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Co-evolutionary coupling leads a way to a novel concept of R&D - Lessons from digitalized bioeconomy

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A R T I C L E I N F O

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A B S T R A C T

Given the increasing role of research and development (R&D) in competitive markets in the digital economy while confronting the dilemma between R&D expansion and a productivity decline, transformation of the R&D model has become a crucial subject for global digital leaders.

The authors of this paper postulate that neo open innovation harnessing the vigor of external innovation resources which then developed into a new concept of R&D that self-transforms during an R&D process initiated by Amazon by coupling with users.

The authors further develop these postulates by proposing the embedding of a growth characteristic identical to biological coupling.

An empirical analysis focusing on the forefront endeavors of global bioeconomy firms and also by Amazon was conducted.

A notable endeavor toward a circular economy initiated by its global leader UPM- Kymmene Corporation (UPM) demonstrated the significance of a coupling effect with downstream digital commerce leader Amazon. This effect can be attributed to harnessing the function of the growth characteristic identical to biological coupling through co-evolution of the dual coupling of bioeconomy and digitalization and of upstream and downstream operations.

This co-evolutionary coupling is expected to provide a novel concept of R&D that grows its function in a self-propagating way during the R&D process.

An insightful suggestion supporting to a novel concept of R&D in the digital economy is thus proposed.

1. Introduction

While research and development (R&D) expansion has become crucial for competitiveness in the digital economy, as a fatal consequence of the fundamental nature of digital innovation with logistic growth [1,2] and the two-faced nature [3], global digital leaders have been confronting the dilemma between R&D expansion and a productivity decline [4]. Thus, transformation of the R&D model has become a crucial subject.

The authors postulated that neo open innovation harnessing the vigor of external innovation resources [5,6] which then developed into a new concept of R&D that transformed routine or periodic alteration activities (non-R&D) into significantly improving ones (substantial R&D) during an R&D process initiated by Amazon [7,8].

Inspired by biological coupling, this paper was designed to further develop these postulates by embedding a growth characteristic in an R&D process.

First, an empirical analysis focusing on the forefront endeavors of 50 global bioeconomy firms was conducted.

A notable endeavor toward a circular economy initiated by its global leader UPM- Kymmene Corporation (UPM) demonstrated the significance of the coupling effect with downstream digital commerce leader Amazon [9], which is also keen to a circular economy corresponding to the shift of customer preferences to ecological behavior [10].

This effect can be attributed to harnessing the function of a growth characteristic identical to biological coupling through the co-evolution of the dual coupling of bioeconomy and digitalization and of upstream and downstream operations.

Thus, a novel concept of R&D that grows its function in a self-propagating way during its R&D process can be expected to move

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forward to operation.

This novel concept emerged as a consequence of notable steps toward achievement of the long-lasting goal of transition from a traditional fossil economy to a bioeconomy-based circular economy, and this can be attributed to the dramatic advancement of digital solutions in recent years [9].

While the forest-based bioeconomy incorporates the potential broad cross-sectoral benefits with sophisticated function, the natural environment, locality constraints, and incessant challenge of distance have impeded the balanced development of this economy [11–14].

However, driven by digital solutions, the bioeconomy has taken big steps forward in recent years. Digitalization has enabled real-time, end-to-end supply chain visibility. It has also improved delivery accuracy, stock level optimization, and alignment with demand planning.

Supported by advanced digital innovations such as artificial intelligence (AI), machine learning, virtual reality (VR), augmented reality (AR), and big data analysis, the coupling of digitalization and the bioeconomy is leading to a digitalized bioeconomy that can satisfy the shift in people's preferences for eco-consciousness, which in turn, induces the coupling of upstream and downstream operations in the value chain [15–18].

Given the unique feature of the value chain structure being identical to the forest-based bioeconomy (as illustrated in Fig. 1), this dual coupling emerges with the co-evolution of the dual couplings of the bioeconomy and digitalization and of upstream and downstream operations.

This co-evolutionary coupling transforms the forest-based bioeconomy into a digital platform industry and explores a new, four-dimensional sphere encompassing time and space with a growth characteristic beyond the existing concept of the digital innovation.

In their previous study, the authors demonstrated the co-evolution of the dual couplings of the bioeconomy and digitalization and of upstream and downstream operations was considered the locomotive power of the metabolism that had led to world circular economy leader UPM's resurgence by achieving the long-lasting goal of transition from a fossil economy to a circular economy in the second decade of this century [9].

This transition to a circular economy beneficiated not only UPM but also downstream leaders. In line with customers' increasing concerns about ecological behaviors, suppliers have become required to provide eco-certification through their whole value chains. Ferdousi et al. [15] surveyed consumers' ecological behaviors in such chains and demonstrated that "People those who have adopted ecological behavior are generally intended to buy green products." As reviewed earlier, downstream leader Amazon is sensitive to consumers' ecological behaviors [10] and keen to construct a win-win strategy with upstream leaders toward a circular economy, as is generally stressed as beyond-influencer marketing [19]. Amazon stressed that as Earth's most customer-centric company, it works every day for the lowest environmental impact shopping experience on the planet. Thus, coupling between upstream and downstream is indispensable for achieving the goal of transitioning from a fossil economy to a circular economy. As a matter of fact, both UPM and Amazon are members of the Sustainable Packaging Coalition (SPC) and are dedicated to collaborative activities for developing an eco-friendly, sustainable packaging system.[1] In addition, increasing dependence on frustration-free packaging, particularly from the second decade of this century, reinforced the coupling between leaders in both streams.

While it is generally understood in physics that two objects are said to be coupled when they are interacting with each other, biological organisms can achieve a variety of biological functions efficiently by using the coupling effects of multiple factors and they can demonstrate optimal adaptations to the environment [20]. Since a growth characteristic is one of the core functions of biological coupling, this provides insightful suggestions to R&D management in the digital economy regarding R&D growth by avoiding the dilemma between R&D expansion and productivity decline, and also by minimizing the financial burdens and risks that have become critical problems.

Harnessing a growth characteristic via biological coupling involves such functions as leveraging awakening and activating latent self-propagating functions indigenous to ICT [21] and essential to sustainable innovation in the digital economy. Thus, co-evolutionary coupling leads the way to a novel concept of R&D in the digital economy.

To date, while many studies analyzed the systems nature of the forest-based bioeconomy (e.g., Refs. [9,14,22–26], none has presented an empirical analysis with a view to demonstrate the above co-evolutionary coupling embedding a growth characteristic as biological coupling.

The authors of this paper aimed to conceptualize this coupling with a growth characteristic and attempted to provide a practical insight for its operationalization. By means of a stepwise empirical analysis taking 50 global forest-based bioeconomy leaders, elucidation of a unique feature of the co-evolutionary coupling toward circular economy embedding a growth characteristic was attempted together with the analyses of the reaction of downstream leader Amazon.

An insightful suggestion supporting a novel concept of R&D in the digital economy was thus provided.

Organization of this paper is as follows: Section 2 reviews new global streams of the digitalized bioeconomy. The market value of the digitalized bioeconomy is examined in Section 3. In section 4 analysis of co-evolutionary coupling is presented. In section 5 the authors demonstrate the significance of self-propagating function. In Section 6 is a summary of noteworthy findings, policy suggestions, and future research.

2. Global new streams of digitalized bioeconomy

Given a transformative endeavor of the digitalized bioeconomy identical to geopolitical regions, leading challenges emerge in each of four respective regions: America, Europe, Asia, and Africa were identified first from both growth potential and business prospects.[2]

2.1. Development trajectory of global bioeconomy firms

In line with the advancement of the digital economy, global bioeconomy firms have been endeavoring to create digital solutions, which inevitably urges them to an *R&D-driven, income-seeking* strategy as illustrated in Fig. 2. Fig. 2 illustrates the *R&D-driven operating income (OI)-seeking* trajectory in 50 global bioeconomy firms encompassing forest, paper and packaging firms in 2017 (see the details of the 50 firms in Table A1 in Appendix 1).

Given that R&D increase depends on a revenues (sales) increase, this strategy leads these firms to R&D and sales-driven income (operating income) seeking a trajectory (*R-S-driven OI-seeking trajectory*).[3]

Table 1 shows results of the analysis of this trajectory in 50 global bioeconomy firms in 2017 by applying their *OI* increasing trajectory to an *R-S*-driven logistic growth function.

[1] Established in 2004, SPC brings together 455 businesses, educational institutions, and government agencies to collectively strengthen and advance the business case for more environmentally friendly sustainable packaging through strong member support, an informed and science-based approach, supply chain collaborations, and continuous outreach to build eco-friendly packaging systems that encourage economic prosperity and the sustainable flow of materials.

[2] As a prelude aiming at identifying the focal actor of the analysis, this section depends on the authors' preceding analysis with a similar objective [49].

[3] Revenues and net income can be appropriated by sales and operating income, respectively as Revenues = Sales + Interest income + Dividend income. Net income = Operating income + investment income – interest expense + one-time extraordinary income – one-time extraordinary expenses – taxes.

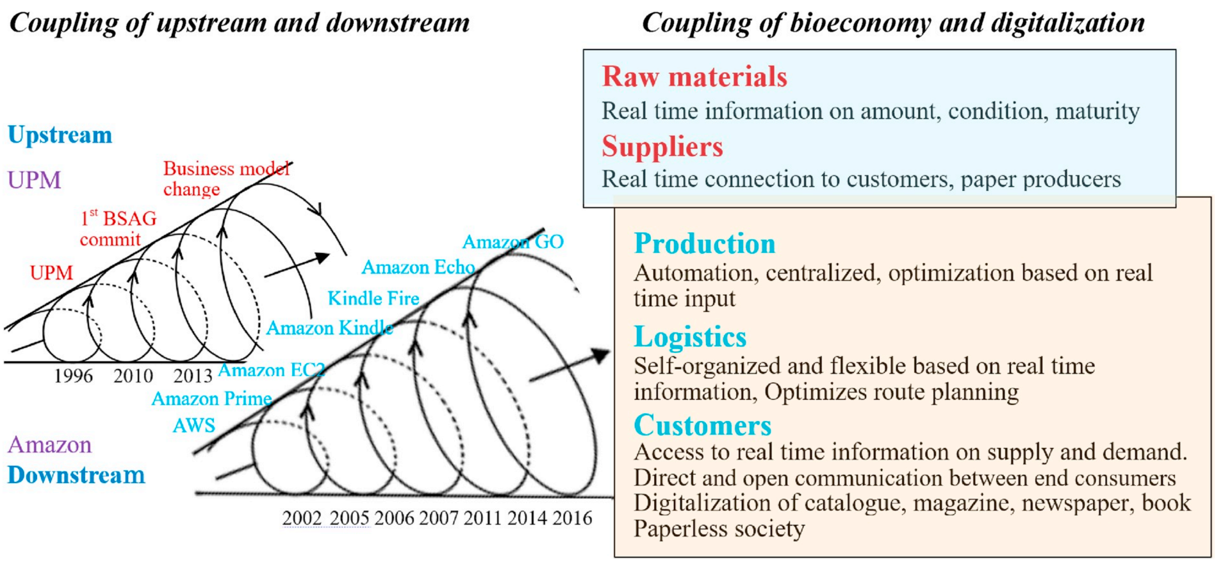


Fig. 1. Co-evolutionary coupling in the value chain of the forest-based bioeconomy.

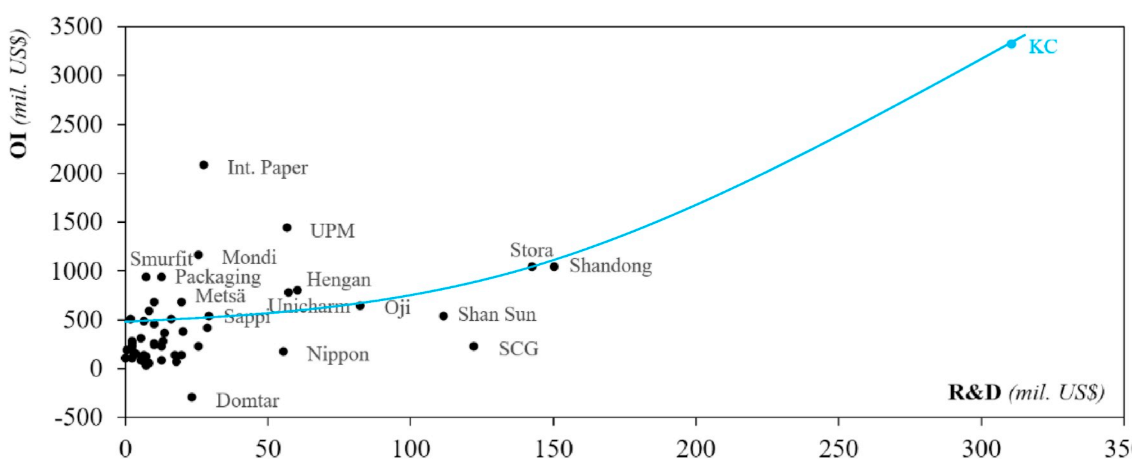


Fig. 2. R&D-driven *OI*-seeking trajectory in 50 global bioeconomy firms (2017).

Table 1 demonstrates statistically significant values where respective coefficients indicate a_1 and a_2: velocity of *OI* increase; *b*: initial state of *OI* level; and *c*: adjustment of Domtar's low level of *OI*, which is exceptional to 49 other firms, in the regression analysis.

Table 1 suggests that rapid *OI* increase in 50 global bioeconomy firms in the digital economy significantly depends on R&D and sales.

Inspired by this finding, with the understanding that rapid income increase is decisive to global firms in the digital economy [27], Table 2 identifies the top 20 prospecting global bioeconomy firms from growth potential. This potential was analyzed based on the potential of rapid *OI* increase by utilizing a synchronized index (*SI*) that demonstrates the velocity of *OI* increase.

2.2. Leading bioeconomy firms in geopolitical regions

Given the geopolitical significance of bioeconomy firms in the digital economy, Table 3 shows classifications of the top 20 prospecting firms in four regions: America, Europe, Asia, and Africa. In order to evaluate the comparative advantage and prospects of values that top firms will realize, Table 3 also shows comparisons of market capitalization which represent business prospects [28] between the top two *SI* value firms in each respective region over the last 5 years.

Based on the comparison both by growth potential and business prospects using *SI* values and market capitalization between the top two *SI* value firms in each respective region, the following four firms with higher market capitalization were chosen to represent prospecting firms

Table 1

Development trajectory of *OI* in 50 global bioeconomy firms (2017).$OI = \frac{N}{1+be^{-a_1R-a_2S}} + cD$

N	a_1	a_2	b	c	adj. R^2	D
6360.86 (1.39)*	0.004 (2.39)	0.0001 (5.46)	29.02 (5.35)	−729.68 (−2.85)	0.828	Domtar

OI: operating income; *N*: carrying capacity; *R*: R&D expenditure; *S*: sales; *D*: dummy variable; a_1, a_2, *b* and *c*: coefficients.
The figures in parentheses indicate the t-statistics: all are significant at the 1% level except *: 5%.

Table 2
Top 20 prospecting global bioeconomy firms (2017).

