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Digitalized Bioeconomy: Planned Obsolescence-Driven Circular Economy Enabled by Co-Evolutionary Coupling

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Abstract

Driven by digital solutions, the bioeconomy is taking major steps forward in recent years toward achievement of the long-lasting goal of transition from a traditional fossil economy to a bioeconomy-based circular economy.

The coupling of digitalization and bioeconomy is leading towards a digitalized bioeconomy that can satisfy the shift in consumers' preferences for eco-consciousness, which in turn induces coupling of up-down stream operation in the value chain.

Thus, the co-evolution of the coupling of digitalization and bioeconomy and of upstream and downstream operations is transforming the forest-based bioeconomy into a digital platform industry.

Aiming at addressing this transformation, a model was developed that explains above mentioned dynamism and demonstrated its reliability through an empirical analysis focusing on the development trajectory of UPM (forest-based ecosystem leader in Europe and a world pioneer in the circular economy) over the last quarter century, highlighting its efforts towards planned obsolescence-driven circular economy.

It was comprehended that with the advancement of digital innovations, UPM has incorporated a self-propagating function that accelerates digital solution. Furthermore, this self-propagating function was triggered by coupling with a downstream leader, Amazon, in the United States.

The dynamism in transforming a forest-based bioeconomy into a digital platform industry is thus clarified, and new insights common to all industries in the digital economy are provided.

Keywords: Digitalized bioeconomy; Digital-bio coupling; Upstream-downstream coupling; Circular economy; Planned obsolescence.

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1. Introduction

The marked advancement of the Internet has generated the digital economy, changing the way we conduct business and our daily lives (Tapscott, 1994). This advancement has hence created a digital economy and also transformed the traditional bio-based economy¹, particularly, in the present context, the forest-based bioeconomy, into a consolidated platform. This transformation is not associated to natural resources and technologies only but also complex future trajectories of societies, firms and individuals. These trajectories are informed by socio-cultural and ethical perspectives as well as techno-economic perspectives (VTT, 2017). Wider socio-economic transformations, not merely technological and material processes can be expanded by the service strategies of such an economy (Pelli et al., 2017).

Thus, driven by digital solutions, the bioeconomy is taking major steps forward in recent years, enabling the potential achievement of the long-lasting goal of transitioning from a traditional fossil-based economy towards a bio-based circular economy (MISTRA, 2017).

Consumer preferences have tended to shift towards supra-functionality and now go beyond basic economic value, encompassing social, cultural and emotional values (McDonagh, 2008; Watanabe et al., 2015). In this context, a circular economy ultimately seeks to decouple global economic development from infinite resource consumption (Ellen Macarthur Foundation, 2015). Accordingly, the coupling of digitalization and bioeconomy that emerges digitalized bioeconomy satisfies a downstream shift in consumer preferences (Watanabe et al., 2018b).

Furthermore, these preferences induce further upstream coupling of the value chain. Thus, the co-evolutionary coupling of bioeconomy and digitalization and of upstream and downstream operations is transforming the forest-based bioeconomy into a digital platform industry.

Mega trends: population growth, urbanization, demographic change, resource scarcity, role of renewables, digitalization, e-commerce, climate change, responsibility and compliance highlight the importance of bioeconomy-based circular economy. New emerging technologies such as industrial biotechnologies, 3D printing and energy technologies give new ways to create innovative solutions without compromising the sustainability. All these bring economic, social and environmental value to the stakeholders and the society.

¹ Based on EC definition (Bioeconomy for Europe, 2012), here the bio-based economy (bioeconomy) has been defined and recognized as follows (Watanabe et al., 2018b):

The economy encompassing the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. The forest-based bioeconomy is an important sub-sector of the bioeconomy. Advancement of digitalization has transformed this economy and this transformation is not about natural resources and technologies but about the complex future potential trajectories of societies, firms, and individuals.

To date, many studies have analyzed the systems nature of the forest-based bioeconomy. Several studies have pointed out the possibility of creative disruption by stemming from the abovementioned mega trends confronting the pulp and paper industry (PPI) as opportunities rather than threats (e.g., Hetemaki et al., 2014; Hetemaki, 2016). The possibility of achieving digital solutions has accelerated these studies.

Therefore, we attempt to demonstrate the above hypothetical view by conducting an empirical analysis of the core business activities at the forefront of both the upstream and downstream operations of the forest-based bioeconomy chain. In particular, we showed a transformative stream resulting in the construction of a creative disruption platform and the embracement of digital solutions (Watanabe et al., 2017). While this analysis provides new insight into a forest-based bioeconomy within a digital economy, digitalization does not stop the transformation stream as the PPI produces more diversified products (Toppinen et al., 2017) such as biofuels, biocomposites, biochemical and renewable materials for plastic industry. In addition, actors from different sectors interact and play different roles (Giurca et al., 2017), and all stakeholders involved in the forest-based bioeconomy should be considered (Mustalahti, 2018).

Consequently, new insight is provided into the forest-based bioeconomy as well as numerous industries in the digital economy that are constructing a creative disruption platform by embracing digital solutions.

Based on these expectations, we attempted to trace this transformation by developing a model that explains abovementioned dynamism and demonstrated its reliability through an empirical analysis focusing on the development trajectory of UPM (forest-based ecosystem leader in Europe and a world pioneer in the circular economy) over the last quarter century since after the emergence of the digital economy, highlighting its efforts towards planned obsolescence-driven circular economy.

The process of consolidating a platform similar to a super computer called ‘super digital biofore computer’ by consolidating upstream and downstream operations as well as producers and consumers (prosumer) was envisioned, wherein ‘biofore’ implies a sustainably growing bio-forest (Watanabe et al., 2018b).

Since an enabling mechanism of this ‘super computer’ has been strongly required, the operationalization of the aforementioned concept of the co-evolutionary coupling of bioeconomy and digitalization and of upstream and downstream operations is also necessary.

Therefore, this paper attempts to operationalize the dynamism of this co-evolution by tracing the above mentioned transformation dynamism. In order to demonstrate the reliability of the model used for the analysis, an empirical analysis focusing on the development trajectory of UPM over the last quarter century was conducted, with special attention placed on the resurgence of the planned, obsolescence-driven circular economy.

In long-lasting debate on planned obsolescence (e.g., Swan, 1972; Bulow, 1986;

Aladeojebi, 2013), many industries focused on a profit maximization strategy and produced goods and services with intentionally shorter economic lives to stimulate consumers to make repeated purchases in a shorter period of time. While some recent analyses (e.g., Fabian, 2016; Satyro et al., 2018) discussed a significance of planned obsolescence toward a circular economy, no analysis has undertaken planned obsolescence strategy in the context of the development stage of the industry toward a circular economy.

In light of the transformation of a fossil economy towards a bioeconomy-based circular economy amidst an abundance of digital solutions, this paper attempts to explore new insights into creative disruptive platform that is expected to be initiated by a planned obsolescence-driven circular economy enabled by the co-evolution of the coupling of bioeconomy and digitalization and of upstream and downstream operations.

In line with an orientation towards a planned obsolescence-driven circular economy, UPM has incorporated a self-propagating function that accelerates digital solutions. Furthermore, this self-propagating function was promoted through coupling with a downstream leader, Amazon, in the United States.

The dynamism in transforming a forest-based bioeconomy into a digital platform industry is thus clarified, and new insights common to all industries in the digital economy are provided.

The structure of this paper is as follows: Section 2 explores the dynamism in constructing a consolidated platform ecosystem. Section 3 reviews the co-evolution of the dual couplings of the bioeconomy and digitalization, and of upstream and downstream operations. Section 4 analyzes sustainable development with an orientation towards planned, obsolescence-driven circular economy. Section 5 briefly summarizes noteworthy findings, implications and suggestions for future works.

2. Dynamism in Constructing a Consolidated Platform Ecosystem

2.1 Digital Solution for Transformation into a Creative Disruption Platform

We previously demonstrated that the advancement of digital innovation transforms the value chain of the forest industry into a creative disruption platform in a stepwise manner creating a consolidated platform ecosystem (Watanabe et al., 2018b).

The conventional linear supply chain from forestry to consumption (step 1) transforms into creative disruption platforms within the upstream and downstream industries (step 2). Disruption in upstream is induced (step 3) by the espousal of digital solutions and creation of new business systems in the downstream (step 4). This is how we can expect the emergence of creative disruption in the value chain of forest-based bioeconomy. Moreover, diversified production to address the people's shifting preferences for eco-consciousness, different actors' varying roles and interaction in the value chain as well as stakeholders involvement accelerate the consolidation of up-downstream operations and thus leads forest-based bioeconomy into a digital platform industry (step 5).

