,150	57,833	3411	103,758
2006	327,198	51,147	713	125,912	12,330	135,907	327,198	37,758	1933	51425	51146.9	752	122,686	59,030	3604	117,857
2007	353,780	50,178	761	116,358	11,493	144,841	353,780	35,904	2099	50296	50178.1	807	130,345	60,257	3570	123,086
2008	362,201	52,871	838	83,586	14,519	141,608	362,201	33,810	2245	55513	52870.54	770	132,905	60,006	3779	124,050
2009	346,088	52,689	793	44,165	13,096	144,211	346,088	34,498	2018	50640	52688.63	640	119,158	61,045	3165	143,751
2010	369,856	56,708	844	83,384	13,410	172,146	369,856	33,986	2082	50777	56708.15	584	127,752	60,600	3141	131,150
2011	371,421	56,620	949	97,966	14,220	175,458	371,421	36,123	2162	48309	56619.69	603	145,307	62,712	3052	130,502
2012	375,894	57,024	958	108,729	14,180	180,983	375,894	34,330	2297	52152	57023.54	591	152,625	65,477	2942	123,990

2013	381,462	57,692	1340	115,383	14,808	188,356	381,462	33,453	2512	58104	57691.66	666	157,927	64,708	3023	133,114
2014	386,076	57,357	2175	124,645	14,864	190,056	386,076	32,158	2846	54430	57357.06	884	161,014	65,487	3590	139,962
2015	403,409	55,321	1460	137,621	14,512	185,619	403,409	31,158	2341	63672	55321.34	700	152,509	64,344	2971	147,636
2016	425,626	56,514	883	146,182	15,107	198,603	425,626	29,545	2382	58462	56513.88	610	143,771	62,188	3327	158,446
2017	433,359	55,110	837	149,114	15,870	200,788	433,359	30,860	2391	60773	55110.26	556	153,411	61,451	3478	162,136
2018	436,492	57,812	912	148,207	15,601	210,273	436,492	29,001	2340	65061	57811.96	641	161,374	60,767	3593	165,487
2019	470,389	57,514	708	149,391	16,058	208,576	470,389	29,058	2174	65004	57514.43	654	166,982	61,092	3777	182,383

	Germany															
		Automobile			Chemistry			Electronics			Machinery			Medicine		
Year	re	pr	pt	va	pr	pt	va	pr	pt	va	pr	pt	va	pr	pt	va
2002	220,716	6456	776	1436	5214	472	33,644	11,086	782	29,792	6456	388	58,328	9902	584	12,504
2003	227,275	7215	697	1971	5143	446	38,923	10,981	725	35,556	7215	450	70,504	10,040	573	16,793
2004	233,090	7622	818	1877	5371	417	43,474	10,651	689	41,595	7622	407	82,263	10,426	489	19,629
2005	235,349	8973	801	2363	5554	414	43,546	12,530	882	40,314	8973	542	84,181	10,929	589	22,044
2006	248,649	9449	861	2428	5500	473	44,210	12,555	996	45,485	9449	532	91,901	11,320	638	23,545
2007	252,496	9977	923	3078	5655	523	51,349	12,967	1240	48,176	9977	579	110,715	11,389	594	26,982
2008	268,147	11,080	951	2800	5662	598	55,032	12,625	1591	53,982	11,080	655	122,913	11,659	568	31,294
2009	260,556	11,804	1105	3002	5879	533	47,314	13,836	1552	46,511	11,804	651	90,526	11,946	520	28,523
2010	265,020	12,804	966	2854	6003	523	53,121	13,641	1380	51,679	12,804	559	100,372	11,985	474	27,198
2011	282,688	12,912	1119	3163	6152	575	56,488	14,526	1581	57,312	12,912	659	118,306	12,204	459	29,602
2012	284,915	15,023	1339	2852	6408	586	51,141	13,938	1879	52,290	15,023	741	111,598	12,969	483	28,403
2013	290,067	14,103	1224	2695	6591	535	53,014	14,044	2034	54,474	14,103	653	116,588	12,819	457	29,553
2014	310,912	15,338	1247	3446	6452	515	55,584	13,774	1688	57,259	15,338	607	122,054	13,441	391	31,318
2015	293,701	16,147	1118	3411	6685	527	50,551	12,901	1698	45,899	16,147	607	104,313	13,076	357	25,351
2016	305,915	17,555	1120	3273	6575	503	52,828	12,571	1594	47,618	17,555	594	106,957	12,724	340	28,475
2017	318,006	16,628	1082	3068	6687	523	56,173	12,979	1660	50,541	16,628	620	115,919	12,906	370	25,004
2018	327,878	17,486	1087	3605	6814	589	58,734	11,722	1877	52,206	17,486	698	129,240	12,545	380	30,865
2019	324,563	17,282	961	3600	6734	537	50,973	12,591	1996	42,432	17,282	684	120,827	12,881	362	24,796

Source: Author's.

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