SI rank	Firm	Country	*SI* value	OI	Sales	R&D	OI/S	R/S	OI/R	OI rank	Sales rank	R&D rank	OI/S rank	R/S rank	OI/R rank
1	KC	US	3.07	3299	18259	311	0.18	0.017	10.61	1	2	1	3	4	13
2	Int. Paper	US	2.29	2069	21743	28	0.10	0.001	73.89	2	1	11	11	19	2
3	Stora	Finland	1.70	1019	11325	143	0.09	0.013	7.13	6	4	3	13	5	16
4	Oji	Japan	1.62	633	12838	83	0.05	0.006	7.63	11	3	6	16	7	14
5	UPM	Finland	1.36	1419	11285	57	0.13	0.005	24.89	3	5	8	7	10	8
6	Nippon	Japan	1.16	157	9330	56	0.02	0.006	2.80	19	8	9	19	8	18
7	Sumitomo	Japan	1.06	481	9926	17	0.05	0.002	28.29	15	6	16	17	17	7
8	Shandong	China	1.04	1023	4417	151	0.23	0.034	6.80	5	18	2	1	3	15
9	Smurfit	Ireland	1.00	924	9653	8	0.10	0.001	115.50	8	7	20	10	20	1
10	Mondi	UK	0.90	1148	8000	26	0.14	0.003	44.15	4	9	12	5	14	5
11	Unicharm	Japan	0.80	774	5721	58	0.14	0.010	13.34	9	12	7	6	6	12
12	SCG	Thailand	0.74	212	2517	123	0.08	0.049	1.72	17	20	4	14	1	19
13	Shan Sun	China	0.73	523	2796	112	0.19	0.040	4.67	14	19	5	2	2	17
14	Packaging	US	0.70	931	6445	13	0.14	0.002	71.62	7	10	17	4	16	3
15	DS	UK	0.65	570	6153	9	0.09	0.001	63.33	12	11	19	12	18	4
16	Sappi	S. Africa	0.65	526	5296	30	0.10	0.006	17.53	13	14	10	9	9	9
17	Metsä	Finland	0.65	655	5682	20	0.12	0.004	32.75	10	13	15	8	13	6
18	Domtar	Canada	0.61	−317	5157	24	−0.06	0.005	−13.21	20	15	13	20	11	20
19	Sonoco	US	0.59	367	5037	21	0.07	0.004	17.48	16	16	14	15	12	10
20	Rengo	Japan	0.54	211	4863	13	0.04	0.003	16.23	18	17	18	18	15	11

SI: Synchronized index; *SI* value $= a_1 R + a_2 S = 0.004 R + 0.0001S$.
See the full name of the firm in Table A1 in Appendix 1.

Table 3
Geopolitical distribution of prospecting bioeconomy firms (2017).

Region	Firms (*SI* value, numbers indicate *SI* rank among 20 firms)	Market capitalization (mil. US$, 2010 fixed prices)				
		2013	2014	2015	2016	2017
America	1. KC (3.07)	**35219**	**38692**	**35447**	**44884**	**40695**
	2. Int. Paper (2.29)	18534	20226	19309	15714	20747
	14. Packaging (0.70), 18. Domtar (0.61), 19. Sonoco (0.59)					
Europe	3. Stora (1.70)	7058	7069	6539	7908	10294
	5. UPM (1.36)	**7966**	**8749**	**9082**	**12180**	**13648**
	9. Smurfit (1.00), 10. Mondi (0.90), 15. DS (0.65), 17. Metsä (0.65)					
Asia	4. Oji (1.62)	**3609**	**4351**	**4029**	**4059**	**4552**
	6. Nippon (1.16)	1783	2147	1712	2107	2045
	7. Sumitomo (1.06), 8. Shandong (1.04), 11. Unicharm (0.80), 12. SCG (0.74), 13. Shan Sun (0.73), 20. Rengo (0.54)					
Africa	16. Sappi (0.65)	**1106**	**1611**	**1165**	**1982**	**2441**

in each respective region, on both growth potential and business prospects as summarized in Table 4.

3. Market value of digitalized bioeconomy

3.1. Market capitalization (MC)

Aiming at measuring the potential and prospects of the market value of a digitalized bioeconomy in transition, market capitalization (MC) and its sales ratio (MC/S) were used. MC is obtained by multiplying the number of a publicly traded firm's outstanding shares by the current share price. Since this represents the comparative advantage and prospects of values that the firm will realize, it is generally highly appraised as a good indicator of firms about their business prospects [28].

Fig. 3 illustrates trends in MC (in a logarithmic scale) in the four firms representing the four geopolitical regions. Fig. 3 demonstrates KC's highest level followed by UPM, Oji and Sappi.

However, if we compare the recent growth rate after 2012, we note UPM's conspicuously high growth rate over the last five years as demonstrated in Figs. 4 and 5. UPM demonstrated a notably high rate of growth from the beginning of the second decade of this century toward a circular economy [9]; see the details in Section 4).

3.2. Price-to-sales ratio (ratio of MC and sales: MC/S)

While MC represents the value of business prospects, it depends not only on the qualitative value of business prospects but also on the quantity of business activities. Therefore, in case when evaluating the value of business prospects placed on firm's sales, the price-to-sales ratio is used. This is the ratio of a firm's market capitalization and its sales (MC/S), thereby used as an indicator of the value placed on the firm's sales. MC/S is also known as a sales multiple. Contrary to the enterprise value-to-sales ratio (EVSR), it is supportive in making comparative prospects to assess each firm's business model. Figs. 6 and 7 illustrate the trends of MC/S in recent years in the four firms; these demonstrate a clear contrast between UPM's rapid increase and KC's decline in MC/S.

3.3. Governing factors of market capitalization

Market capitalization is a dependent variable determined by other variables, both by indigenous efforts and external stimulations. Co-evolutional advancement of these efforts and stimulations are essential for sustainable growth of MC and also of MC/S.

Table 4
Bioeconomy firms in the 4 regions (2017).

Firm	Country	*SI* value	OI	Sales	R&D	OI/S	R/S	OI/R	Business type/segments
KC	US	3.07	3299	18259	311	0.18	0.017	10.61	**Personal care** (disposable diapers, training and youth pants, swim pants, baby wipes, feminine and incontinence care products, and other related products) **Consumer tissues** (facial and bathroom tissue, paper towels, napkins and related products) **K–C professional** (wipers, tissue, towels, apparel, soaps and sanitizers.)
UPM	Finland	1.36	1419	11285	57	0.13	0.005	24.89	**Forest-based bio products** (biochemicals, biocomposites, biofuels, energy, labels, pulp and paper, plywood and timber). Acquisition of Myllykoski and Rhein Papier in 2010 accelerated the transformation into a circular economy-based business model consists of five principles: (i) circular supplies, (ii) resource recovery, (iii) product life extension, (iv) sharing platforms, and (v) products as a service.
Oji	Japan	1.62	633	12838	83	0.05	0.006	7.63	**Household and industrial materials** (packaging materials and products, household papers and disposable diapers) **Functional materials** (specialty papers, thermal papers, adhesive products) **Forest resources** (pulp, power generation, and lumber processing) **Printing and communication** (newsprint, printing and publication paper, copying paper)
Sappi	South Africa	0.65	526	5296	30	0.10	0.006	17.53	**Forest-based bio products** (printing paper, packaging and specialty papers, casting and release paper, dissolving wood pulp, biomaterials and bioenergy)

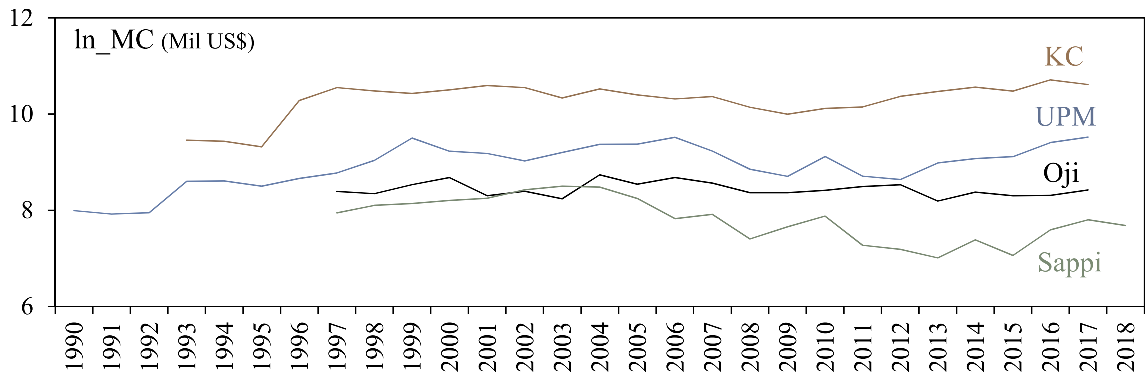


Fig. 3. Trends in MC in the 4 firms in a logarithmic scale.

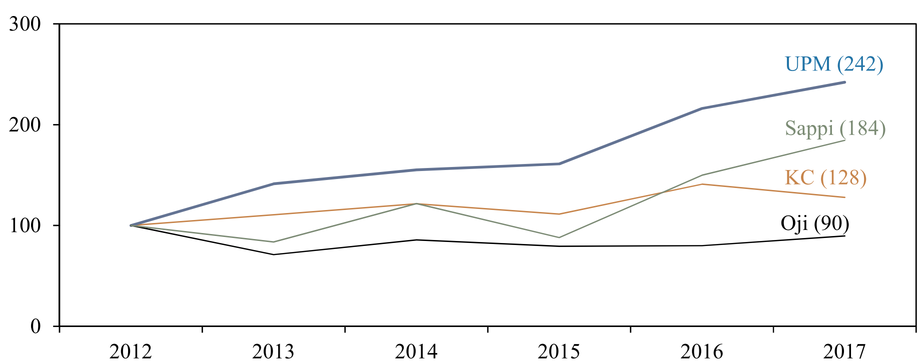


Fig. 4. Trend in increase ratios of MC in the 4 firms (2012–2017) – index: 2012 = 100.

3.3.1. *Indigenous efforts*

In conducting a comparative prospects assessment of a firm's business model, the following indigenous efforts should be taken for governing factors decisive to MC [28]:

(1) Sales and Operating Income

A firm's growth, generally measured by the rate of growth in sales, has a positive effect on the market value of a firm as this growth usually leads to an increase in operating income and R&D. Since the operating income (close to net income as net income = operating income + investment income – interest expense + one-time extraordinary income – one-time extraordinary expenses – taxes) enables firms' new activities and/or rewards to shareholders by providing dividends, investors expect the firm to do well in the future. Therefore, if operating income goes up, the stock price and subsequently the MC increases.

(2) R&D

While R&D decreases the firm's profit in the short term, it creates the potential for higher profits in the medium and long terms. Therefore, its increase is considered a positive sign for the firm's future profits leading to the MC increases. However, since R&D incorporates a pregnant period before commercialization and it carries the risk of failure, an R&D

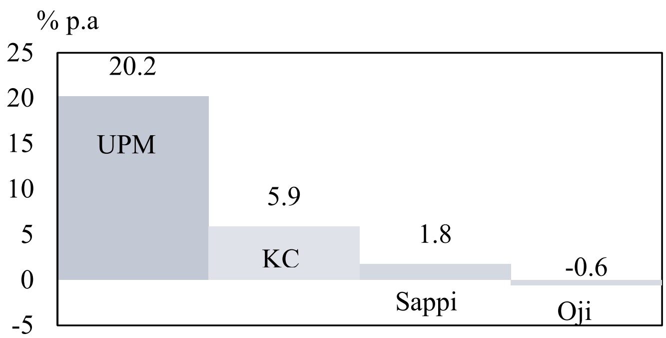


Fig. 5. Average growth rate of MC in the 4 firms (2013–2017).

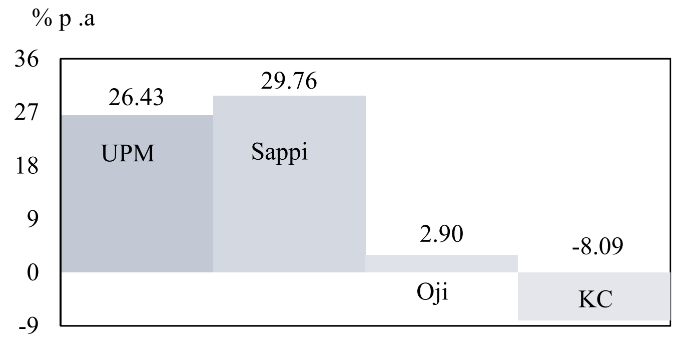


Fig. 7. Average growth rate of MC/S in the 4 firms (2013–2017).

challenge without investors' confidence results in an MC decrease [29, 30].

3.3.2. External stimulations

In addition to the above indigenous efforts, the MC as a dependent variable, is subject to external stimulations such as external market conditions, both global and local. Furthermore, as a consequence of the unique feature of value chain structure of the forest-based bioeconomy, the MC of the upstream firm is subject to coupling effects with downstream environments [31].

(1) External Market Conditions
 1) Global Market Conditions
  (i) Macro-economic factors such as interest rates, inflation, economic growth, trends in oil prices, and exchange rates.
  (ii) Political factors such as control of the government, elections, and also uncertainty stemming from a change in political circumstances.
  (iii) Natural and man-made disasters with economic consequences.
 2) Local Market Conditions
  Irregular happenings such as changes in business, its administrative system, acquisitions, and geo-political changes specific to the firm.
 3) International Policies and Commitments

International policies and commitments influence and bind ways of production and consumption.

(2) Coupling Effects with Downstream Firms

Coupling effects with downstream environments cannot be overlooked as a consequence of the economy with a value chain structure. In line with advancement of the digital economy and the subsequent increasing dependence on digital solutions, these effects have been significantly increasing [14]. The advancement of digital innovation has been transforming the influencer platform across the countries. Augmented Reality (AR) and Virtual Reality (VR) accelerate this transformation. Amazon is trying multiple approaches to leverage influencer marketing and the influencer economy [32].

In addition, increasing concerns regarding the circular economy and its impact on consumer ecological behaviors inevitably drive the coupling with partners who are leading the circular economy [15].

3.4. Institutional structure governing leading forest-based bioeconomy firms

Following the above review, the MC for leading forest-based bioeconomy firms can be depicted as follows, paying special attention to external stimulations both by external market conditions and coupling effects with downstream firms:

$$MC = F\,(S,\ OI,\ R,\ Ex,\ CE) \tag{1}$$

where *S*: sales; *OI:* operating income*; R*: R&D investment; *Ex*: external market conditions; *CE*: coupling effects with downstream firms.

Given the *R-S-driven, OI-seeking trajectory* in global bioeconomy firms as reviewed in Table 1, *OI* and strong inducement by *R* are considered as providing significant impacts on MC, and *S* can be treated as a dependent variable of *OI* and *R* in these impacts. Therefore, equation (1) can be transformed into equation (2) as follows:

$$MC = \mathrm{F}\,(OI,\ R,\ Ex,\ CE) \tag{2}$$

Translog (transcendental logarithmic) expansion on the first term:

$$\ln MC = a + b \ln OI + \mathrm{c} \ln \mathrm{R} + \mathrm{d} \ln Ex + \mathrm{e} \ln CE + f\ D \tag{3}$$

where *a* – *f*: coefficients; and *D*: dummy variables for local market conditions (irregular happenings identical to the firm).

Utilizing equation (3), governing factors of MC in the four firms over the last two to three decades were analyzed. A summary is presented in Table 5.

In this analysis, external market conditions (*Ex*) are proxied by the *S&P 500 Index,* while coupling effects with downstream firms (*CE*) were examined by analyzing the interacting effects of market value of downstream leaders [14]. Given Amazon's conspicuously higher stock

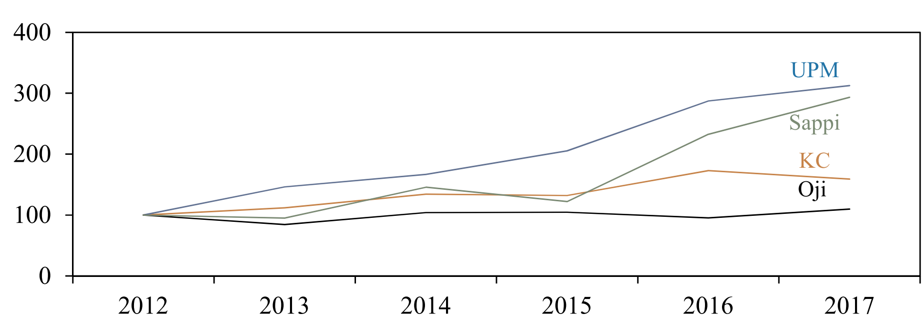


Fig. 6. Trends in the increase ratio of MC/S in the 4 firms (2012–2017) – index: 2012 = 100.