The forest-based ecosystem leader in Europe, UPM in Finland, has undertaken a strong initiative to restructure its business model and has moved towards digital-driven solutions and an eco-design approach since the beginning of the second decade of this century, whereas Amazon has aggressively embraced digital solutions to diversify its products and to improve users' experience on the downstream side. Thus, similar to the conspicuous business accomplishments of Amazon on the downstream side, UPM has demonstrated notable accomplishments on the upstream side as evidenced in **Figs. 1** and **2**.

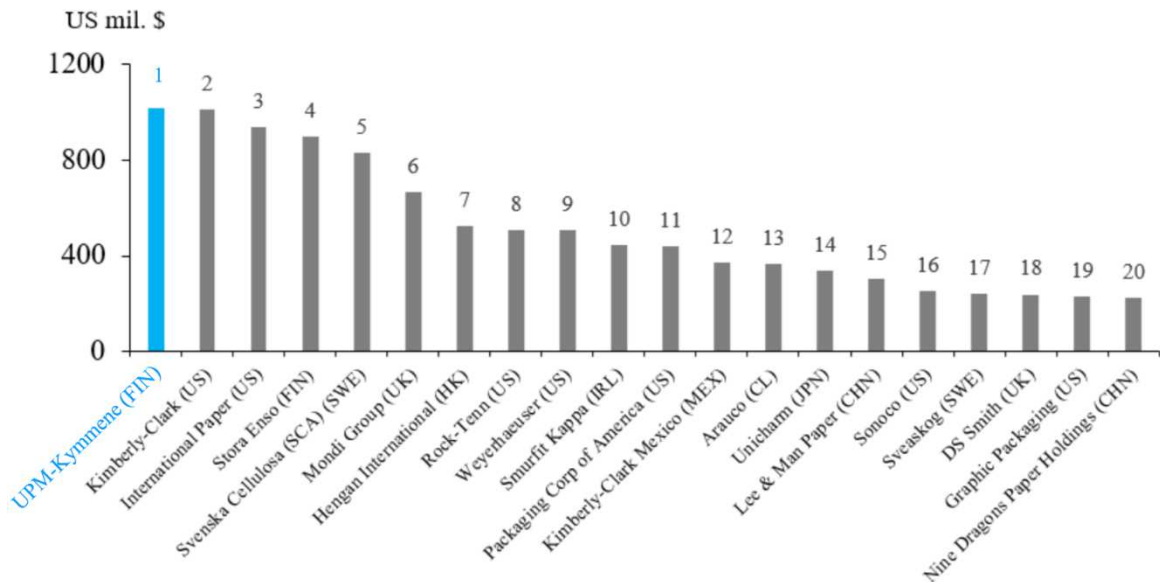


Fig. 1. Top 20 Global Forest, Paper and Packaging Industry Firms in the World by Net Income (2015).

Source: PWC (2016).

Fig. 1 demonstrates UPM's notable accomplishment of gaining the world's highest net income within the paper and packaging industry in 2015. Fig. 2 demonstrates its resurgence from the beginning of the second decade of this century, as the company has maintained sustainable market capitalization growth since 2012.

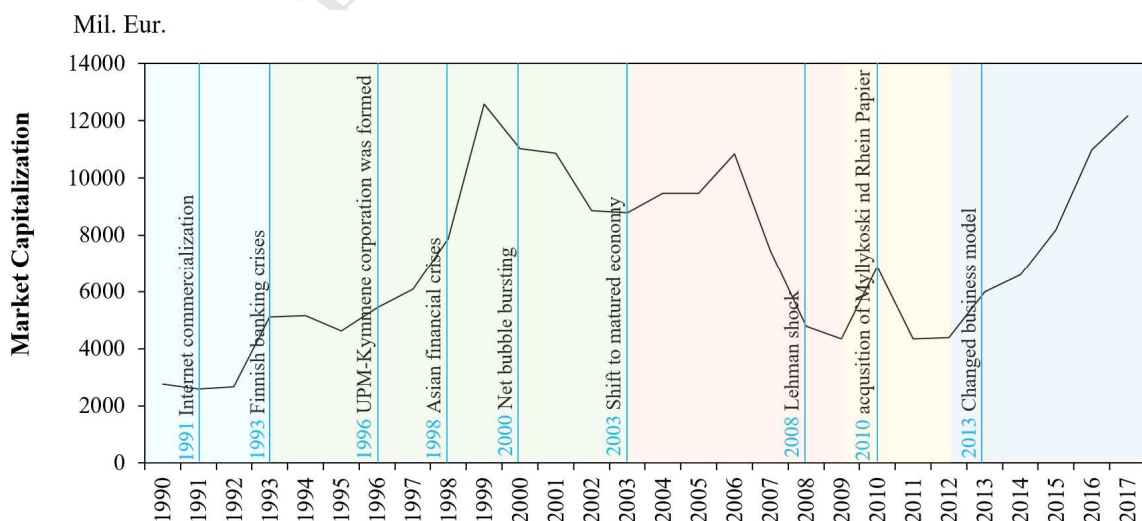


Fig. 2. Trend in UPM's Market Capitalization (1990 – 2017) – 2010 fixed price.

Source: UPM annual reports (annual issues).

2.2 Planned Obsolescence-Driven Circular Economy

1) UPM's Endeavor Towards Developing a Circular Economy

UPM's resurgence can be attributed to its strategic shift towards a planned obsolescence-driven circular economy that is enabled by digital solutions integrating both upstream and downstream operations. It has taken strong initiative to shift from the fossil economy towards a circular economy.

UPM was established in 1995 by the merging of the Kymmene Corporation and Repola Ltd with its subsidiary United Paper Mills Ltd, as illustrated in **Fig. 3**. The new company started operations on May 1, 1996.

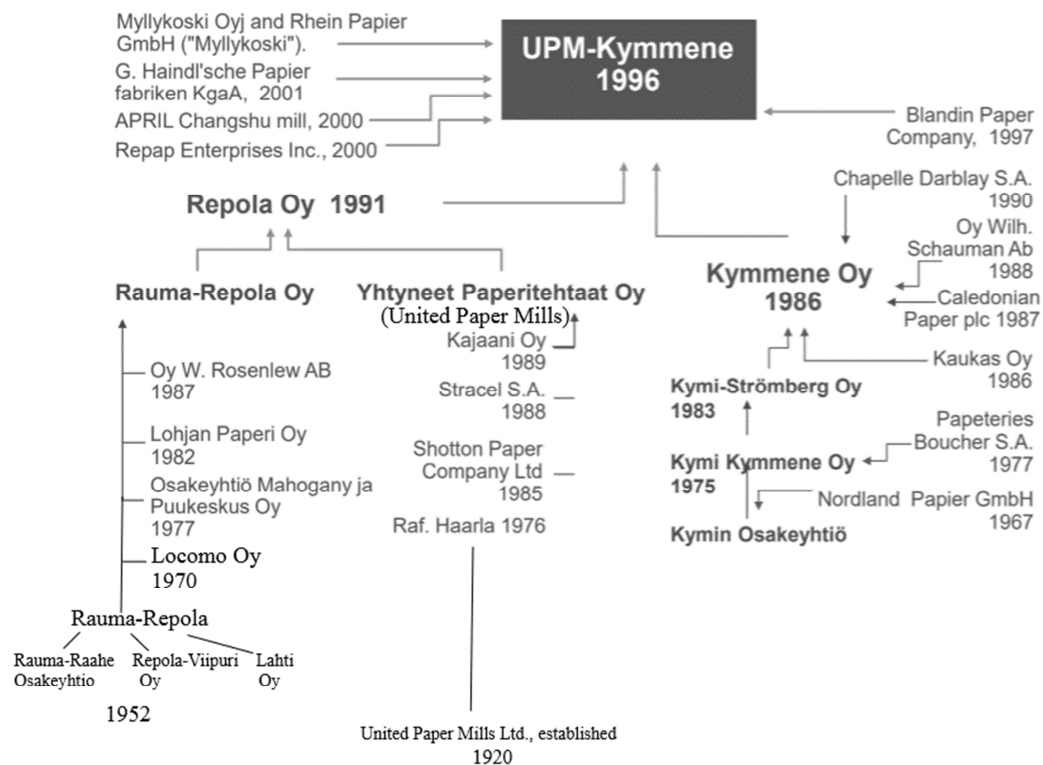


Fig. 3. Development Trajectory of UPM.

Source: Elaborated by the authors based on UPM (2016).

UPM has a long tradition in the Finnish forest products industry. The group's first mechanical pulp mill, paper mills and sawmills started operations at the beginning of the 1870s. Pulp production began in the 1880s and pulp was converted to paper by the 1920s, with plywood production beginning the following decade. The present group comprises approximately 100 production facilities that originally functioned as independent companies. Among others, the following companies and forest industry operations were merged into the group: Kymi, United Paper Mills, Kaukas, Kajaani Schauman, Rosenlew, Raf. Haarla and Rauma-Repola.