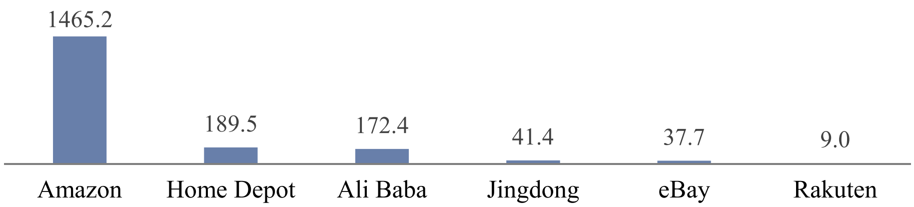


Fig. 8. Stock prices of global E-commerce leaders (2017) – US $. Source: Yahoo! Finance [33].

Table 5
Factors governing MC in the 4 firms. $\ln MC = a + b \ln OI + c \ln R + d \ln Ex + e \ln CE + f1\, D1 + f2\, D2$

	Const.	*OI*		*R&D*		*Ex*		Coupling effect		Dummy variables		adj. R^2	DW	Dummy period	
	a	b_1	b_2	c_1	c_2	d_1	d_2	e_1	e_2	f_1	f_2			D_1	D_2
		−2008	***2009-***	***−2008***	***2009-***			***−2008***	***2009-***						
KC (America)	2.35	0.44	–	0.80	0.50	–		–	0.28	0.29	−0.21	0.922	2.53	1997, 1998 2014, 2015	2008
(1995–2017)	(1.85) $*_2$	(11.34)		(3.40)	(2.23) $*_1$				(7.46)	(6.33)	(-2.50)				
						−2010	***2011-***	***−2010***	***2011-***						
UPM (Europe)	1.84	0.09		0.40		0.65	0.37	0.13	0.38	0.44	−0.57	0.847	1.83	1993, 2001	2009
(1990–2017)	(1.80)	(1.70)$*_2$		(1.57)$*_2$		(4.33)	(1.83)	(2.31)	(2.58)	(3.05)	(-2.80)				
		−2007	***2008-***					***−2007***	***2008-***						
Oji (Asia)	5.37	–	0.04	0.60		–		0.10	–	0.20	−0.25	0.920	2.47	2000, 2004	2003 2013
(1999–2017)	(11.16)		(2.91)	(5.69)				(4.49)		(7.54)	(-7.42)			2006, 2017	
		−2007	***2008-***	***−2007***	***2008-***	***−2007***	***2008-***	***−2007***	***2008-***						
Sappi (Africa)	14.67	−0.12	0.30	−1.60	–	–	−1.60	–	0.55	−0.58		0.898	1.52	2006, 2015	
(1997–2018)	(10.20)	(-1.99) $*_1$	(2.98)	(-4.22)			(-6.04)		(5.58)	(-4.97)					

The figures in parentheses indicate *t*-statistics: All are significant at the 1% level except $*_1$: 5%, and $*_2$: 10% level.

price compared to other global e-commerce leaders in 2017 as demonstrated in Fig. 8, the trend in its stock price was used as a proxy of this effect.

The backward elimination method with 10% significance criteria was used.

Table 5 demonstrates the following notable features in the four firms (figures in the parentheses indicate elasticity):

(1) **KC:** (i) R&D constantly induced MC (0.80 by 2008, 0.50 after 2009); (ii) *OI* inducement by 2008 (0.44) substituted with the coupling effect after 2009 (0.28).
(2) **UPM:** (i) R&D and *OI* constantly induced MC (0.40 and 0.09, respectively); (ii) Sensitive to external stimulations as external market conditions that induced MC significantly by 2010 (0.65, 0.37) which shifted to a coupling effect with downstream leader Amazon from 2011 (0.13, 0.38).
(3) **Oji:** (i) R&D constantly induced MC (0.60); (ii) Inducement of the coupling effect by 2007 (0.10) substituted to *OI* after 2008 (0.04).
(4) **Sappi:** (i) *OI* and the coupling effect changed to positive inducement after 2008 (0.3 and 0.55); (ii) *OI* and R&D reacted negative inducement by 2007 (−0.12 and −1.60) demonstrating failure to gain confidence from investors.

Among four firms, it is noted that UPM demonstrated a sophisticated R&D-driven virtuous cycle utilizing all resources including the coupling with downstream firms and also external market inducement [34]. This led to its conspicuous performance of MC/S increases as reviewed in Figs. 6 and 7. This was driven by an extremely high level of R&D productivity to MC (MC/R) after 2011 with the transition into a circular-economy-based business model [35,36], as demonstrated in Fig. 9. This transition significantly increased the coupling effect.

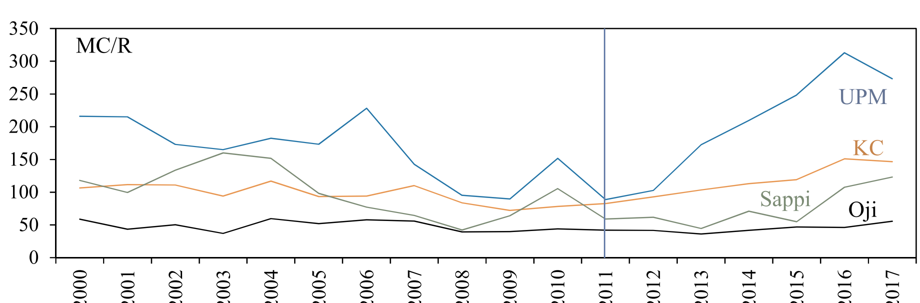


Fig. 9. Trends in MC/R in the 4 firms (2000–2017).

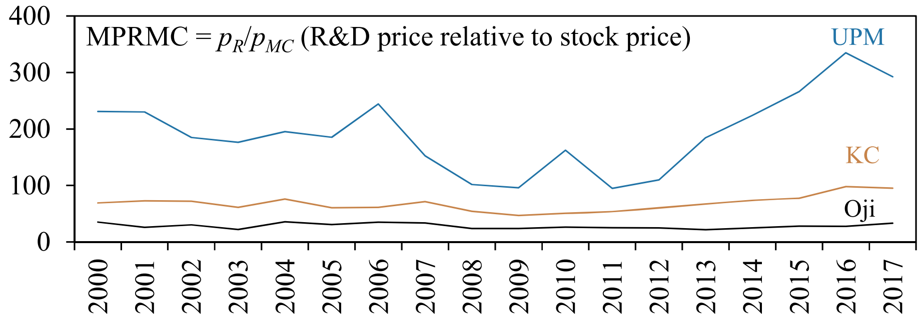


Fig. 10. Trend in marginal productivity of R&D to MC in the 3 firms (2000–2017).

Table 6
Correlation between MC/R, MC/S and MC in UPM (1990–2017).

$\ln \frac{MC}{S} = -6.27 + 1.16 \ln \frac{MC}{R} + 0.32D_1 - 0.25D_2$	$adj.\ R^2 = 0.936 \quad DW = 1.94$
(-20.44) (19.21) (4.34) (-3.00)	
$\ln MC = 2.98 + 1.16 \ln \frac{MC}{R} + 0.45D_3$	$adj.\ R^2 = 0.892 \quad DW = 1.27$
(7.47) (14.93) (6.36)	

D: dummy variables (D_1: 2008, 2009, 2011 = 1, others = 0; D_2: 2014, 2015 = 1, others = 0; D_3: 2004, 2005, 2007–2009, 2011, 2012 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level.

3.5. Sophisticated R&D-driven Co-evolution initiated by UPM

The above comparative analysis highlights sophisticated R&D-driven, co-evolutional cycles utilizing external resources (both in downstream and external markets) that UPM may incorporate as follows:

(1) Sophisticated R&D system in inducing MC
  (i) Consistent R&D elasticity

UPM: 0.40; KC: 0.80–0.60; Oji: 0.60; Sappi: negative.

(ii) Maintains conspicuously high marginal productivity of R&D to MC (*MPRMC*) that corresponds to R&D price relative to stock price as demonstrated in Fig. 10.

$$\varepsilon_{MCR} = c = \frac{\partial \ln MC}{\partial \ln R} = \frac{\partial MC}{\partial R} * \frac{R}{MC}$$

Elasticity of R&D to MC

$$\text{MPRMC} = \frac{\partial MC}{\partial R} = c * \frac{MC}{R} = \frac{p_R}{p_{MC}} \tag{4}$$

where p_R: R&D price; p_{MC}: Stock price.

(iii) Such a high level of *MPRMC* leads to a high level of MC/R (= *MPRMC/c*: proportional to R&D price) that induces MC/S as well as MC strongly, as demonstrated in Table 6.

Since MC/R is proportional to the R&D price as depicted in equation (4), this suggests the R&D price increase induces MC/S significantly.

Such an R&D-driven MC and MC/S inducing dynamism - beyond the dilemma between R&D expansion and productivity decline - prompts us to conduct an effective utilization of external resources for innovation and also the self-propa gating new market value creation as growth proceeds indigenous to ICT [21] as illustrated in Fig. 11.

(2) Well balanced resources allocation to MC creation

R&D contributes to MC not only directly but also via *OI* (Table 1) as *OI* constantly induced MC.

(3) Effective utilization of external stimulations

External stimulations by external market conditions (*Ex*) and coupling effects with downstream firms (*CE*) steadily contribute to MC with a noteworthy increase in the latter after 2011.

These inducements prompt the co-evolutionary coupling, the co-evolution of the dual coupling of bioeconomy and digitalization and of upstream and downstream operation in activating the above function. Particularly, coupling effects with downstream firms significantly increased after 2011. This can be attributed largely to UPM's new circular economy-seeking R&D challenge [14,34–37] and downstream leader Amazon's strategic change towards circular economy[4] (see the (see the details of this background in Section 5).

Table 7 highlights UPM's R&D challenge toward the circular economy by comparing it with other global bioeconomy leaders.

4. Co-evolutionary coupling

4.1. Sources enabling UPM's high performance in MC creation

Analysis in the preceding section suggests that UPM's notable high performance in MC creation can be attributed to its balanced contributing structure by R&D, *OI*, and external stimulations both by external market conditions and coupling effects with downstream firms as illustrated in Fig. 12.

Table 5 and 6 demonstrate that R&D and its price increase induce MC and MC/S significantly. Tables 8 and 9 demonstrate that induced MC induces sales and induced sales induce R&D, thus an R&D-driven virtuous cycle among them has been constructed.

This regression leads to the following correlation and suggests that MC induces MC/S significantly.

$$\ln \frac{MC}{S} \approx -7.50 + 0.79D_1 \ln MC + 0.81D_2 \ln MC$$

[4] UPM made its first commitment for BSAG in 2010 and a subsequent shift towards a circular-economy-based business model in 2013 by undertaking a circular economy-seeking R&D challenge in 2011. Similarly, Amazon's strategic change toward a circular economy commenced full-fledged operations in 2011. It insisted on offering the least environmental impact shopping experience on the planet and introduced its frustration-free packaging program in 2008 to accelerate the use of sustainable packaging. Frustration-free packaging differentiates and optimizes the customer's experience with easy-to-open packaging. It minimizes the environmental impact with 100% recyclable materials and reduces packaging costs by shipping products in their original packaging to eliminate the need for an extra box. Amazon tripled the number of items shipped with frustration-free packaging in 2011. Under this program, Amazon works with supply chain partners worldwide and helps them innovate sustainable packaging solutions [50]. In addition, Amazon launched Amazon Tote Pilot in 2011 as a new eco-friendly program. While this program concluded shortly, it demonstrated Amazon's strong consciousness to the circular economy.

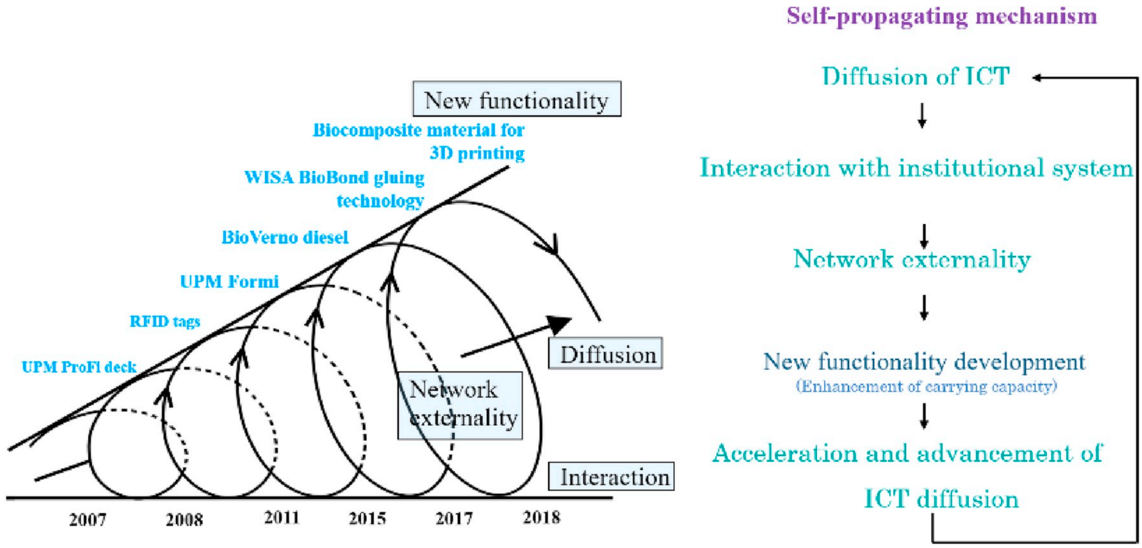


Fig. 11. Self-propagating development in UPM.

Table 7
Major R&D focus in the 4 firms.

KC	Kimberly Clark R&D activities include researching materials and technology innovations to deploy a more circular business model. KC emphasizes the zero-waste mindset across the value chain and adopts circular design principles to keep post-consumer waste out of landfills. In addition, they reduce and eliminate the materials of concern to ensure the safety and well-being of their customers.
UPM	The eco-design approach is at the core of R&D efforts in the development of new technologies and products. UPM invests in bioeconomy innovations, forest biodiversity and the circular economy to create sustainable solutions by minimizing dependency on fossil-based materials. UPM collaborates with customers, research institutions, universities and technology providers to develop creative circular economy solutions and user-friendly digital tools and services. The first commitment for the Baltic Sea Action Group (BSAG) in 2010 triggered these endeavors.
Oji	Oji aims to develop new possibilities, skills and high-tech materials in the paper and forest sectors. They are devoting their R&D efforts in developing cellulose fibers as they can potentially be used in many fields such as construction, chemicals, packaging and so on. Oji is introducing cutting-edge, continuous process technology for biochemical material development as well as highly-function film production technologies and medicinal plant cultivation techniques.
Sappi	Sappi's R&D efforts are adhered to consolidation and growth in the industry through cost competitiveness and optimization of equipment and forestry assets. They promote the innovation culture to develop sustainable solutions for the company. Sappi follows the partnership approach and develops long-term relationships with global firms and customers. They are growing their nanocellulose competency due to its wide range of application in construction, chemicals, personal and homecare products, composites and packaging papers.

4.2. Assimilation of external innovation resources

Such an R&D-driven virtuous cycle notwithstanding the dilemma between R&D expansion and productivity decline suggests a significant role that assimilated external resources in innovation, particularly absorption of soft innovation resources *(SIRs)* from external markets in both upstream and downstream businesses [5,6].

Here, *SIRs* are considered as a condensate and crystal of the advancement of the Internet and consist of Internet-based resources that have been either sleeping or untapped or are the results of multisided interactions in the markets where consumers are looking for functionality beyond an economic value. The common feature of *SIRs* is that they are not accountable in the traditional GDP terms [5,6]. In the context of co-evolutionary coupling toward a circular economy, harnessing such resources particularly through *circular suppliers*, *resource recovery*, *product life extension*, *sharing platforms*, and the *involvement of downstream firms' potential* is considered to play a significant role [9]. The advancement of the Internet plays a pivotal role for this harnessing [38].

Prompted by such a hypothetical view, assimilation capacity and the subsequent effect of assimilated *SIRs'* contributions to MC growth were analyzed.

As reviewed earlier, MC for leading forest-based bioeconomy firms can be depicted as follows:

$$\ln MC = a + b \ln OI + c \ln R + d \ln Ex + e \ln CE + fD \tag{5}$$

Here, gross R&D incorporating both indigenous R&D (R_i) and *SIRs* can be depicted as follows [7,8,39] where z is assimilation capacity:

$$R = R_i + z\, SIRs = R_i\left(1 + z\frac{SIRs}{R_i}\right) \quad z\frac{SIRs}{R_i} < < 1 \tag{6}$$

$$\therefore \ln R = \ln R_i\left(1 + z\frac{SIRs}{R_i}\right) \approx \ln R_i + z\frac{SIRs}{R_i} \tag{7}$$

Here, *SIRs* can be represented by Internet dependence as *SIRs* can be considered a condensate and crystal of the advancement of the Internet [5,6,9,38].

By synchronizing equations (3) and (5), the following equation is obtained:

$$\ln MC = a + b \ln OI + c \ln R_i + c^{'}\frac{SIRs}{R_i} + d \ln Ex + e \ln CE + fD \tag{8}$$

where $c^{'} = cz$. Therefore, assimilation capacity z can be identified as follows:

$$z = \frac{C^{'}}{C} \tag{9}$$

Utilizing equation (6), the governing factors of UPM's MC taking assimilated innovation resources explicitly over the period of 1990–2017 were analyzed, as demonstrated in Table 10.

SIRs were proxied by the Internet dependence in Finland (see Appendix 4 in Ref. [9]).

From Table 10 assimilation capacity can be identified as summarized in Table 11.

4.3. Effects of external innovation resources assimilation

By comparing the results of Table 10 (treating assimilated external innovation resources in an explicit structure) and Table 5 (treating these

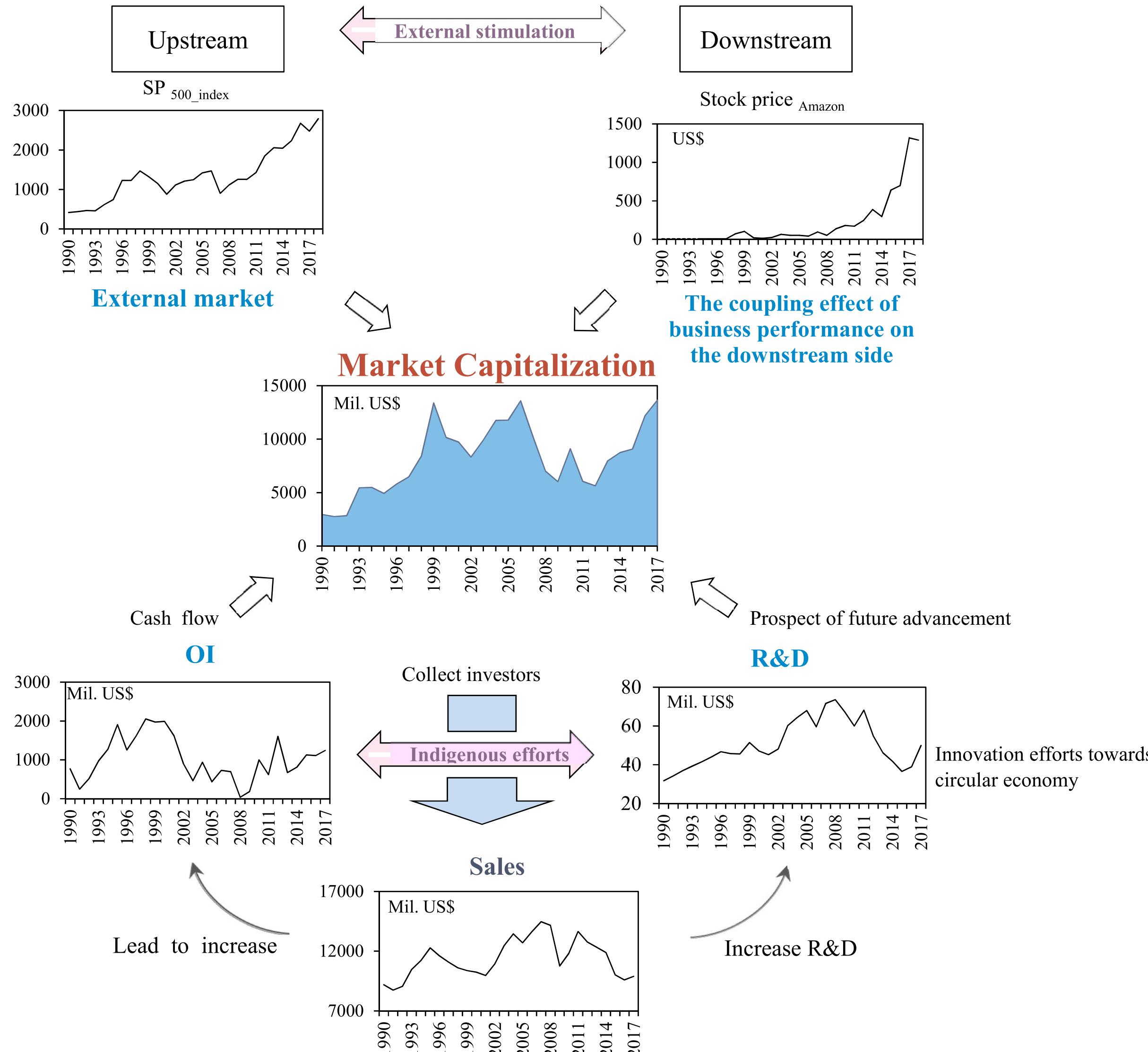


Fig. 12. Co-evolutionary development of MC in UPM (1990–2017).

Table 8
Correlation between MC and sales in UPM (1990–2017).

$\ln S = 7.50 + 0.21D_1 \ln MC + 0.19D_2 \ln MC - 0.18D_3 + 0.25D_4$					$adj.\ R^2 = 0.797$ $DW = 1.70$
(28.91	(7.00)	(6.57)	(-4.26)	(8.18)	

D: dummy variables (D_1: 1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0.
D_3: 1999–2001 = 1, others = 0; D_4: 1995, 2007, 2008, 2011–2014).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level.

Table 9
Correlation between sales and R&D in UPM (1990–2017).

$\ln R = -10.41 + 1.53D_1 \ln S + 1.54D_2 \ln S - 0.23D_3 + 0.38D_4$					$adj.\ R^2 = 0.815$ $DW = 1.43$
(-7.70)	(10.58)	(10.56)	(-3.51)	(3.66)	

D: dummy variables (D_1: 1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 1995, 2012–2014 = 1, others = 0; D_4: 2009 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level.

resources in an implicit structure), the effects of external innovation resources assimilation to MC increase were analyzed.

Taking the balance between equation (6) and equation (3), the following equations are obtained:

$$\ln MC - \ln MC = 0 = \sum p_i X + c' SIR_S \big/ R_i \tag{10}$$

where p_i: balance of *a, b, c, d, e* between equations (6) and (3); *X*: *OI*, R_i, *Ex*, *CE* (constant dummy variables are neglected).

$$SIR_S \big/ R_i = -\left(\sum p_i X\right) \big/ c' \tag{11}$$

The effects of external resources on respective factors' contributions to MC growth is summarized as tabulated in Table 12 in a way that decomposes the constitution of external resources (relative to indigenous R&D).

Table 12 demonstrates that assimilated external resources were substituted for MC growth contribution initiated by *OI* and indigenous R&D (R_i). It is noted that external resources contribution, particularly of coupling effect from downstream after 2011, has demonstrated significant inducement.

Table 10
Governing factors of UPM's MC taking assimilated external innovation resources (1990–2017).

$$\ln MC = 2.02 + 0.19 \ln OI + 0.74D_1 \ln R + 0.42D_2 \ln R + 0.22\frac{SIRs}{R} + 0.32 \ln Ex + 0.12D_1 \ln CE + 0.22D_2 \ln CE - 0.48D_3 + 0.33D_4 \quad adj.\ R^2 = 0.923 \quad DW = 2.47$$

(2.24) (4.89) (3.39 (2.55) (2.13) (2.41) (2.58) (2.71) (-5.29) (3.07)

D: dummy variables (D_1: 1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 2009, 2010, 2012 = 1, others = 0; D_4: 1993, 2001 = 1, others = 0).
The figures in parentheses indicate t-statistics: All are significant at the 1% level.

Table 11
Assimilation capacity in UPM.

1990–2010	0.30	(0.22/0.74)
2011–2017	0.52	(0.22/0.42)

4.4. The effects of coupling with downstream firms

Tables 10 and 11 suggest a possible causality between the increase in assimilation capacity and the effect of downstream firms in inducing UPM's MC, as illustrated in Fig. 13. Table 12 shows data to support this view.

These analyses suggest a notable coupling with downstream firms, particularly after 2011. This can be demonstrated by the significant impact of downstream firms on UPM's R&D price (price of gross R&D) increase as follows:

As reviewed in section 3.5, under competitive circumstances where UPM seeks maximum profit, the R&D price p_R can be depicted as follows:

$$MPRMC = \frac{\partial MC}{\partial R} = c^* \frac{MC}{R} = \frac{P_R}{P_{MC}} \tag{12}$$

where p_{MC}: stock price, c: elasticity of R&D to MC.

Therefore,

$$pR = \ MPRMC * p_{MC} \tag{13}$$

This price increased dramatically after 2011 as demonstrated in Fig. 14. This increase was triggered by UPM's circular economy-seeking R&D challenge from 2011 and also Amazon's strategic change toward a circular economy commencing full-fledged operations from 2011, as reviewed earlier.

This price increase contributes to increases in MC/R and MC/S as demonstrated in Table 13 and 14.

Increased MC/S stimulates interaction with downstream firms and activates coupling with them. Fig. 15 shows results of an analysis which suggest a correlation between MC/S and the coupling effects with downstream leader Amazon, which demonstrates a notable correlation after 2011. Advanced MC/S activates the coupling effect with downstream, thereby the co-evolutionary coupling between upstream and downstream firms emerged after 2011 when UPM's new circular economy-seeking R&D challenge and downstream leader Amazon's strategic change toward the circular economy commenced full-fledged operations (see footnote 4).

Table 15 demonstrates such coupling effects as upstream leader UPM's R&D-driven MC/S increase has induced downstream leader Amazon's stock price (CE) increase significantly, particularly after 2011.

As reviewed in Section 3, the stock price of Amazon is governed by operating income and R&D investments, particularly R&D investments as an R&D-driven company. In addition, Table 15 demonstrates that upstream leader UPM's business operations and prospects as

Table 12
Effects of external resources assimilation on the MC growth rate in UPM (1990–2017).

$SIR_s/R_i = a + b \ln OI + c \ln R_i + d \ln Ex + e \ln CE$					
1990–2010	−0.82	−0.45	−1.55	1.50	0.05
2011–2017	−0.82	−0.45	−0.09	0.23	0.73

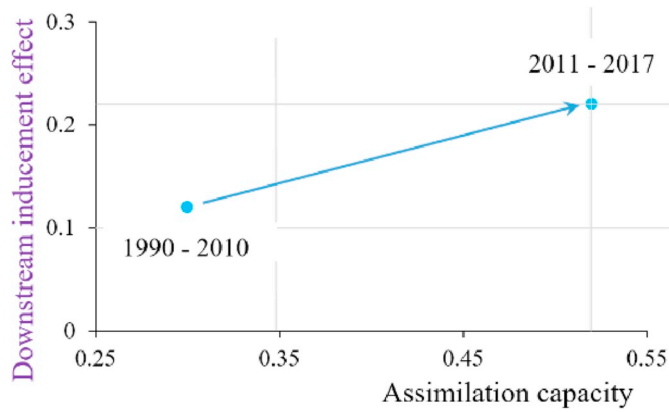


Fig. 13. Correlation between assimilation capacity and downstream firms inducement effect in UPM.

represented by R&D-driven MC/S, also induces Amazon's stock price significantly; this is particularly noted for results after 2011.

Such R&D-driven coupling effects from upstream to downstream firms, in turn, also provide significant effects to upstream by impacting UPM's R&D structure.

Fig. 16 shows results of an analysis in which a correlation was noted between the coupling effects with downstream leader Amazon and the price of UPM's gross R&D (see Fig. 14) which demonstrates that the coupling effects with downstream leader induced the price increase significantly after 2011.

Table 16 offers data to support analyses of the effects of external stimulations in increasing R&D prices in UPM, which demonstrates that coupling effects with downstream leader Amazon after 2011 significantly induced price increases and endorsed the above coupling effects with downstream firms.

Increased R&D prices consistently encourage R&D investments supportive of UPM's R&D-driven circular-economy endeavors.[5]

4.5. Utilization of external innovation resources via coupling with downstream firms

4.5.1. Assimilation of soft innovation resources via coupling

These analyses prompt a hypothetical view that such increases in UPM's gross R&D prices can be attributed to effective utilization of assimilated soft innovation resources (*SIRs)* via coupling with downstream leader Amazon.

Based on the preceding analyses, the data in Fig. 17 are offered as proof of this hypothetical view by demonstrating the significant increase in elasticity of coupling effects to assimilated *SIRs'* increases.

Elasticity of coupling effects to assimilated *SIRs'* increases $\varepsilon_{S_R CE}$is depicted as follows:

[5] From Tables 8, 13 and 14, $\frac{\partial \ln S}{\partial \ln MC} \equiv h$ (0.21 (1990–2010), 0.19 (2011–2017)), $\frac{\partial \ln MC/R}{\partial \ln P_R} = \frac{\partial \ln MC}{\partial \ln P_R} - \frac{\partial \ln R}{\partial \ln P_R} \equiv i$ (similarly, 0.58, 0.61), $\frac{\partial \ln MC/S}{\partial \ln P_R} = \frac{\partial \ln MC}{\partial \ln P_R} - \frac{\partial \ln S}{\partial \ln P_R} \equiv j$ (0.65, 0.67). $\frac{\partial \ln S}{\partial \ln P_R} = \frac{\partial \ln MC}{\partial \ln P_R} \cdot \frac{\partial \ln S}{\partial \ln MC} = h \cdot \frac{\partial \ln MC}{\partial \ln P_R}$, Substitute Table 14 $\frac{\partial \ln MC}{\partial \ln P_R}(1 - h) = j$ From Table 13 $\frac{j}{1-h} - \frac{\partial \ln R}{\partial \ln P_R} = i$, Therefore, $\frac{\partial \ln R}{\partial \ln P_R} = \frac{j}{1-h} - i \ = 0.24$ (1990–2010), 0.22 (2011–2017).

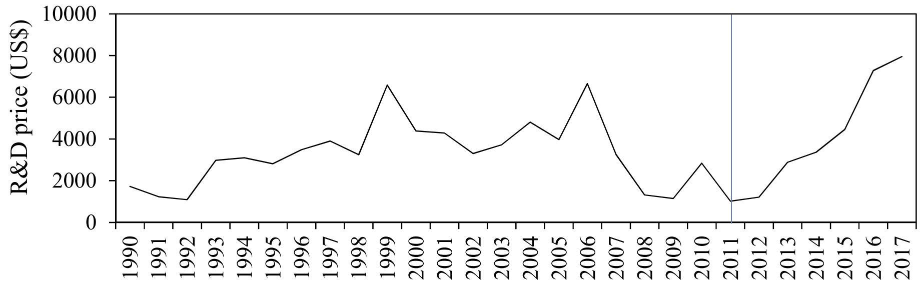


Fig. 14. Trend in UPM's gross R&D price (1990–2017).

Table 13
Correlation between R&D price and R&D productivity to MC in UPM (1990–2017).

$$\ln\frac{MC}{R} = 0.31 + 0.58D_1 \ln P_R + 0.61D_2 \ln P_R - 0.18D_3 + 0.16D_4 \qquad adj.\ R^2 = 0.982 \quad DW = 1.88$$

(2.15)* (31.34) (33.83) (-6.83) (5.44)

D: dummy variables (D_1: 1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 1990–1997, 2017 = 1, others = 0; D_4: 1998–2002 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level except *5% level.

$$\varepsilon_{S_R CE} = \frac{\partial \ln z\, S_R}{\partial \ln CE} = z\cdot\frac{\partial S_R}{\partial CE}\cdot\frac{CE}{S_R}$$

where $S_R = SIRs$; $z = 0.30$ (1990–200), 0.52 (2011–2017) (Fig. 13).