In 2008, UPM adopted a new, market driven business structure comprising three business groups: Energy and Pulp, Paper, and Engineered Materials (UPM, 2008). Later in 2013, UPM once again implemented a new business structure to drive a clear change in profitability. Thus, UPM further developed its business portfolio and changed from a

vertically integrated forest industry to a company with six separate business areas: UPM Biorefining, UPM Energy, UPM Raflatac, UPM Paper Asia, UPM Paper Europe and UPM Plywood (UPM, 2013).

While UPM started as a resource intensive firm, it recognized the potentially fatal shift from a fossil economy to a non-fossil economy within the emerging context of sustainable development, as illustrated in **Fig. 4**.

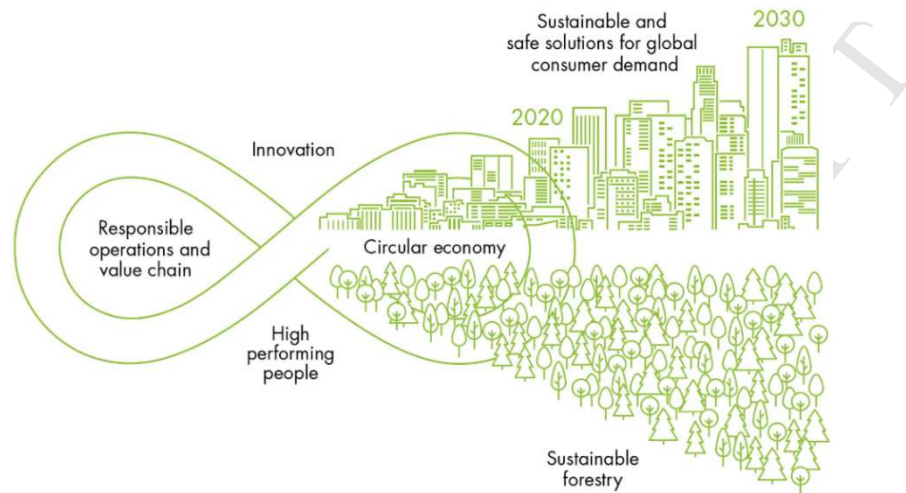


Fig. 4. Transforming Direction of Business Model Toward Bioeconomy-based Circular Economy.

Source: UPM Annual Report (2017).

Circular economy thinking addresses two crucial global issues i.e. climate change and scarcity of natural resources. In circular economy, materials, production waste and products are recycled several times to create added-value through smart solutions. Moreover, waste generation is avoided by maximizing the use of renewable energy and materials. UPM aims to achieve the target of no process waste to landfills by 2030. **Fig. 5** demonstrates the UPM's circular economy approach.

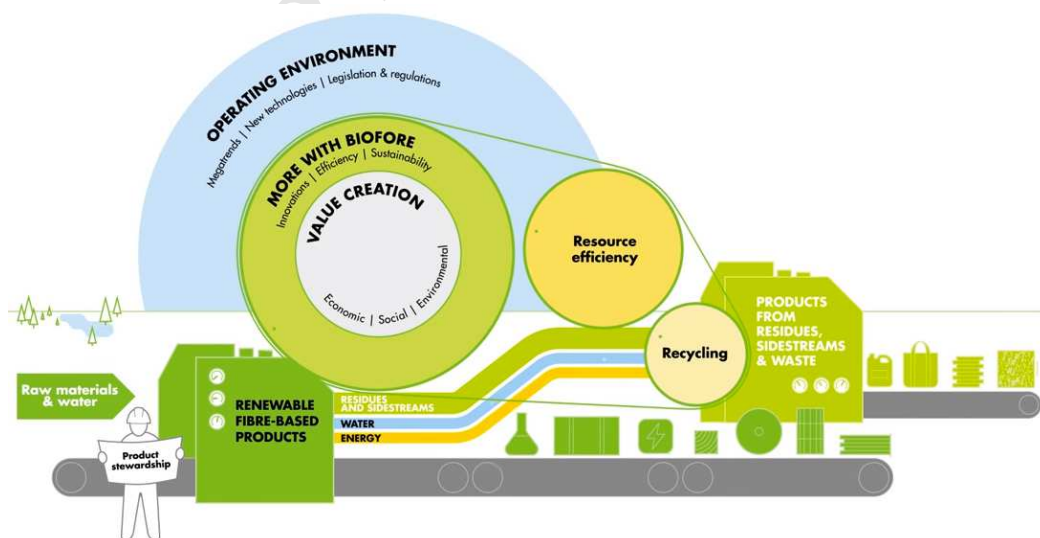


Fig. 5. Scheme of a UPM's Circular Economy.

Source: UPM Circular Economy (2018).

For longtime UPM is pursuing eco-design approach, covering the impacts of entire lifecycle and special attention is paid to the biodegradability of products. ‘More with Biofore’ is at core of UPM’s circular economy strategy. Three building blocks of this approach are innovations, resource efficiency and sustainability therefore, UPM innovates products from residues, sidestreams and waste. UPM make renewable products that replace non-renewable materials with renewable materials. Unlike fossil-based resources, the sustainable use of renewable resources adds no new carbon dioxide into the atmosphere. For example, UPM’s biofuels and bioenergy replace fossil fuels. UPM Formi (suitable material for injection moulding) composite is composed of wood-based cellulose and plastic. Moreover, increasing use of recycled nutrients at UPM’s effluent treatment plants, are the significant developments to achieve the goal of zero waste to landfills.

The UPM Kaukas mill (Lappeenranta in south east Finland) is a frontrunner in the circular economy. The mill site makes efficient use of wood-based raw materials and converts residues into goods with economic value. The production facility comprises a pulp mill, paper mill, sawmill and biomass power plant that produces bio-energy, as illustrated in **Fig. 6**, all of which consume a considerable amount wood-based raw materials. All raw materials are efficiently utilized to minimize waste. This integrated mill is a world-leading industry frontrunner in the efficient use of resources and the harnessing of side streams and is hence leading UPM’s circular economy-based business model.

This 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 (Salmela, 2016). These five principles can be satisfied by digital solutions. Thus, it is evident that UPM’s resurgence can be attributed to its digital solutions-driven eco-design approach.

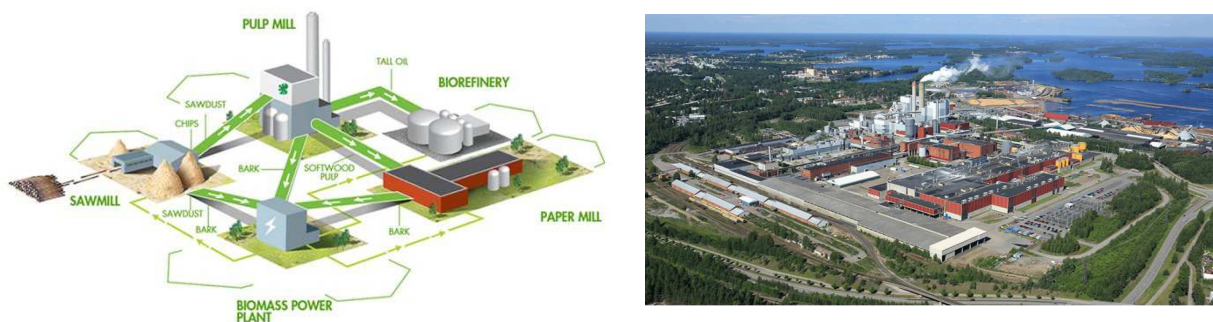


Fig. 6. UPM Kaukas Mill (Lappeenranta, Finland).

Source: Biofore (UPM, 2017b).

These endeavors are supported by the advancement of digital innovation and ICT-driven disruptive business strategy. Similar to the leading challenge observed in the downstream of the value chain initiated by Amazon, this challenge has been undertaken by leading firm UPM in the upstream of the chain. UPM extensively use digital solutions in processes in the mills; however, in the future digitalization will increasingly be visible in customer-fronted processes such as sales, supply chain and quality monitoring. For instance, UPM launched eOrder service for paper ordering in 2017. ‘The service developed for UPM ProFi, a biocomposite material for decking, helps in managing the

certified installer base by combining online marketing and training, external services and customer relationship management platform'. Another example is UPM Metsäni application, a mobile service for forest owners provides them volume, age structure and estimated value of the forest. The objective of this application is to increase the wood trade by engaging the private forest owners. Thus, digitalization continuously creates new opportunities for pulp and paper industry.

2) Metabolism Initiated by Planned Obsolescence Strategy

In line with the increasing burden of R&D investment, the advancement of the digital economy and the significance of the circular economy, the strategy of planned obsolescence has become important in constructing firms' business models (Keeble, 2013; Obeng et al., 2014).