Based on the results shown in Table 12,

$$\frac{\partial \frac{S_R}{R}}{\partial \ln CE} = \frac{\partial \frac{S_R}{R}\cdot CE}{\partial CE} = \left(\frac{1}{R}\frac{\partial S_R}{\partial CE} - \frac{S_R}{R^2}\frac{\partial R}{\partial CE}\right)\cdot CE = e = 0.05\left(1990 - 2010\right),\ 0.73\left(2011 - 2017\right)$$

(Table 12). Therefore,

$$\frac{\partial S_R}{\partial CE} = \left(\frac{e}{CE} + \frac{S_R}{R^2}\cdot\frac{\partial R}{\partial CE}\right)R$$

Consequently,

Table 14
Correlation between R&D price and MC/S in UPM (1990–2017).

$$\ln\frac{MC}{S} = -5.61 + 0.65D_1 \ln P_R + 0.67D_2 \ln P_R - 0.41D_3 + 0.47D_4 \qquad adj.\ R^2 = 0.828 \quad DW = 1.07$$

(-11.61) (10.77) (11.02) (-3.10) (2.46)

D: dummy variables (D_1:1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 1995, 1996 = 1, others = 0; D_4: 2009 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level.

$$\varepsilon_{S_R CE} = z\cdot\frac{\partial S_R}{\partial CE}\cdot\frac{CE}{S_R} = z\left(\frac{e}{CE} + \frac{S_R}{R^2}\cdot\frac{\partial R}{\partial CE}\right)R\cdot\frac{CE}{S_R} = z\left(e\frac{R}{S_R} + \frac{CE}{R}\cdot\frac{\partial R}{\partial CE}\right)$$
$$= z\left(e\frac{R}{S_R} + \frac{\partial \ln R}{\partial \ln CE}\right) = z\left(e\frac{R}{S_R} + \frac{\partial \ln P_R}{\partial \ln CE}\cdot\frac{\partial \ln R}{\partial \ln P_R}\right) \equiv z\left(e\frac{R}{S_R} + f\cdot g\right)$$

where $f = \frac{\partial \ln P_R}{\partial \ln CE} = 0.15$ (1990–2010), 1.09 (2011–2017) (Table 16).
$g = \frac{\partial \ln R}{\partial \ln P_R} = 0.24$ (1990–2010), 0.22 (2011–2017) (Footnote 5)

$$\varepsilon_{S_R CE} = z\left(e\frac{R}{S_R} + f\cdot g\right)$$

4.5.2. *Eco-oriented resonance between upstream and downstream leaders*

Considering the close direct or indirect supply chain link between UPM and Amazon [14] and also given that Amazon is sensitive to consumers' ecological behaviors [10], extraordinary market impacts are demonstrated by its conspicuously high stock price compared to that of other global e-commerce leaders, as reviewed earlier (Fig. 8), suggest coupling between UPM and Amazon. The significant effects of such coupling can largely be attributed to the eco-oriented "resonance" with Amazon.

In Fig. 18 data are presented to demonstrate such "resonance"

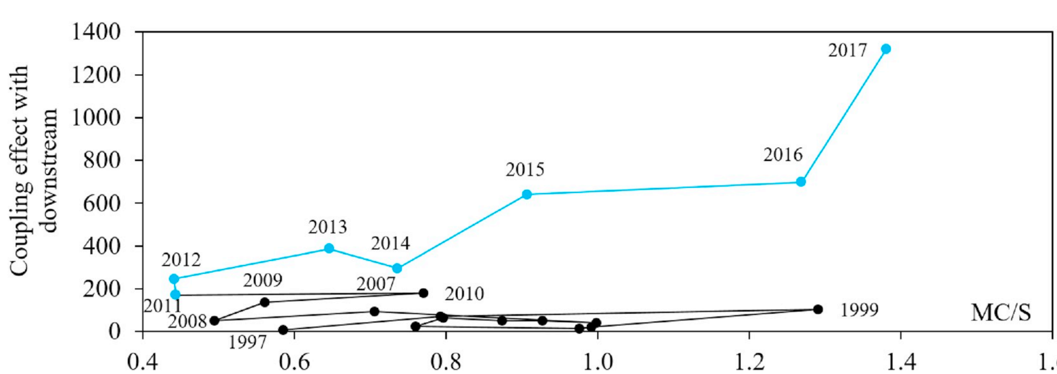


Fig. 15. Correlation between MC/S and coupling effect with downstream in UPM (1997–2017).

Table 15
Factors governing stock price in amazon after IPO (1997–2017).

$\ln CE = 1.36 + 0.21 \ln OI + 0.31 D_1 \ln R + 0.39 D_2 \ln R + 0.33 D_1 \ln \frac{MC}{S} + 0.72 D_2 \ln \frac{MC}{S} - 0.55 D_3 + 1.72 D_4$ (4.93) (8.39) (5.69) (8.69) (5.69) (8.69) (-6.55) (11.51)	$adj.\ R^2 = 0.987$ $DW = 2.08$

D: dummy variables (D_1:1997–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 2001, 2002, 2004–2006, 2008, 2016 = 1, others = 0; D_4: 1998, 1999 = 1, others = 0).
The negative value of OI in 1997–2001 was treated as 1 US$ mil.
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level except *10% level.

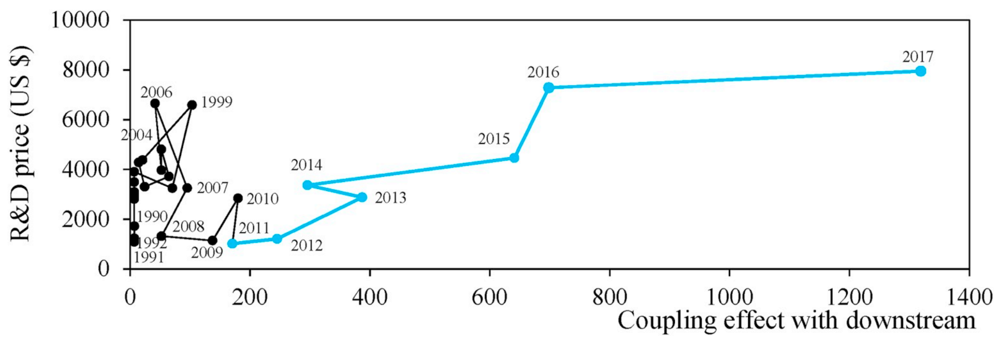
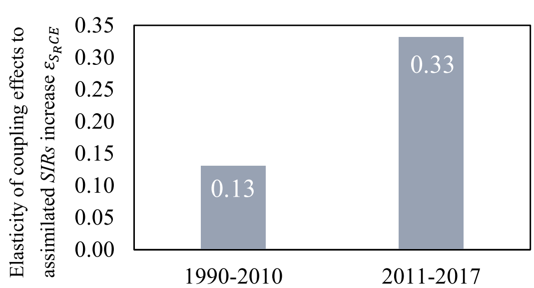


Fig. 16. Correlation between coupling effects with downstream and R&D price in UPM (1990–2017).



	1990-2010	2011-2017	Reference
z	0.30	0.52	Table 11
e	0.05	0.73	Table 12
f	0.15	1.09	Table 16
g	0.24	0.22	Footnote 5
*R/S*R *average*	8.02	0.54	Table 10
$\varepsilon_{S_R CE}$	**0.13**	**0.33**	

Fig. 17. Trend in elasticity of coupling effects to assimilated *SIRs* in UPM (1990–2017).

between eco-leaders in both upstream and downstream, UPM and Amazon. In the context of eco-challenges, Amazon tripled its number of shipped items sent in frastration free packaging from 2011 depending on the potential import from the upstream industries as illustrated in the upper part of Fig. 18. Such eco-seeking trade can be attributed to certain "resonance" between UPM and Amazon as suggested by the correlation of stock prices between the two leaders with 2011as an inflection point, as illustrated in the lower part of Fig. 18.

Such a resonance between upstream and downstream leaders can be traced, as illustrated in Fig. 19. Since 2008, UPM has been shifting its business model to include consciousness of energy and the environment. In 2008, it adopted a new market-driven business structure comprising three business groups: energy and pulp, paper, and engineering materials [40]. Later in 2013, UPM once again implemented a new business structure to drive a clear change in profitability. This period correspond to the UPM's first commitment for Baltic Sea Action Group (BSAG) in 2010. Consequently, while UPM started as a resources-intensive firm, it recognized the potentially fatal shift from a fossil economy to a bio-economy within the emerging context of sustainable development toward a circular economy [35–37]. Thus, UPM has been recognized as one of the world's circular economy leaders.

Such a pioneer endeavor in the upstream firm drew attention to downstream leader Amazon since it is sensitive to consumers' ecological behaviors and subsequent keen concern to construct a win-win strategy with upstream leaders toward the circular economy. As Earth's most customer-centric company, Amazon insisted on offering a shopping experience with the least environmental impact on the planet.

Consequently, it is assumed that the resonance among leaders both in the upstream and the downstream emerged in the beginning of the second decade of this century.

While further empirical and theoretical analyses are required,[6] such resonance has been steadily shifting from a virtual, intangible one to a tangible one as summarized in Table 17. Numerical analyses of coupling effects from UPM to Amazon (Table 15) and also from Amazon to UPM (Fig. 17) support these observations.

4.6. Co-evolutionary coupling: new R&D model in the digital economy

4.6.1. Dynamism leading to Co-evolutionary coupling

On the basis of the foregoing analyses, data are included in Fig. 20 to demonstrate the co-evolutionary coupling (the co-evolution of the dual couplings of bioeconomy and digitalization and of upstream and downstream operations) that UPM has been deploying.

T_n, F_n and Fi_n mean Table, footnote and Fig. number, respectively. Numerical values indicate elasticity (1990–2010 and 2011–2017, respectively).

This co-evolutionary coupling provides the following three-dimensional insights supportive of a novel concept of R&D in the digital economy:

[6] A Probabilistic Partnership Index (PPI) sectoral analysis [51] may provide a constructive insight on the substantial interactions between two partners.

Table 16
External stimulations inducing R&D price in UPM (1990–2017).

$\ln P_R = 2.81 +$	$0.72D_{11} \ln Ex +$	$0.68D_{12} \ln Ex +$	$0.55D_{13} \ln Ex -$	$0.20D_2 \ln Ex +$	$0.15D_1 \ln CE +$	$1.09D_2 \ln CE +$	$0.45D_3 -$	$0.51D_4$	$adj.\ R^2 = 0.952 \quad DW = 2.27$
(4.62)	(7.29)	(6.80)	(5.33)	(-1.58)*	(3.31)	(11.12)	(7.14)	(-6.09)	

D: dummy variables (D_1:1990–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_{11}: 1990–2001 = 1, others = 0; D_{12}: 2002–2007 = 1, others = 0; D_{13}: 2008–2010 = 1, others = 0; D_3: 1993, 1994, 2006, 2010, 2014, 2016 = 1, others = 0; D_4: 1991, 1992, 1998, 2009 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level except *10% level.

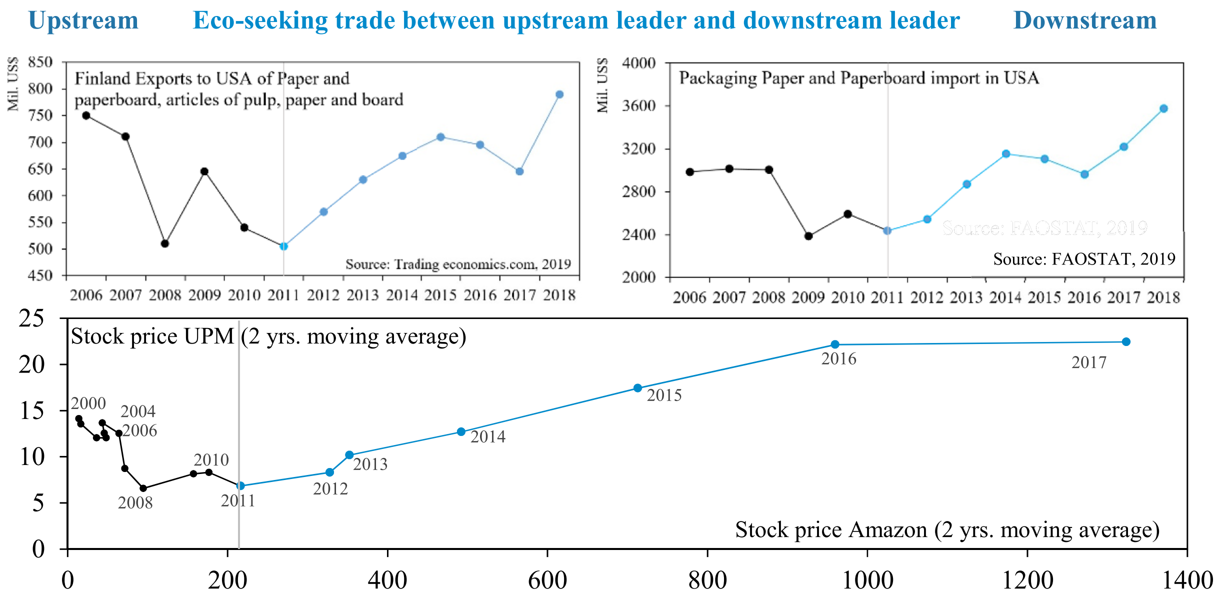


Fig. 18. Possible resonance between UPM and amazon by eco-trade and stock price [52].

(1) R&D-driven virtuous cycle
 (i) **R&D** (gross R&D) induced **MC.**
 (ii) Induced **MC** induced **sales** and **MC/S.**
 (iii) Induced **sales** induced **R&D**, thus the R&D-driven virtuous cycle has been constructed.

(2) Coupling with downstream Leader Amazon
 (i) Induced **MC/S** significantly induced the **coupling with downstream** after 2011.
 (ii) Reinforced **coupling** reinforced **assimilation of *SIRs***, particularly of highly-qualified *SIRs* after 2011, leading to a dramatic increase in the **R&D price.**
 (iii) The **R&D price increase,** in turn, accelerated the **MC/S** increase. Thus, a virtuous cycle involving downstream leader has been constructed.

(3) Spiral increase in R&D productivity of MC (MC/R)
 (i) Increases in the **R&D price** also accelerated the **MC/R** increase which induced two virtuous cycles through **MC** and **MC/S** increases, leading to a **spiral increase in MC/R.**
 (ii) Thus, notably high levels of the **MC/R** structure (Fig. 9) initiated by the R&D-driven virtuous cycle have been constructed.

4.6.2. Contributors to Co-evolutionary coupling

The spiral increase in MC/R is a core source of UPM's ability to become world leader in the circular economy [37]. This can be attributed to its success in assimilating growth characteristics identical to biological coupling [20] through the co-evolution of the dual couplings of bioeconomy and digitalization and of upstream and downstream operations.

The former coupling can be attributed to digital solutions supported by advanced digital innovations such as artificial intelligence (AI), machine learning, virtual reality (VR), augmented reality (AR), and big data analysis that can satisfy the shift in people's preferences for eco-consciousness, which, in turn, induces coupling of upstream and downstream operations in the value chain [15–18].

The effective inducement of coupling of upstream and downstream operations can be attributed particularly to downstream leader Amazon's eco-consciousness as Earth's most customer-centric company. However, it should not be overlooked that UPM's world-leading circular economy endeavor may have been triggered by such coupling by stimulating Amazon's sensitivity to consumers' ecological behaviors and subsequent keen concern to construct a win-win strategy with upstream leaders toward a circular economy.

5. Activation of self-propagating function

5.1. Spinoff of the Co-evolution of three mega trends

The above co-evolutionary coupling provides insights into the analysis of a new stream of innovation in the digital economy amidst the spinoff of the co-evolution of three mega trends from *traditional ICT* to *advancement of ICT*, *GDP growth* to uncaptured GDP and *economic functionality* to *supra-functionality beyond economic value* as shown in the upper left of Fig. 21 [4,14].

Watanabe et al. [41] previously postulated that while the advancement of the Internet has provided people with utility and happiness, it cannot be captured through GDP data that measure economic value resulting in productivity declines; hence, they defined these as uncaptured GDP. The authors then demonstrated the foregoing co-evolution as a new stream of innovation in the digital economy.