It is generally understood that planned obsolescence seeks to intentionally produce goods and services with short economic lives, stimulating consumers to repeat purchases in a shorter period of time (Slade, 2006). However, it seeks the opposite in a circular economy. Nowadays, huge buying power from the consumers' perspective and the exponential incline of online social media emerge consumer-led obsolescence (Keeble, 2013). This inevitably increases the significance of psychological obsolescence which can be defined as the subjective devaluation of product perception based on learned experience, emotional attachments or benefits, status achievement, fashion, or esthetic quality. In psychological obsolescence consumers' reaction to product longevity differs depend on the "stage" of people, nation and producers (Fabian, 2015).

Under such circumstances, contrary to traditional understandings, obsolescence management differs depending on the development stage of the industry in the digital economy (see details in Sections 4.3.1 and 4.3.2).

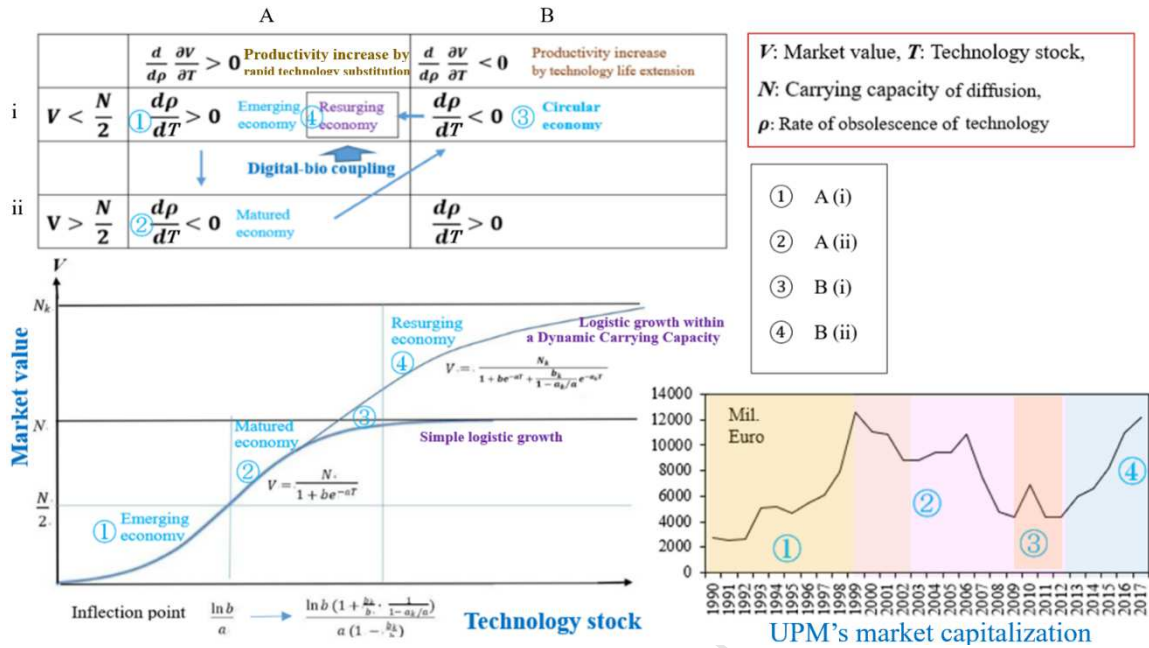
Provided that firms seek profitable R&D with minimum R&D investment and maximum utilization of digital solutions, profit maximization can be attained by the following strategy, as illustrated in **Fig. 7** (see details in Fig. 12 and **Appendix 2**):

- A. Traditional economy where productivity increases by rapid technology substitution
 - (i) Increased rate of obsolescence of technology in an emerging economy
 - (ii) Decrease rate of obsolescence of technology in matured economy
- B. Circular economy where productivity increases by technology life extension
 - (i) Decreased rate of obsolescence of technology in emerging economy
 - (ii) Increased rate of obsolescence of technology in a resurging economy

UPM's digital solutions-driven eco-design approach towards a circular economy seeks to increase productivity through extending the life of technology (T) (i.e., decreasing the rate of obsolescence of technology [ρ]) in contrary to the general strategy of increasing productivity by rapidly substituting old technologies with new technologies (i.e., shortening technology life through increasing the rate of obsolescence of technology).

Given UPM's noteworthy resurgence driven by a circular economy-based business model, the metabolism of the planned obsolescence strategy can be considered by shifting the $A(i) \rightarrow A(ii) \rightarrow B(i) \rightarrow B(ii)$ cycle, which is supported by the

co-evolution of the dual couplings of digital solutions and biotechnology and of upstream and downstream operations (see the detailed empirical evidence in Section 4).



a, b, a_k, b_k : coefficients of diffusion function.

Fig. 7. Metabolism in Planned Obsolescence Strategy.

This metabolism provides insights into the analysis of shifting trends and, in particular, new stream of innovation in the digital economy in the co-evolution of three mega trends; co-evolution between advancement of ICT, paradigm change and people's preferences shift from economic functionality to supra-functionality beyond economic value as shown in the upper left of **Fig. 8**.

We previously postulated that the advancement of ICT initiated by the Internet has provided people with utility and happiness, which cannot be captured through GDP data that measure economic value resulting in productivity decline; hence, we define these as uncaptured GDP. We then demonstrated the foregoing co-evolution as a new stream of innovation in the digital economy (Watanabe et al., 2016).

Under such circumstances, against productivity decline, global ICT firms have aimed to transform their business models through incorporating new streams of digital solutions-driven disruptive business model that spontaneously creates uncaptured GDP instead of passively depending on it as shown in the middle of Fig. 8 (Watanabe et al., 2018a).

Locomotive power of this stream can largely be attributed to the effective utilization of soft innovation resources² that activate self-propagating function identical to ICT and that induce functionality development, leading to supra-functionality beyond economic value that encompasses social, cultural and emotional values, corresponding with people's shift in preferences as reviewed earlier (Watanabe et al., 2018a).

UPM's digital solutions-driven planned obsolescence approach enables the long-lasting goal of achieving a circular economy and shifting away from a traditional fossil economy.

² Soft innovation resources include (i) shifts in preferences towards supra-functionality, (ii) sleeping resources, (iii) drawing upon past information, (iv) providing utmost gratification ever experienced, (v) memory and future dreams and (vi) untapped resources and vision.

This process corresponds with the transformative stream spontaneously creating uncaptured GDP by harnessing identical soft innovation resources 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. 8. This provides insights particularly into the firm level transformative strategy.

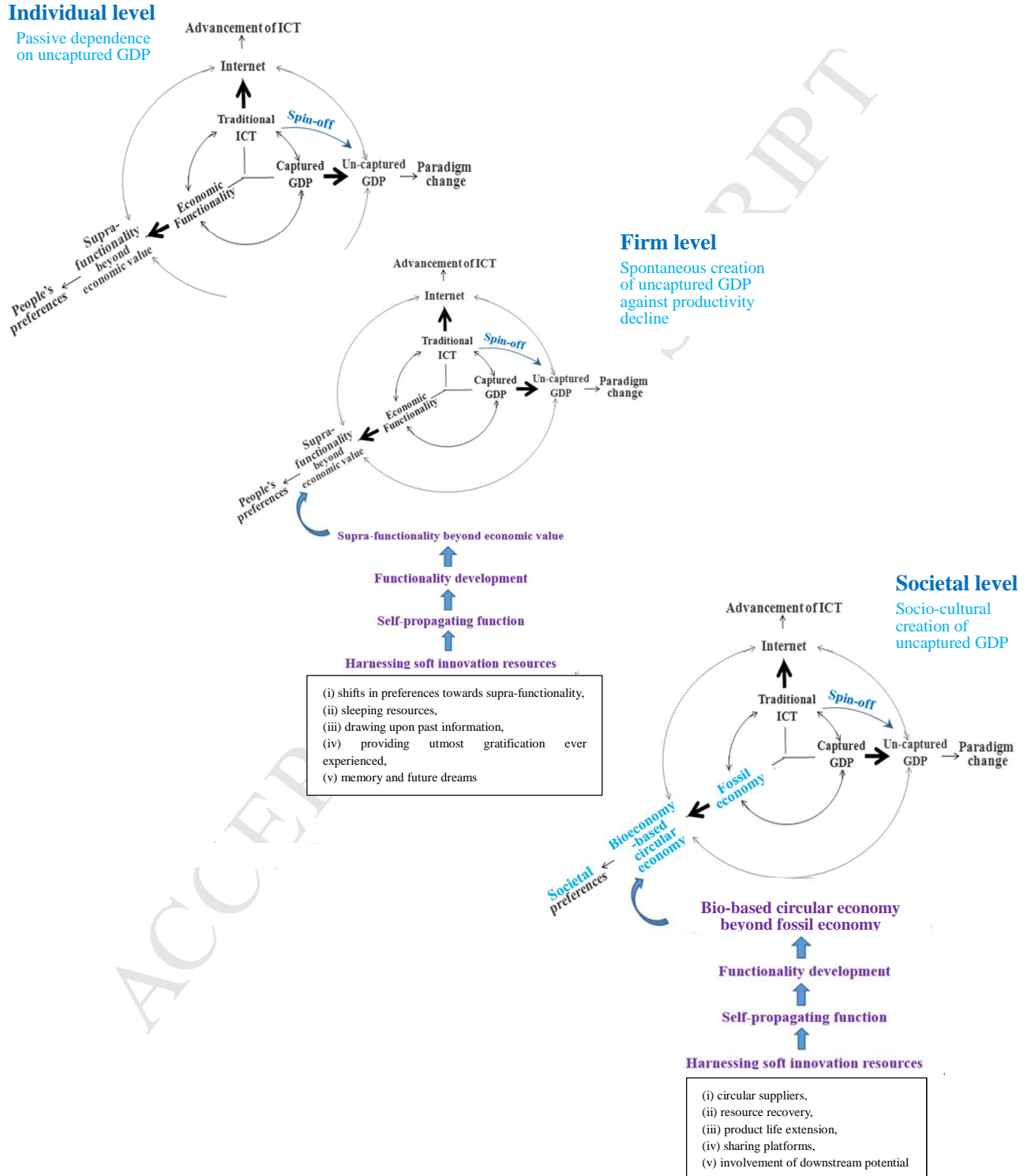


Fig. 8. Shifting Trends in the Co-Evolution of Three Mega Trends: Contrast Between the Individual Level, Firm Level and Societal Level.

3. Co-Evolution of Dual Couplings

3.1 Coupling of the Bioeconomy and Digitalization

Inspired by the foregoing observations, the co-evolution of the dual couplings of bioeconomy and digitalization and of upstream and downstream operations was analyzed, as this is considered the locomotive power of the metabolism that has led to UPM's noteworthy resurgence.

Fig. 9 illustrates this anticipating coupling of the bioeconomy and digitalization observed in the forefront forest hub (Tieto, 2017).

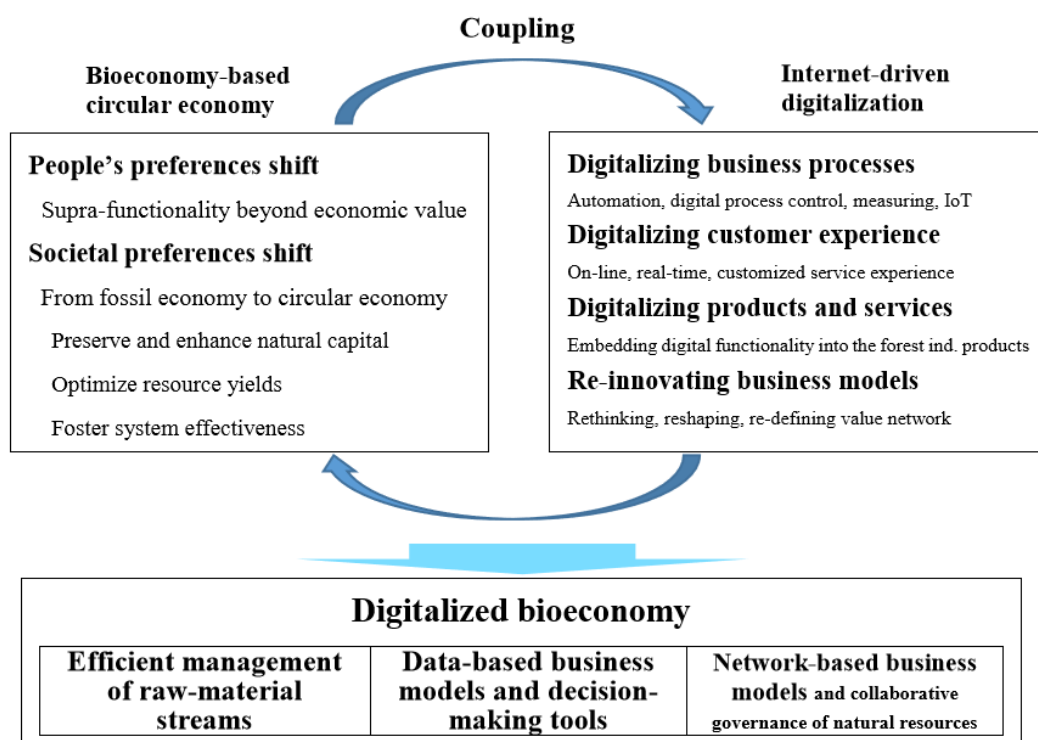


Fig. 9. Coupling of the Bioeconomy and Digitalization.

A bioeconomy-based circular economy, which has formed the focus of UPM, as illustrated in Fig. 6, is coupled with internet-driven digitalization which promotes the digitalization of business processes, customer experiences and products and services in addition to the re/innovating of business models.

From this coupling, a digitalized bioeconomy emerges in which the efficient management of raw material streams, data-based business models and decision making tools enable the formation of network-based business models and the collaborative governance of natural resources.

3.2 Coupling of Downstream and Upstream Operations

UPM targeted to enhance its global market reach and business agility through new B2B eCommerce solution developed by one of the largest IT services provider in Europe, Tieto (Tieto, 2017). In providing eCommerce solution, Tieto is responsible for end-to-end service delivery, including design, development and integration. It brought greater flexibility and simplicity to UPM's operations. Tieto's eCommerce Cloud solution enables fast time-to-market, providing agility in development and adaptability for future business needs. Tieto has also joined Amazon Web Services (AWS) to provide the holistic and modern omni-channel solutions as one service (<https://www.tieto.com/node/85026/awspubliccloud>). Thus, through Tieto a virtual link has been established between upstream leader UPM and downstream leader Amazon as illustrated in **Fig. 10**.

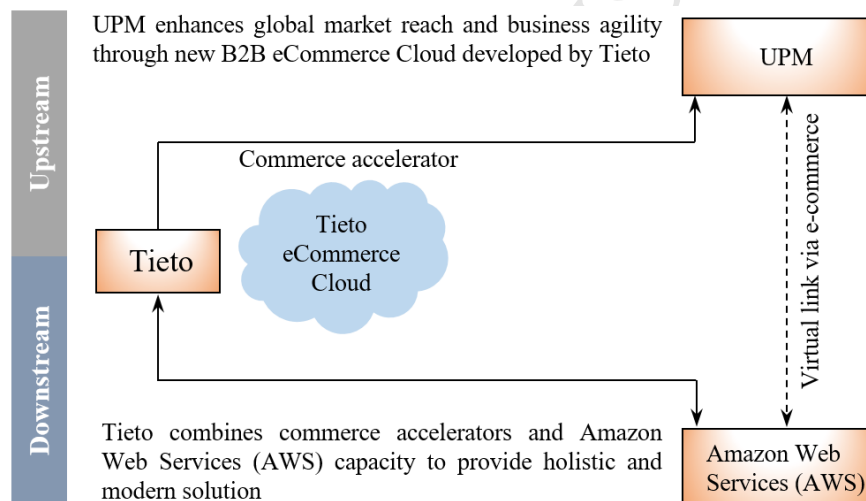


Fig. 10. Scheme of the Acceleration of Global Market Reach via Integrating Upstream and Downstream Operations.

These endeavors activated the effects of coupling with downstream operations as illustrated in **Fig. 11**.

The market capitalization of UPM is governed by its indigenous efforts as its profit increase (e.g., improvement in operating income: OI) and innovation effort (e.g., increase in R&D investment). It is also subject to external situations, such as the economic environment as demonstrated by the SP500 Index in the EU. Furthermore, given the creative disruption between upstream and downstream flows, UPM's market capitalization is influenced by Amazon's creative disruption efforts in the downstream, as represented by its stock price.

By means of a correlation analysis between market value of UPM and the governing factors of both upstream and downstream flows over the 1998-2016 period, we previously demonstrated the significance of the forgoing dynamism enabled by the coupling of upstream and downstream operations (Watanabe et al., 2018).