Under such circumstances, against productivity declines, global ICT firms have aimed to transform their business models by incorporating new streams of digital solutions-driven disruptive business models that spontaneously create uncaptured GDP instead of passively depending on it, as shown in the middle of Fig. 21 [42].

Locomotive power of this stream can largely be attributed to the

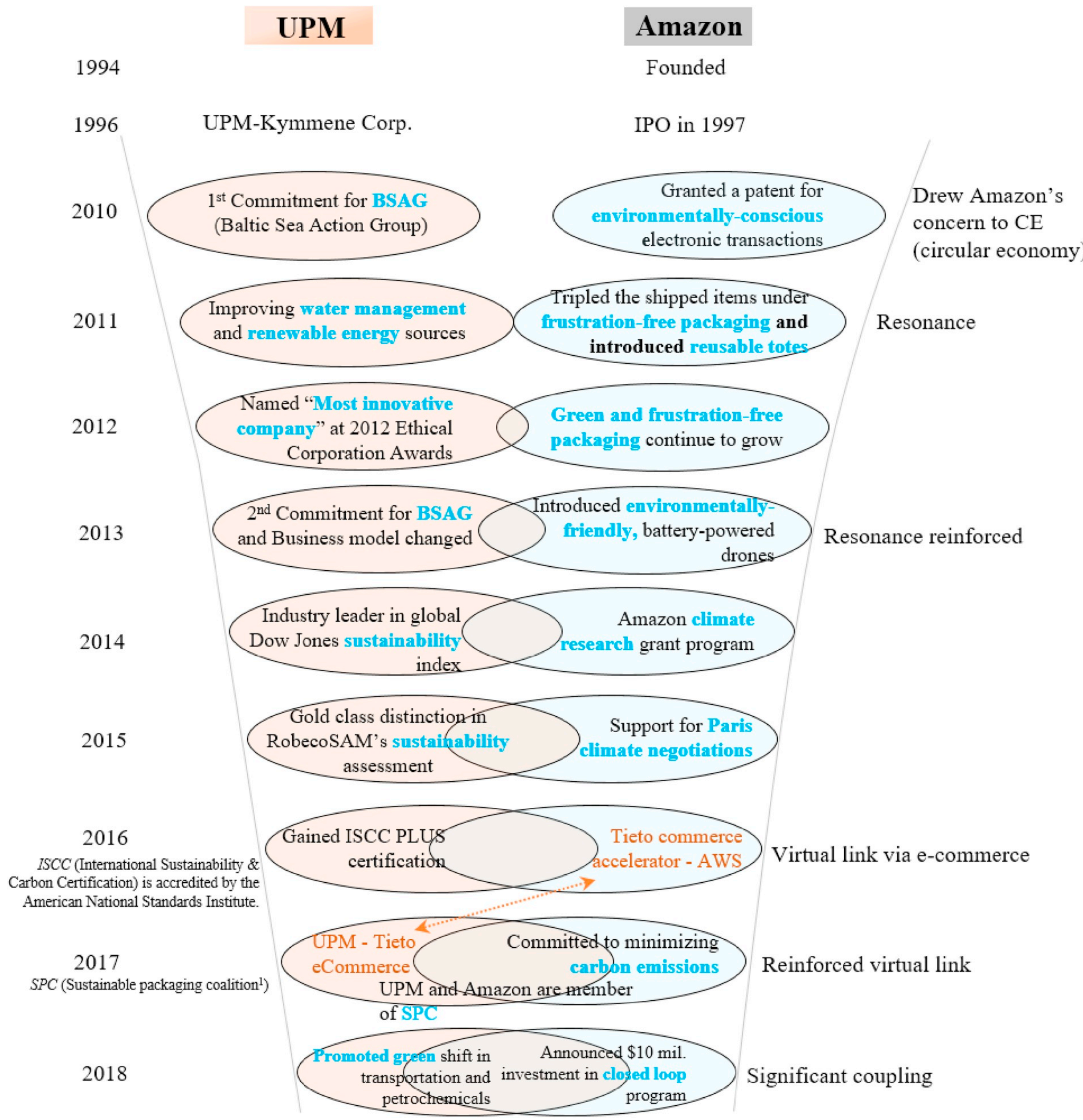


Fig. 19. Reinforcing resonance leading to the Co-evolutionary coupling between UPM and amazon (1994–2018).

Table 17
Shifting trend in resonance between UPM and amazon.

Eco-trade	Increase in trade of eco products corresponding to Amazon's introduction of its frustration-free packaging program in 2008 and the launching of reusable totes in 2011.	2008
Eco-certification	Demonstration of constructing a green supply chain.	2012
e-Commerce	Virtual link via e-Commerce through Tieto's coordination (UPM-Tieto Vs Tieto-Amazon)	2016
Coalition member	General collaboration as the members of Sustainable Packaging Coalition (SPC).	2017

effective utilization of *SIRs* that activate latent self-propagating functions identical to ICT and that induce functionality development, leading to supra-functionality beyond economic value that encompasses social, cultural and emotional values, corresponding with a shift in people's preferences [3]. This correspondence encourages user-driven innovation [8], which induces further advancement of the Internet. This advancement, in turn, accelerates the co-emergence, awakening, and inducement of *SIRs*.

Thus, a virtuous cycle involving external innovation resources functioning toward people's shift in preferences can be constructed.

UPM's digital solutions-driven endeavor enables realization of the long-lasting goal of achieving a circular economy and shifting away from a traditional fossil economy. This process corresponds with the transformative stream spontaneously creating uncaptured GDP by harnessing identical *SIRs* as (i) circular suppliers, (ii) resource recovery, (iii) product life extension, (iv) sharing platforms, and (v) involvement of downstream potentials, as illustrated in the lower right of Fig. 21. Similar to user-driven innovation in a firm level virtuous cycle, achievement of the above long-lasting goal toward a circular economy encourages societal innovation which also induces further advancement of the Internet [38]. This advancement, in turn, accelerates the co-emergence, awakening, and inducement of *SIRs*. Thus, a virtuous cycle involving growth characteristics by digital solutions and external

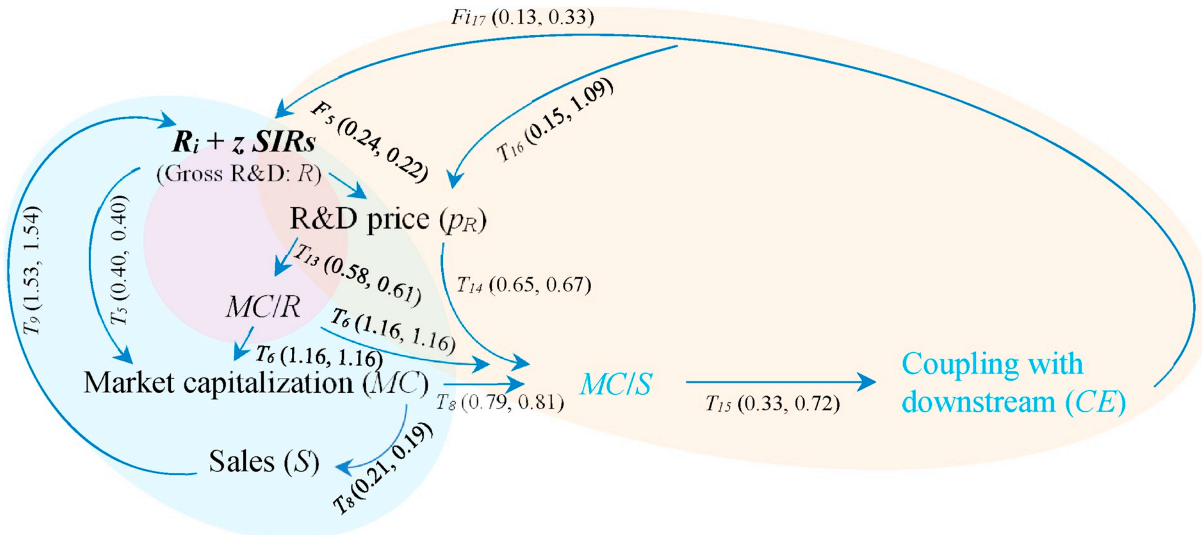


Fig. 20. Co-evolutionary coupling in UPM (1990–2017).

innovation resources can be constructed.

This provides insights in identifying factors and actors influencing co-evolutionary coupling.

5.2. Causal effects of coupling partners

In the above analysis key factors were identified as well as actors influencing co-evolutionary coupling. In firm level coupling, user-driven innovation plays a key role in constructing a virtuous cycle typically observed in Amazon's R&D-driven business model [8]. Such a business model has enabled Amazon to absorb external resources extensively and assimilate them into its indigenous business. Amazon has deployed the "architecture of participation," thus making the most of digital technologies by harnessing the power of its users to create even more value [43], as illustrated in Fig. 22. The "Architecture of participation" was postulated by O'Reilly [44]; and it implies that users help extend the platform and thus are supportive in predicting the future of the host company.

Ritala et al. [45] demonstrated that, through coupling with its competitors, and collaborating with them, Amazon has succeeded in building new capabilities, gaining better leverage, and boosting its brand and technologies.

Tou et al. [8] identified that Amazon's deployment of this strategy is quite similar to that of Canon, known as a coopetition strategy [46]. This strategy harnesses the vigor of mobile phone development in the consumer market leveraged by users, based on coopetition between Canon's printers and personal computers (PCs) produced by its rival firms [47], as illustrated in Fig. 23. This coupling also demonstrate the supportiveness of coupling in predicting the future of the host company.

Evans et al. [54] also demonstrated Amazon's benefit of coupling through strategic action for coopetition. They stressed that Amazon seized strategic opportunities presented by the successive wave of disruption, ruthlessly cannibalizing its own business where necessary.

5.3. Activation of self-propagating function

The circular economy-driven restructuring enabled UPM to incorporate new functionality and to shift to a new development trajectory toward a bioeconomy-based circular economy beyond the fossil economy [14].

This shift corresponds to a shift from a simple logistic growth (*SLG*) trajectory that incorporates a fatality in saturating its value with the fixed upper limit to a logistic growth within a dynamic carrying capacity (*LGDCC*) trajectory value which continues to increase as it creates new carrying capacity during the process of development. As illustrated in Fig. 24 UPM's trajectory shifted from *SLG* to *LGDCC* in 2012 [9].

Since this shift was enabled by activating a self-propagating function [42] that incorporated a growth engine (see Appendix 2 mathematics of this dynamism), this analysis demonstrates UPM's circular economy-driven restructuring. This restructuring had a full-fledged start in 2013, by activation of a self-propagating function based on the assimilation of growth characteristics via biological coupling through co-evolutionary dual coupling of bioeconomy and digitalization and of upstream and downstream operation.

This coupling involves such functions as leveraging awakening and activating latent self-propagating functions indigenous to ICT [42] and essential to sustainable innovation in the digital economy. Demonstration of this dynamism is presented in Fig. 25.

The core function of this dynamism is to activate the latent self-propagating function through growth by incorporating such growth characteristics as leveraging a gross R&D increase.

This increase can be attributed to increases in indigenous R&D (R_i) and assimilated external resources centered on soft innovation resources *SIRs*. The latter increase depends largely on coupling effects (*CE*) from downstream firms as demonstrated earlier in Table 17.

Table 18 shows results from an analysis of factors contributing to activating UPM's self-propagating function ($N_L(R)$)which demonstrates that R&D resources both internal (gross R&D: *R*) and external (*CE*) contributed significantly to an increase in the self-propagating function. These contributions can be attributed to co-evolutionary coupling as demonstrated in Fig. 20. It is noted that the coupling effect with downstream firms significantly increased after 2011.

Increased self-propagating function shifted *SLG* to *LGDCC* as illustrated in Fig. 24 and induced functionality development leading to bio-based circular economy beyond fossil economy corresponding to societal preferences as illustrated in Fig. 25.

On the basis of the foregoing analysis, a novel concept of R&D learning from biological coupling can be postulated as illustrated in Fig. 26.

6. Conclusion

Given the increasing role of R&D in competitive markets in the digital economy while most digital economies are now confronting the dilemma between R&D expansion and a productivity decline, transformation of the R&D model has become a crucial subject for global

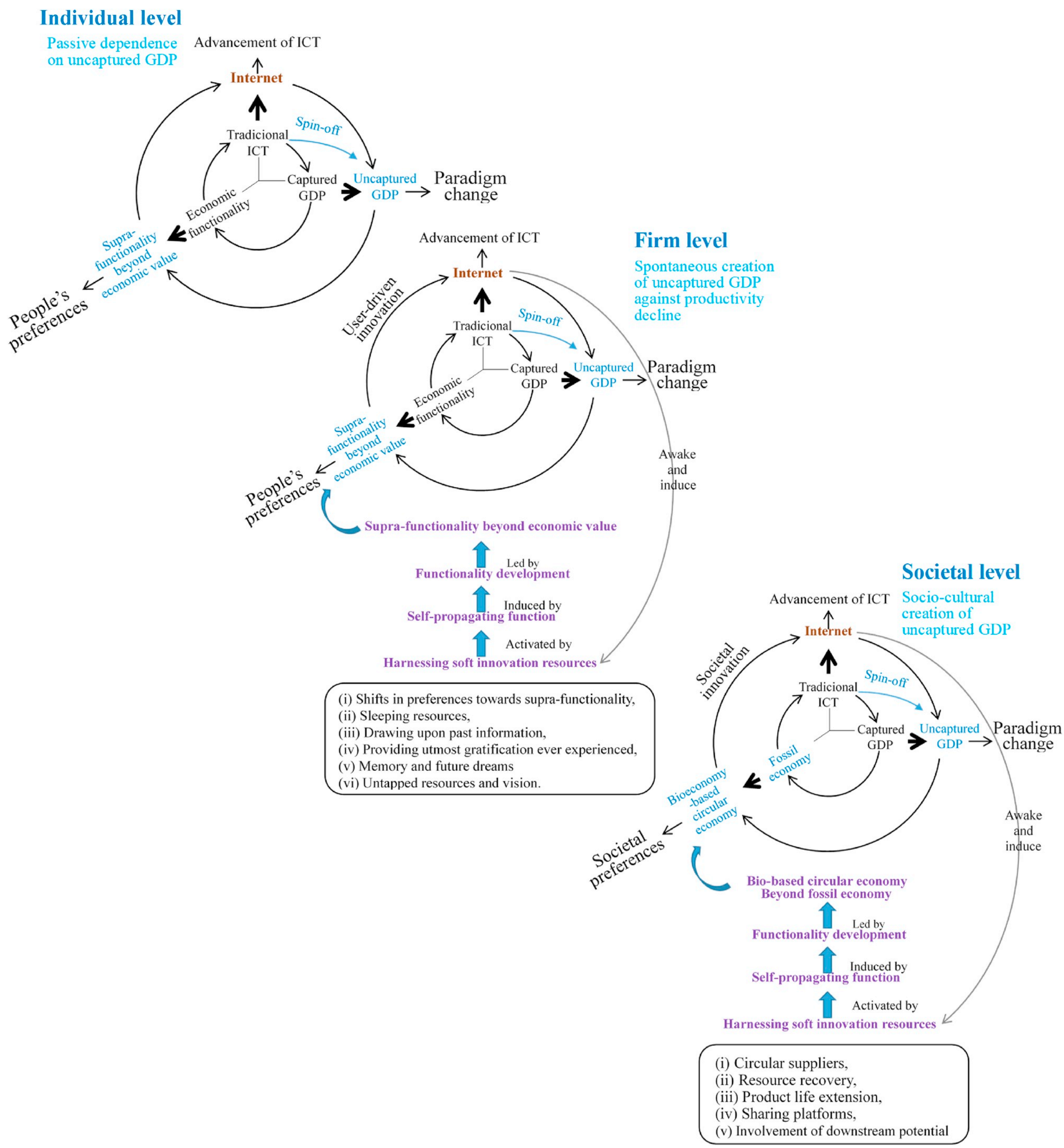


Fig. 21. Shifting trends in the Co-Evolution of three mega trends: Contrasts among the individual level, Firm level and societal level.

digital leaders.

The authors postulated neo open innovation that harnesses the vigor of external innovation resources which then developed into a new concept of R&D that transforms routine or periodic alteration activities into significantly improving activities during an R&D process initiated by Amazon.

With the understanding that biological organisms demonstrate optimal adaptations to the environment by using the coupling effects of multiple factors centered on growth, the authors of this paper attempted to further develop these postulates by embedding a growth characteristic inspired by biological coupling through the co-evolution of the dual coupling of bioeconomy and digitalization and of upstream and downstream operations.

Driven by digital solutions, together with the long-lasting goal of transition from a traditional fossil economy to a circular economy, the coupling of digitalization and bioeconomy is leading to a digitalized bioeconomy that can satisfy the shift in people's preferences for eco-consciousness, which in turn, induces coupling of up-down stream operation in the value chain.

This co-evolutionary dual coupling has led to a new R&D model that absorbs external innovation resources from a broad value chain, identical to the forest-based bioeconomy, and assimilates them into various business entities.

In light of the increasing significance of such a new R&D model that may avoid the dilemma and may also provide relief from increasing the fiscal and environmental burdens of R&D investments, the authors of

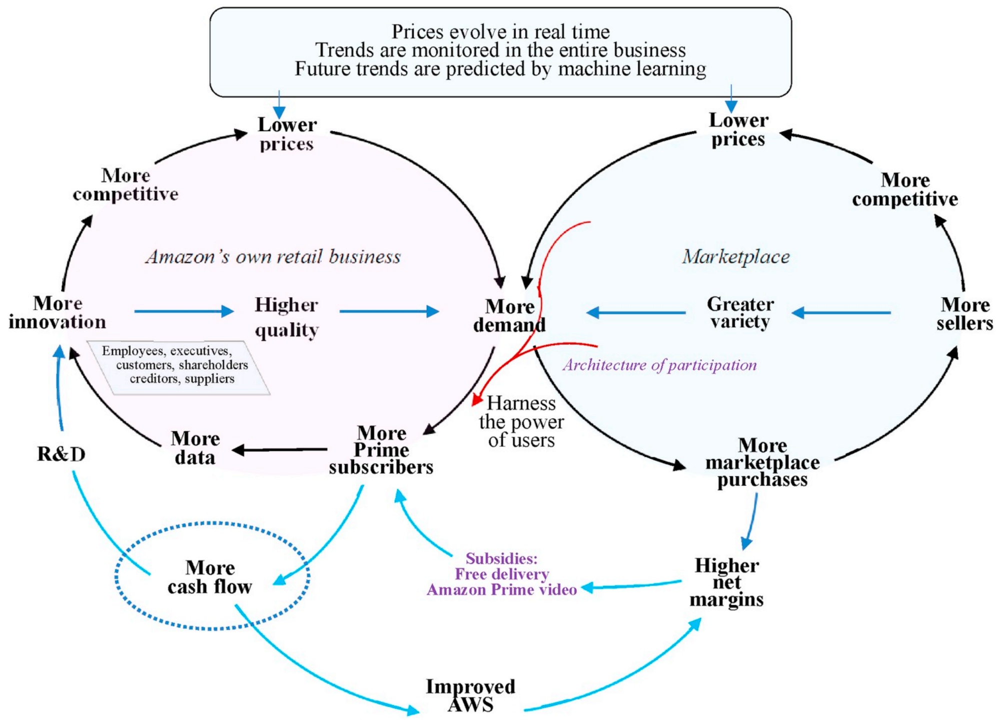


Fig. 22. The dynamism of amazon in harnessing the power of users.
Source: Authors' elaboration based on Colin (2016).

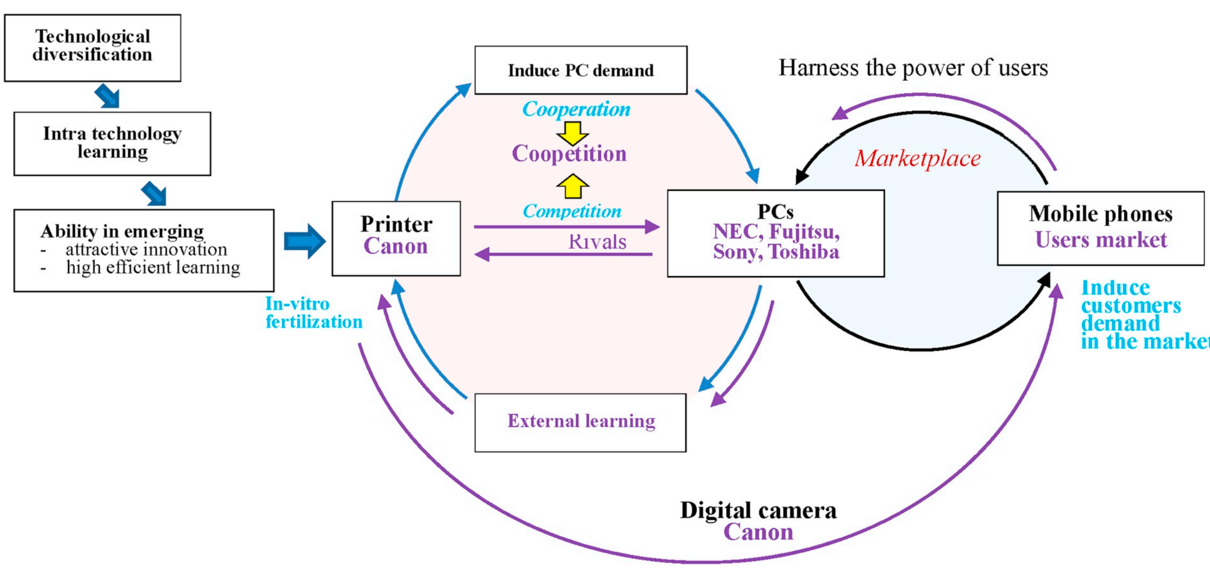


Fig. 23. The dynamism of canon in Co-emerging innovation by harnessing the power of users.
Source: Watanabe [47].

this paper elucidated a dynamism enabling such a dual coupling.

An empirical analysis of leading, global, forest-based bioeconomy firms was conducted first with special attention to the relevance of geopolitical regions fatal to the foot-tight nature of the forest-based-bioeconomy.

It was identified that bioeconomy firms have been present amidst transforming endeavors in the new global stream in the digital economy, which inevitably elects leaders of geopolitical regions by respective growth potential and business prospects.

KC, UPM, Oji, and Sappi represent America, Europe, Asia and Africa, respectively.

Among these four leaders, it is UPM that leads the world's circular economy. This is demonstrated by sophisticated R&D-driven, co-evolutional cycles that smartly utilize external resources. This can be attributed to its balanced contribution structure by R&D, OI, and coupling effects with downstream leader.

With this structure, UPM's R&D induces MC, which in turn, induces sales and MC/S. Increased sales induce R&D, which, together, when assimilated with *SIRs,* increases its price leading to an MC/S increase. Increased MC/S activated coupling effects in the downstream firm, which, in turn, increased R&D prices. Thus, the co-evolutionary dual coupling of digitalization and bioeconomy and of upstream and downstream operations in the value chain have been created. Therefore, a notably high level of MC/R structures have been constructed.

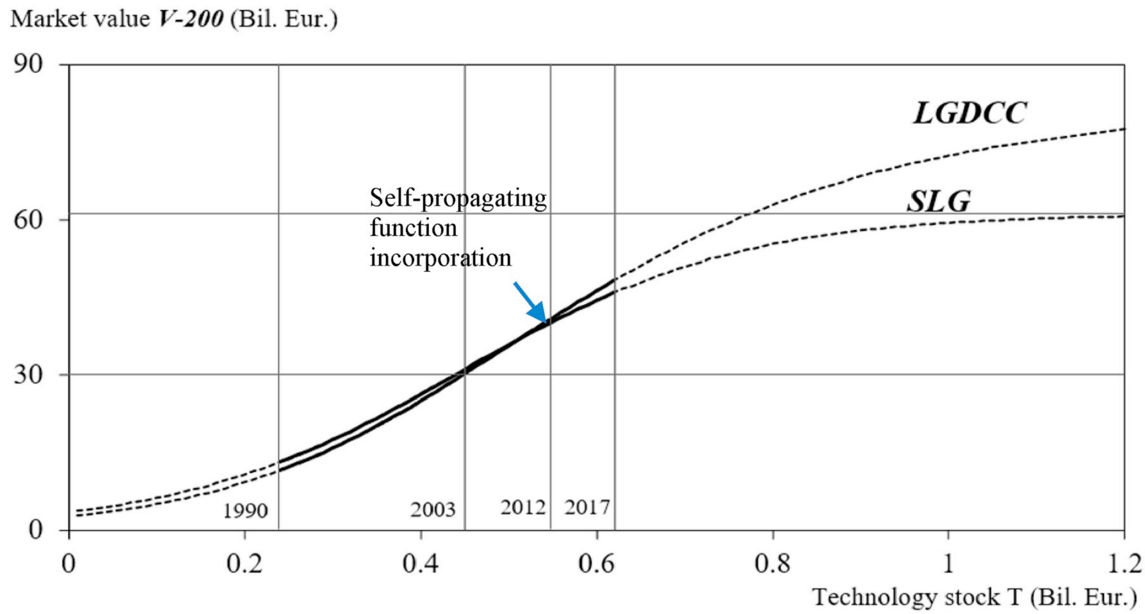


Fig. 24. Trend in UPM's trajectory of technology-driven increase in market value (1990–2017).

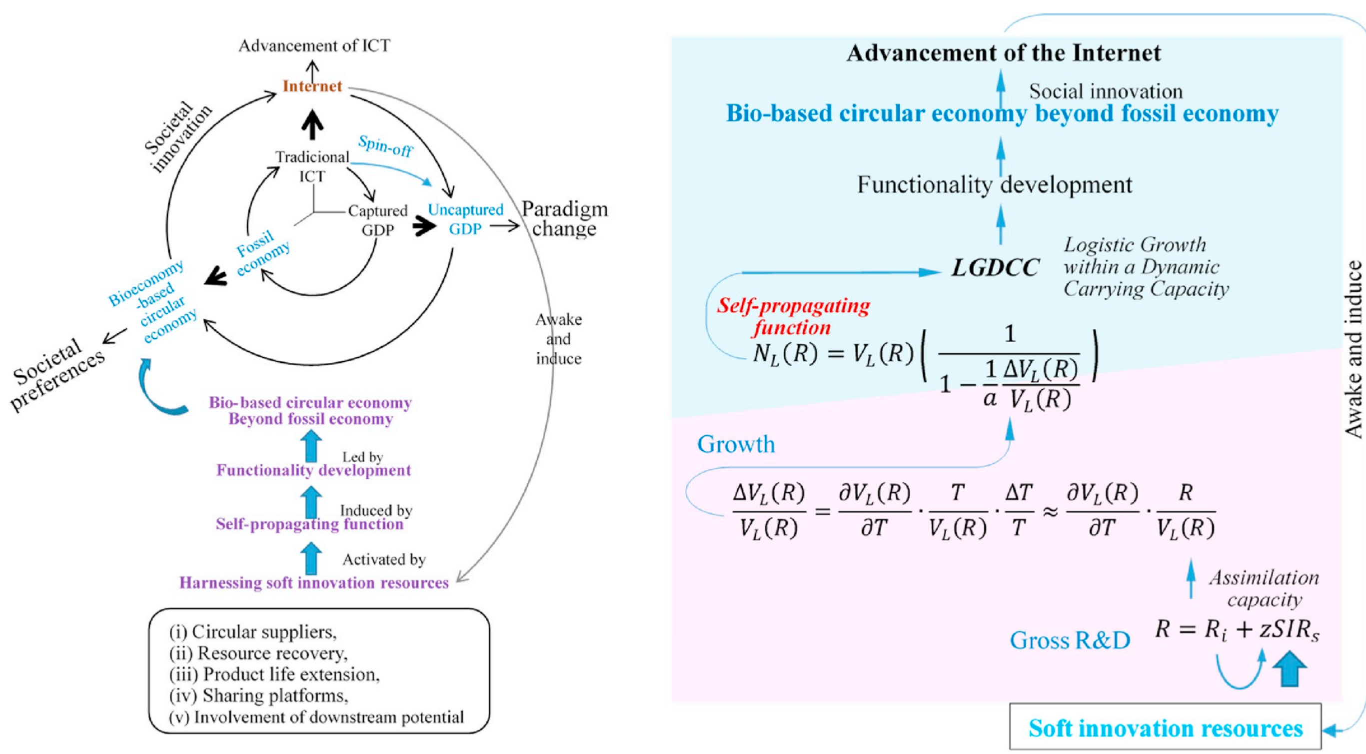


Fig. 25. Dynamism in activating the self-propagating function.

Table 18
Factors contributing to activating self-propagating function in UPM (1995–2017).

$\ln N_L(R) = 3.91 - 0.04 \ln OI + 0.47 \ln R + 0.03D_1 \ln CE + 0.05D_2 \ln CE - 0.14D_3 + 0.11D_4$							*adj.* $R^2 = 0.967$ $DW = 2.61$
(15.53)	(-3.84)	(8.64)	(3.52)	(9.10)	(-8.11)	(5.09)	

D: dummy variables (D_1:1995–2010 = 1, others = 0; D_2: 2011–2017 = 1, others = 0; D_3: 1999–2003, 2017 = 1. Others = 0; D_4: 2010, 2013, 2014 = 1, others = 0).
The figures in parentheses indicate *t*-statistics: All are significant at the 1% level.

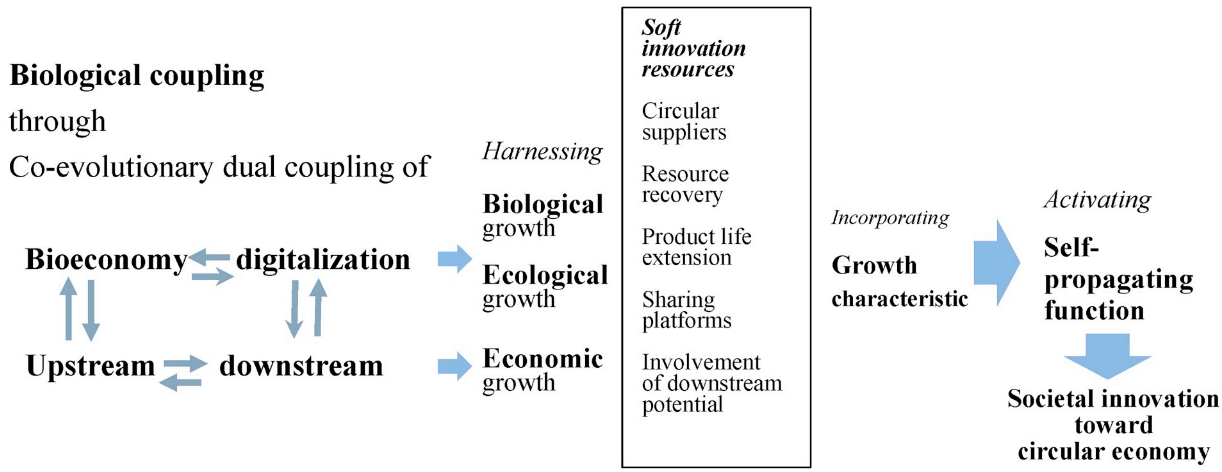


Fig. 26. Novel concept of R&D learning from biological coupling.

A spiral increase in MC/R is a core source of UPM enabling it as a world leader in the circular economy. This can be attributed to its success in assimilating a growth characteristics of biological coupling through the co-evolutionary function of dual coupling of bioeconomy and digitalization and of upstream and downstream operations.

Coupling with downstream firms can be attributed to downstream leader Amazon's eco-consciousness. However, it should not be overlooked that UPM's endeavor as a global, circular economy leader may have triggered this coupling by stimulating Amazon's eco-conscious concerns to the upstream circular economy leaders.