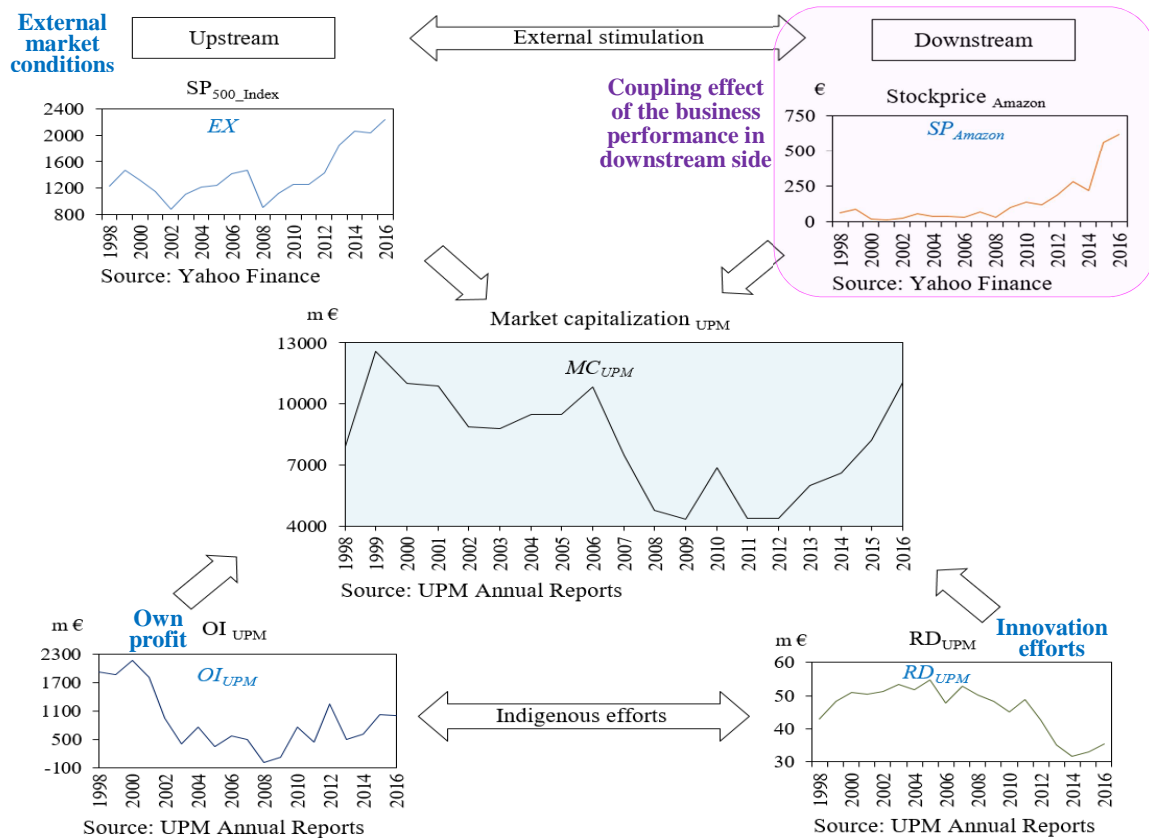


Fig. 11. Coupling of Upstream and Downstream Operations – A Case of UPM’s Market Capitalization Effect (1998-2016).

In Fig. 11 and abovementioned correlation analysis, we noted that UPM has been sustaining an increase in market capitalization since 2012, as reviewed earlier (Fig. 2). The effects of R&D and economic environment on transforming market capitalization into sustainable increases were not entirely remarkable, yet this transformation can largely be attributed to the improvement in operating income and also the stockprice increase of Amazon in the downstream. The former contribution can be primarily attributed to the coupling of bioeconomy and digitalization, as outlined in section 3.1, and the latter contribution can definitely be attributed to the coupling of upstream and downstream operations initiated by the virtual link e-commerce link, as shown in Fig. 10. Furthermore, spiral increases in both couplings thereafter convince us that the co-evolution between these two couplings is well functioning.

4. Sustainable Development Based on a Planned Obsolescence Driven Circular Economy Orientation

4.1 Analytical Framework

UPM's resurgent development by means of a planned obsolescence driven circular economy enabled by co-evolutionary coupling is demonstrated as following.

Given the Internet commercialization in 1991 which triggered the digital economy, this has provided significant impact on UPM's development strategy in shifting from natural resources dependent structure to digital solution seeking structure.

This shift can be examined by digital solution substitution for natural resources as depicted as follows:

$$\ln \frac{I}{E} = a + \varepsilon_{ei} \ln \frac{p_e}{p_i}$$

where I : Internet dependence as a proxy of digital solution³; E : energy consumption as a proxy of natural resources dependence; p_i : Internet price; p_e : energy prices; ε_{ei} : elasticity of Internet substitution for energy; and a : coefficient.

In this equation, in case when $\varepsilon_{ei} > 1$, I substitution for E can be demonstrated⁴.

Table 1 summarizes the result of the above correlation analysis in UPM over the period of 1991-2017 which demonstrates statistically significant.

Table 1 Correlation of UPM's Digital Solution – Resources Dependence Ratio and their Prices Ratio (1991-2017)

$$\ln \frac{I}{E} = -1.697 + 1.264 \ln \frac{p_e}{p_i} + 0.498D_1 - 0.577D_2 \quad \text{adj. } R^2 \text{ 0.986}$$

(-19.68) (34.57) (4.08) (-3.32) DW 1.19

D : Dummy variables

D_1 : 1998, 2016, 2017 = 1, others = 0; D_2 : 1991, 1992 = 1, others = 0.

The figures in parentheses indicate t-statistics: All are significant at the 1% level.

Table 1 demonstrates digital solution (I) substitution for natural resources (E) which endorses that UPM has been endeavouring to shifting from natural resources dependent structure to digital solution seeking structure for its survival in the digital economy.

With this pre-analysis, UPM's resurgent development trajectory analysis was conducted focusing on its digital solution seeking trajectory.

³ Since the Internet has been permeating into broad ICT in the digital economy, Internet dependency can be considered a proxy of digital solution (Watanabe et al., 2018c).

⁴ $\chi \equiv \frac{\text{Internet expenditure}}{\text{Energy expenditure}} = \frac{I p_i}{E p_e}$ $\ln \chi = \ln \frac{I}{E} - \ln \frac{p_e}{p_i} = a + (\varepsilon_{ei} - 1) \ln \frac{p_e}{p_i}$

When $\varepsilon_{ei} > 1$, p_e increase (or p_i decrease) reacts to Internet expenditure increase (I substitutes for E).

The framework of the analysis is outlined in **Figs. 12** and **13** (see the details of the numerical model in **Appendices 1** and **2**).

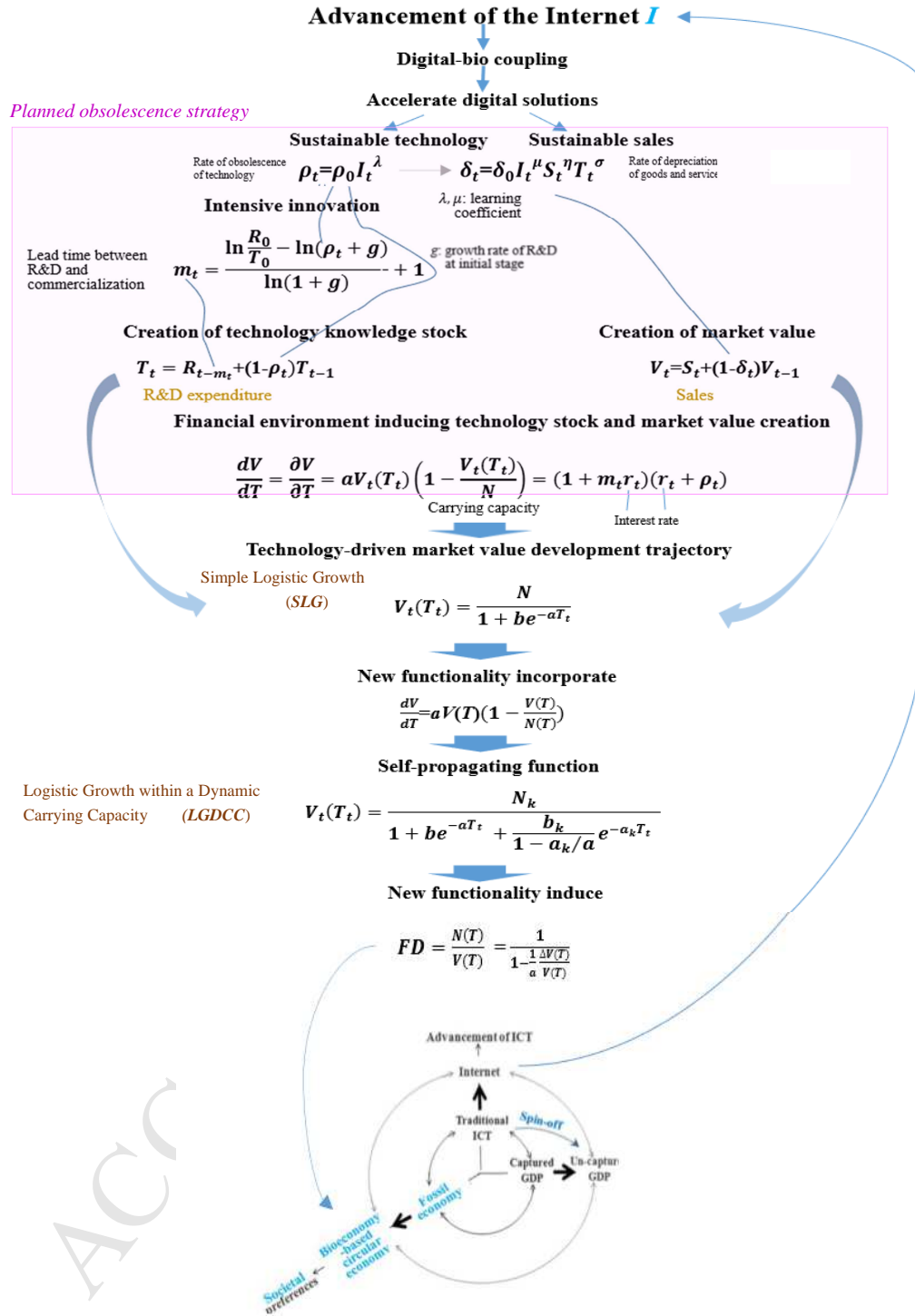


Fig. 12. Framework of a Planned Obsolescence-Driven Circular Economy Enabled by Co-Evolutionary Couplings.