The above co-evolutionary coupling provides insights into the new stream of innovation in the digital economy amidst the spinoff of the co-evolution of three mega trends from *traditional ICT* to *advancement of ICT*, *GDP growth* to uncaptured GDP and *economic functionality* to *supra-functionality beyond economic value.*

UPM's digital solutions-driven endeavor enables the long-lasting goal of achieving a circular economy. This process corresponds with the transformative stream spontaneously creating uncaptured GDP by harnessing such *SIRs* as (i) circular suppliers, (ii) resource recovery, (iii) product life extension, (iv) sharing platforms, and (v) involvement of downstream potentials. Achievement of the above goal toward a circular economy encourages societal innovation which induces further advancement of the Internet, which in turn, accelerates the awakening and inducement of *SIRs*. Thus, a virtuous cycle involving a growth characteristic can be constructed.

This success can be attributed to biological coupling that awakens and activates the latent self-propagating function indigenous to ICT that is essential to sustainable innovation in the digital economy through growth by incorporating such a growth characteristic as leveraging gross R&D increase.

These findings give rise to the following insightful suggestions with respect to dynamism for a new R&D model beyond the existing concept of the digital innovation:

(i) Incorporation of the growth function into the R&D model should be devised.
(ii) Dual co-evolutional coupling should be applied to disruptive business models aiming at overcoming the dilemma between R&D expansion and productivity declines.
(iii) Dynamism enabling co-evolutionary coupling with the vigor of downstream should be elucidated and conceptualized.
(iv) A new four-dimensional sphere encompassing time and space with growth characteristic beyond the existing concept of the digital innovation should be applied in the ecosystem platform.
(v) Co-evolutional innovation among digital innovation, paradigm change, and shifts in people's preferences should be further elaborated by using the dual co-evolutional coupling concept.

Future work should focus on further elucidation, conceptualization and operationalization of the coupling effects derived from growth characteristics identical to biological functions and application of these effects to broad disruptive business models.

In this paper, resonance between upstream and downstream leaders was estimated by the inducing impacts on each counterpart's growth potential and business prospects functions with empirical support of noteworthy strategic actions in respective leaders. Simultaneous interaction analysis by developing PPI sectoral analysis would be worth attempting as this may provide additional constructive insight on the substantial interactions between two partners.

In addition, effects of *SIRs* were analyzed using the trend in the Internet advancement with the understanding that *SIRs* are the condensate and crystal of this advancement. Further comprehensive conceptualization and operationalization efforts should be continued.

Acknowledgements

The research leading to these results is part of a project titled, "Platform Value Now: Value capturing in the Fast Emerging Platform Ecosystems," supported by the Strategic Research Council at the Academy of Finland [grant number 293446].

Appendix 1. Basic Statistics for the Analysis

Table A1
Top 50 Global Forest-based Bioeconomy Firms (2017) - by OI order

Firm Name	Short Name	Country	OI	Sales	R&D	OI/S	R/S	OI/R
Kimberly-Clark	KC	US	3299	18259	311	0.18	0.017	10.61
International Paper	Int. Paper	US	2069	21743	28	0.10	0.001	73.89
UPM-Kymmene	UPM	Finland	1419	11285	57	0.13	0.005	24.89
Mondi Group	Mondi	UK	1148	8000	26	0.14	0.003	44.15
Shandong Chenming	Shandong	China	1023	4417	151	0.23	0.034	6.80
Stora Enso	Stora	Finland	1019	11325	143	0.09	0.013	7.13
Packaging Corp of America	Packaging	US	931	6445	13	0.14	0.002	71.62
Smurfit Kappa	Smurfit	Ireland	924	9653	8	0.10	0.001	115.50
Hengan International	Hengan	Hong Kong	780	2933	61	0.27	0.021	12.79
Unicharm	Unicharm	Japan	774	5721	58	0.14	0.010	13.34
West Fraser Timber	WFT	Canada	670	3955	11	0.17	0.003	60.91
Metsäliitto	Metsä	Finland	655	5682	20	0.12	0.004	32.75
Oji Paper	Oji	Japan	633	12838	83	0.05	0.006	7.63
DS Smith	DS	UK	570	6153	9	0.09	0.001	63.33
Sappi	Sappi	South Africa	526	5296	30	0.10	0.006	17.53
Shan Dong Sun Paper	Shan Sun	China	523	2796	112	0.19	0.040	4.67
Arauco)	Arauco	Chile	491	5238	3	0.09	0.000	188.85
Sumitomo Forestry	Sumitomo	Japan	481	9926	17	0.05	0.002	28.29
Klabin	Klabin	Brazil	473	2624	7	0.18	0.003	67.57
Canfor	Canfor	Canada	429	3589	11	0.12	0.003	39.00
Lenzing	Lenzing	Austria	403	2547	29	0.16	0.011	13.90
Sonoco	Sonoco	US	367	5037	21	0.07	0.004	17.48
Graphic Packaging	Graphic	US	343	4404	14	0.08	0.003	23.82
Svenska Cellulosa	SCA	Sweden	294	1949	6	0.15	0.003	49.00
Billerud	Billerud	Sweden	262	2614	14	0.10	0.005	18.71
Cheng Loong	Cheng	Taiwan	254	1434	3	0.18	0.002	84.67
Holmen	Holmen	Sweden	253	1887	11	0.13	0.006	23.00
Mayr-Melnhof Karton	Mayr	Austria	242	2635	3	0.09	0.001	80.67
Sodra	Sodra	Sweden	224	2400	11	0.09	0.005	20.36
Sveaskog	Sveaskog	Sweden	214	726	3	0.29	0.004	71.33
SCG Packaging (Formerly Siam Pulp and Paper)	SCG	Thailand	212	2517	123	0.08	0.049	1.72
Rengo	Rengo	Japan	211	4863	13	0.04	0.003	16.23
Daio Paper	Daio	Japan	210	4254	26	0.05	0.006	8.08
ENCE	ENCE	Spain	169	834	1	0.20	0.001	169.00
Mercer International	Mercer	Canada	167	1169	3	0.14	0.003	55.67
Nippon Paper Group	Nippon	Japan	157	9330	56	0.02	0.006	2.80
Cascades	Cascades	Canada	135	3329	4	0.04	0.001	33.75
Schweitzer-Mauduit	Schweitzer	US	125	982	18	0.13	0.018	7.02
Ahlstrom	Ahlstrom	Finland	117	2210	20	0.05	0.009	5.85
Hokuetsu Paper	Hokuetsu	Japan	115	2339	7	0.05	0.003	16.43
Yuen Fong Yu Paper	Yuen Fong	Taiwan	100	1979	8	0.05	0.004	12.50
Heinzel Holding	Heinzel	Austria	83	2048	1	0.04	0.000	166.00
Moorim group	Moorim	Korea	81	886	3	0.09	0.003	27.00
The Lecta Group	Lecta	UK	75	1645	6	0.05	0.004	12.50
The Pack Corporation	Pack Corp.	Japan	65	805	13	0.08	0.016	5.00
Resolute Forest Products (Formerly Abitibi Bowater)	Resolute	Canada	49	3513	18	0.01	0.005	2.66
Ballarpur Industries	Ballarpur	India	47	333	7	0.14	0.021	6.71
Mitsubishi Paper	Mitsubishi	Japan	38	1800	9	0.02	0.005	4.22
Corticeira Amorim	Corticeira	Portugal	25	797	8	0.03	0.010	3.13
Domtar	Domtar	Canada	−317	5157	24	−0.06	0.005	−13.21

OI: operating income, R&D: research and development, S: sales.
Forest-based bioeconomy firms encompass forest, paper and packaging firms.
Sales, R&D and OI unit: mil. US$ (nominal).
OECD exchange rate was used to convert the currency units into US$.

Table A2
Techno-market Indicators in the Leading 4 Firms (2000–2017)

	KC			UPM			Oji			Sappi		
Year	MC/R	MC/OI	MC/S	MC/R	MC/OI	MC/S	MC/R	MC/OI	MC/S	MC/R	MC/OI	MC/S
2000	106.34	11.20	0.47	215.97	5.11	0.99	58.89	24.76	0.59	118.13	2.64	0.38
2001	111.75	14.11	0.44	215.14	6.00	0.98	43.48	7.51	0.43	99.60	8.33	0.48
2002	111.07	13.03	0.42	173.06	9.24	0.76	50.39	16.85	0.50	133.65	6.65	0.72
2003	94.08	11.32	0.53	164.93	21.52	0.80	36.98	8.27	0.39	160.00	11.18	0.71
2004	116.91	13.05	0.46	182.50	12.52	0.87	59.65	9.68	0.61	151.67	16.94	0.67
2005	93.27	12.90	0.53	173.30	27.25	0.93	51.83	6.99	0.50	98.22	15.87	0.53
2006	94.02	13.46	0.59	228.24	18.65	1.00	57.98	9.66	0.59	77.08	14.80	0.37
2007	110.11	11.66	0.60	142.51	14.66	0.71	55.84	10.13	0.50	64.59	5.73	0.41
2008	83.84	9.78	0.78	95.17	11.88	0.49	39.33	10.85	0.34	42.21	4.57	0.24

(continued on next page)

Table A2 (*continued*)

	KC			UPM			Oji			Sappi		
2009	72.09	7.68	0.88	89.68	11.88	0.56	39.79	12.40	0.32	64.03	10.18	0.37
2010	78.23	8.94	0.80	151.74	9.10	0.77	43.85	5.36	0.34	105.56	7.74	0.40
2011	82.59	10.69	0.80	88.73	9.74	0.44	42.15	5.90	0.34	59.04	17.85	0.21
2012	92.98	12.32	0.64	102.67	3.52	0.44	41.62	7.32	0.33	61.83	3.52	0.23
2013	103.33	11.60	0.57	172.56	11.85	0.65	36.18	6.58	0.28	44.64	7.32	0.22
2014	113.04	16.50	0.47	209.49	10.78	0.74	41.80	7.36	0.34	70.80	5.85	0.34
2015	119.14	15.71	0.48	248.55	8.05	0.91	46.81	10.49	0.34	54.96	4.31	0.29
2016	150.91	14.92	0.37	313.05	10.97	1.27	46.21	6.05	0.31	107.54	5.74	0.54
2017	146.62	13.82	0.40	273.30	10.98	1.38	55.47	7.27	0.36	123.15	6.91	0.69

MC: Market Capitalization; R: Research and Development; S: sales; OI: Operating Income.

Table A3
Trends in Market Capitalization in the Leading 4 Firms (2000–2017)

Year	KC	UPM	Oji	Sappi
2000	36465.07	10160.64	5879.31	3660.21
2001	39882.55	9722.39	4036.96	3823.85
2002	38208.30	8326.85	4424.85	4571.52
2003	30809.30	9915.19	3781.66	4914.46
2004	37140.26	11752.58	6224.58	4833.39
2005	32791.37	11777.76	5120.93	3816.57
2006	30212.59	13594.53	5890.12	2505.65
2007	31717.17	10212.24	5230.00	2732.47
2008	25395.52	7005.25	4295.18	1640.67
2009	21965.03	6029.41	4293.76	2111.07
2010	24800.00	9104.64	4516.16	2639.00
2011	25572.03	6054.94	4887.16	1440.88
2012	31843.85	5638.47	5075.49	1323.11
2013	35219.46	7966.25	3608.53	1106.13
2014	38692.47	8749.22	4351.36	1611.38
2015	35446.67	9082.23	4029.01	1164.99
2016	44883.60	12179.75	4058.57	1982.24
2017	40695.39	13647.66	4552.42	2440.51

Market capitalization unit: mil. US$ (real values based on 2010).
World bank GDP deflator was used.
The OECD exchange rate was used to convert currency units into US$.
Source: Firm's Annual report 2017. Source: Firms' annual reports.Source: Firms' annual reports.

Appendix 2. Dynamism of Emerging Self-propagating Function

1. Bi-polarization Fatality of ICT-driven Development

ICT, in which network externalities function to alter the correlation between innovations and institutional systems, creates new features of the innovation leading to exponential increases. Schelling [1] portrayed an array of logistically developing and diffusing social mechanisms stimulated by these interactions. Advancement of the Internet further stimulates these interactions and accelerates ICT's logistically developing and diffusing feature which is typically traced by the Sigmoid curve [2].

Digital values created by the Internet of things (IoT) can be depicted as follows [42,48]:

$$V = F(X,T) = F(X(T),T) \approx F(T) \ \text{ Growth rate } \frac{\Delta V}{V} = \left(\frac{\partial V}{\partial T}\cdot\frac{T}{V}\right)\cdot\frac{\Delta T}{T} \approx \frac{\partial V}{\partial T}\frac{R}{V} \tag{A1}$$

where T: gross ICT stock; X: other production factors; and R: R&D investment ($\Delta T \approx R$)

In long run, since $T \approx \frac{R}{\rho+g}$, the growth rate can be depicted as follows:

$$\frac{\Delta V}{V} = \left(\frac{\partial V}{\partial T}\cdot\frac{T}{V}\right)\cdot\frac{\Delta T}{T} \approx \frac{\partial V}{\partial T}\cdot\frac{R}{V} = \frac{\partial V}{\partial R}\cdot\frac{\partial R}{\partial T}\cdot\frac{R}{V} = (\rho+g)\frac{\partial V}{\partial R}\frac{R}{V} \tag{A2}$$

where ρ : rate of obsolescence of technology and g: R&D growth rate at the initial period.

Given the logistic growth nature of ICT, the R&D-driven developmental trajectory $V_S(R)$ can be depicted by the following epidemic function that leads to a simple logistic growth function (*SLG*):

$$\frac{dV}{dR} \approx \frac{\partial V}{\partial R} = aV\left(1-\frac{V}{N}\right) \tag{A3}$$

$$\mathrm{SLG} = \mathrm{V_S}\left(\mathrm{R}\right) = \frac{N}{1 + b\, e^{-aR}} \tag{A4}$$

where N: carrying capacity; a: velocity of diffusion; and b: coefficient indicating the initial level of diffusion.

Given the ICT-driven development, its growth follows a Sigmoid trajectory which continues to grow until it reaches carrying capacity (upper limit of growth). In this trajectory, while the growth rate continues to increase before reaching the inflection point corresponding to the half-level of carrying capacity, it changes to decrease after exceeding the inflection point. Thus, ICT-driven logistic growth incorporates the bi-polarization fatality and the increasing and decreasing of marginal productivity before and after the inflection point [8,48].

2. Dilemma between R&D Expansion and Productivity Decline

This causes the dilemma between R&D expansion and productivity declines as R&D expansion exceeding the inflection point results in productivity declines and subsequent growth rate decreases [5]*b*).

Confronting such a dilemma, global ICT-leaders have been endeavoring to find a practical solution by transforming their traditional business model into a new business model.

Given that this dilemma stems from the unique feature of ICT, logistic growth, this feature should be transformed.

3. Transformation of the Unique Feature of ICT: Self-propagating Function

As far as the development trajectory depends on the simple logistic growth (*SLG*) trajectory, its digital value, $V_s(R)$, saturates with the fixed upper limit which inevitably results in the above dilemma. However, once the trajectory shifts to logistic growth within a dynamic carrying capacity (*LGDCC*), its digital value, $V_L(R)$ can continue to increase as it creates new carrying capacity during the process of development.

In particular innovation which creates the new carrying capacity $N_L(R)$ during the diffusion process, equation (A3) is developed as follows:

$$\frac{dV(R)}{dR} = aV\left(R\right)\left(1 - \frac{V(R)}{N(R)}\right) \tag{A5}$$

Equation (A5) develops the following *LGDCC* which incorporates the self-propagating function as carrying capacity increases corresponding to the $V(R)$ increase as depicted in equation (A6) and (A7) [2]:

$$V_L(R) = \frac{N_k}{1 + be^{-aR} + \frac{b_k}{1-a_k/a}e^{-a_k R}} \tag{A6}$$

where N_k: ultimate carrying capacity; *a*, *b*, a_k, *and* b_k: coefficients.

The dynamic carrying capacity $N_L(R)$ in this *LGDCC* is depicted as follows:

$$N_L(R) = V_L\left(R\right)\left(\frac{1}{1 - \frac{1}{a}\frac{\triangle V_L(R)}{V_L(R)}}\right) \triangle V_L(R) = \frac{dV_L(R)}{dR} \tag{A7}$$

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