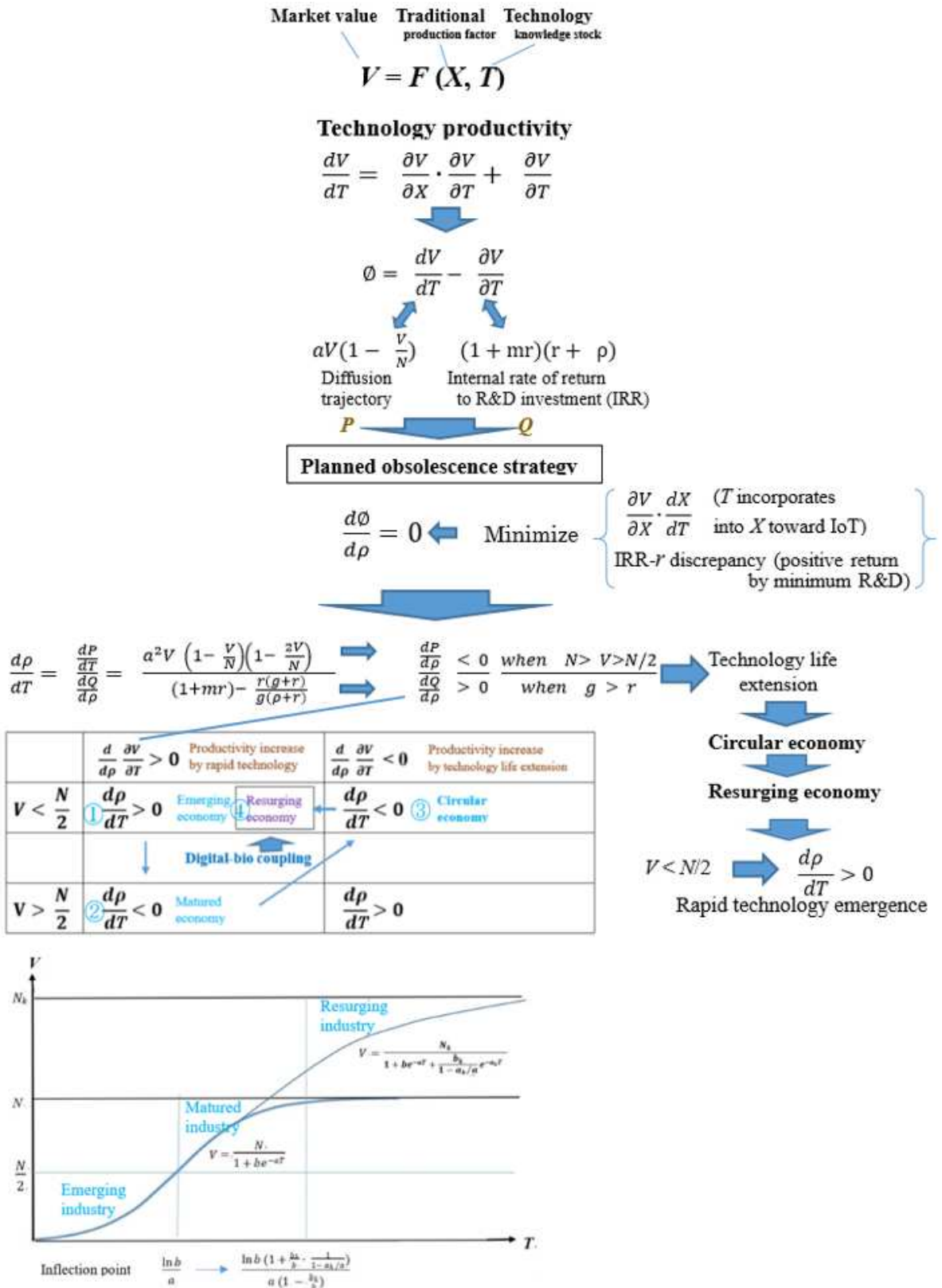


Fig. 13. Framework of Planned Obsolescence Management.

4.2 Data Construction

Data utilized for the analysis are tabulated in **Table 2** (see the details of the data in **Appendices 3 and 4**).

Table 2 Data for the Analysis

Category of Data	References
Primary data	
UPM sales (nominal, real)	UPM annual reports (1997-2017)
UPM R&D expenditure (nominal, real)	UPM annual reports (1997-2017)
UPM R&D intensity	UPM annual reports (1997-2017)
UPM energy cost (nominal, real)	UPM annual reports (1997-2017)
GDP deflator	World Bank national accounts and OECD national accounts data files
Long-term interest rate	OECD, long-term interest rates (2018)
Finland internet dependence	International Telecommunication Union (ITU), statistics (2018)
Constructed data	
Rate of obsolescence of technology	UPM annual reports and ITU data
Lead time between R&D and commercialization	UPM technology stock and ITU data
Rate of depreciation of sold goods and services	UPM technology stock and ITU data
UPM technology knowledge stock	Computed-based UPM annual reports data (1997-2017)
UPM market value	Computed-based UPM annual reports data (1997-2017)

Fig. 14 illustrates trends in UPM's sales, R&D expenditure and R&D intensity.

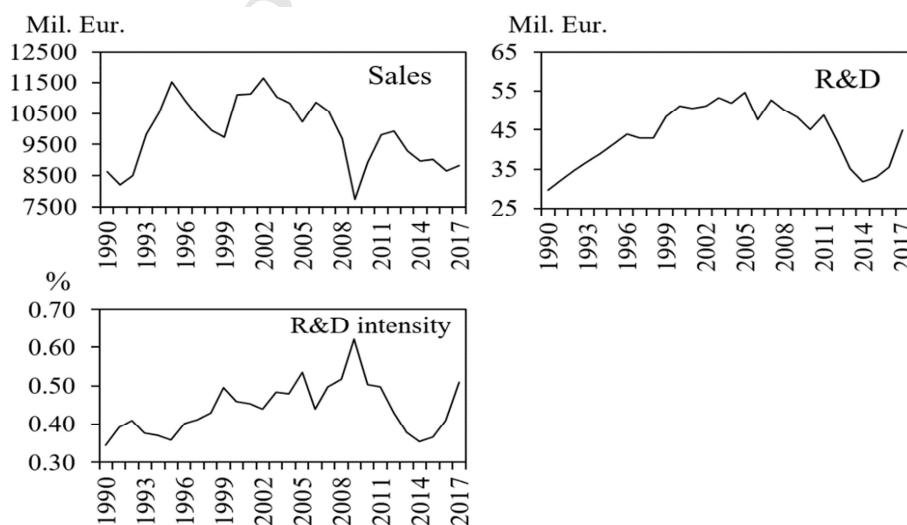


Fig. 14. Trends in UPM Sales, R&D expenditure and R&D Intensity

(1990-2017; 2010 real price).

Source: UPM Annual Reports.

Upon examining Fig. 14 we noted that sales generally increased at the beginning of this century (except during Asian financial crisis in 1998), as the industry enjoyed the benefits of this emerging economy. Thereafter, sales generally decreased as the industry shifted to a matured economy. This continued decrease was once again modified to an increasing trend during the early part of the second decade of this century, allowing UPM to generate the world's top net income in 2015, as shown in Fig. 1. This recovery can be attributed to the shift towards a circular economy, as described in Section 2. R&D investment was demonstrated to be generally subject to trends in sales. **Figs. 15** and **16** illustrate trends in Internet dependence in Finland, Japan, Singapore and the USA and in the long-term interest rate in European countries over the 1990-2017 period, respectively.

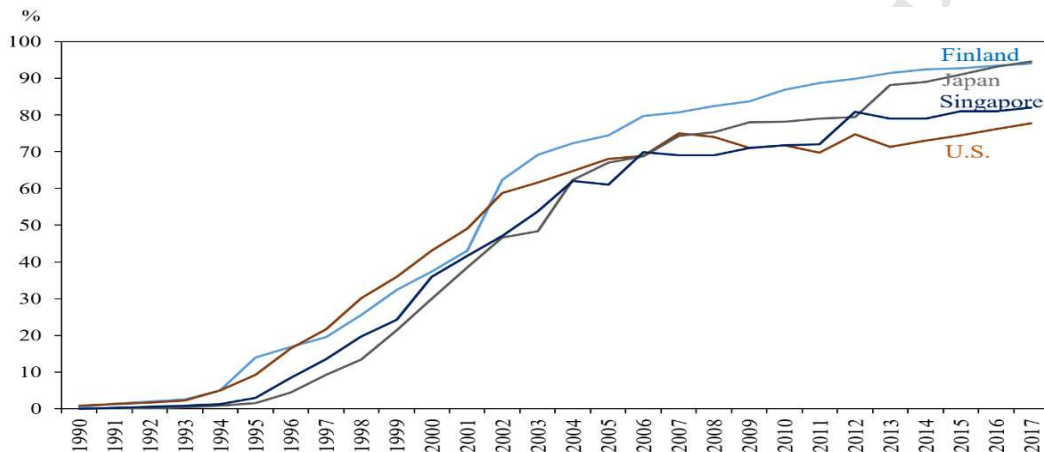


Fig. 15. Trends in Internet Dependence (%; 1990-2017).

Source: International Telecommunication Union.

Fig. 15 shows the high dependence of Finland on the Internet, particularly in this century, and demonstrates the marked role of the Internet in the planned obsolescence strategy.

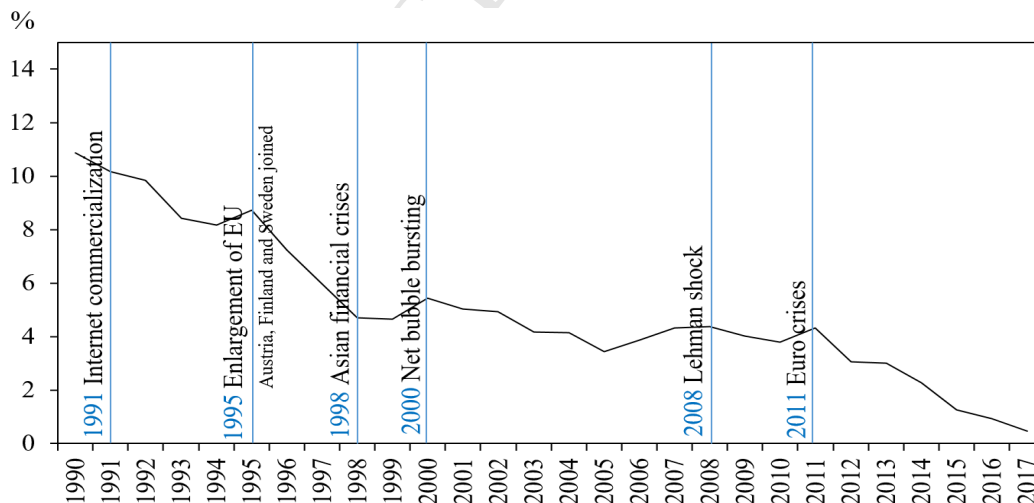


Fig. 16. Trends in the Long-Term Interest Rate in European-Countries (1990-2017).

Source: OECD.

Fig. 16 demonstrates trends in the long-term interest rate in European countries over the 1990-2017 period. This declining trend has induced an extension of technology life corresponding to a circular economy within a matured economy (see the details of this mechanism in **Appendices 2** and **4**).

4.3 Empirical Analysis

4.3.1 Creation of Technology Knowledge Stock and Market Value

Measurement of technology knowledge stock and market value is essential for the analysis of UPM's technology-driven development trajectory towards a circular economy.

Griliches (1980) postulated that technology knowledge stock can be measured as a cumulative stock of R&D investment by considering the obsolescence rate (ρ) for commercialization (m), as illustrated in Fig. 12 (see the details of the equation in **Appendix 1**). It was previously identified that firms attempt to manage this lead time depending on the rate of obsolescence of technology (Watanabe, 1999).

Similarly, market value can be measured as the cumulative stock of sales taking into account their depreciation rate (δ). In this case, contrary to technology knowledge stock, lead time can be considered negligibly small (see also Fig. 12 and **Appendix 1**).

Generally, 'depreciation' in a broad sense (sometimes also called 'obsolescence') can be defined as the loss in service value incurred in connection with the consumption or prospective retirement of a property (NARUC, 1996). It generally results from two principle classes of losses: (i) traditional mortality forces, such as wear and tear from usage, deterioration with age and accidental or chance destruction, and (ii) technological obsolescence (Barreca, 2000). These losses can be derived from either physical obsolescence or technical obsolescence mechanisms (Aladeojebi, 2013). Before the 1970s, the overwhelming drivers of mortality for utility property were traditional mortality forces before the 1970s (Barreca, 2000); however, technological obsolescence has a primary role as technology advances. When technological obsolescence is present, mortality rates increase with the passage of time (Barreca, 2000), leading to a much higher obsolescence/depreciation rate than that of stemming from traditional mortality forces.

In this paper, in line with Griliches (1980), the depreciation rate of technology is framed as the rate of obsolescence of technology, while the depreciation rate of sales is framed as the rate of depreciation of sold goods and services.

4.3.2 Planned Obsolescence Strategy

The above postulates suggest that the rates of obsolescence of technology and depreciation of sold goods and services play decisive roles in measuring technology knowledge stock and market value. Particularly, careful attention should be paid to these rates of obsolescence and depreciation in the context of the resurgence of UPM and its planned obsolescence-driven circular economy.

1) Rate of Obsolescence of Technology

Confronting the stagnating trend in the forest-based bioeconomy of Europe as a consequence of the advancement of the digital economy and growing inertia in emerging economies, the planned obsolescence management strategy has become important in leading European pulp and paper firms (MISTRA, 2017).

Leading pulp and paper firms in Europe have taken sincere consideration of planned obsolescence as a technology strategy (Mubareka et al., 2016) and have implemented digital solutions as an additional strategy stemming from the dramatic advancement of digital innovations (Mustalahti, 2018).

Traditionally, the purpose of this strategy was to force consumers to purchase newer products by shortening the natural end of life of the current products owned by

consumers (Packard, 1960; Swan, 1972; Bulow, 1986; Slade, 2006; Aladeojebi, 2013). However, in line with increasing concerns over the environment and consumer preferences, some concerns with respect to ‘planned longevity’ have arisen (e.g. Swan, 1972; Bulow, 1986; Keeble, 2013; EMF, 2015; Fabian, 2016; Satyro et al., 2018).

In light of the metabolic change in the forest-based bioeconomy, particularly in UPM’s transformative development trajectory towards a circular economy, an optimal obsolescence management strategy encompassing both possibilities of shortening and extending technology life (UPM, 2017a) was sought in this paper based on the principle of profitable R&D with minimum R&D investment and maximum utilization of digital solutions, as demonstrated in Fig. 7. In addition, the state of the development trajectory was taken into account (see the details of mathematical analyses in **Appendix 2**).

There are two forms of obsolescence: external obsolescence and functional obsolescence (Barecca, 2000). The former can be attributed to external circumstances including the development, diffusion and utilization of technology, whereas, the latter results from a flaw in structures, materials or design that diminishes the function, utility and value of an asset (Barecca, 2000). Here, flaw refers to any deficiency in an asset that negatively impact its ability to perform the desired function per customer expectation.

With the rapid advancement of technology, technological obsolescence is the principle cause of functionality obsolescence today, overshadowing external obsolescence, which is relevant for the analysis of the rate of obsolescence of technology for measuring technology knowledge stock.

Hence, technology-driven functionality obsolescence was focused on in this paper in the analysis of the rate of obsolescence of technology.

It was previously demonstrated that firms’ rate of obsolescence of technology can be depicted as a function of their technology knowledge stock level (Watanabe, 1999). UPM’s endeavour to shift towards a planned obsolescence strategy within a circular economy corresponds with a digital solution strategy primarily initiated by the effective utilization and advancement of digital innovation led by the advancement of the internet (*I*) (Tieto, 2017). This preceding approach was utilized through developing Internet dependence rather than inducing general technology knowledge stock. This dependence represents a general trend in co-evolutionary coupling.

As reviewed earlier, profit maximization can be attained by increasing the rate of obsolescence of technology (ρ) (rapid substitution with new technology) in an emerging economy, while the reverse occurs in a matured economy. In a matured economy, an extension of the technology life cycle (decrease ρ) is required, corresponding with the principles of a circular economy (EMF, 2015; UPM, 2017a).

In addition, as reviewed in Fig. 12, given firms’ planned obsolescence management strategy, their rate of obsolescence of technology is subject to the long-term interest rate, as demonstrated in Fig. 16 (see the detailed mechanism in **Appendices 1 and 2**).

Based on the foregoing review and the historical review with international comparisons (Schott, 1978; Bosworth, 1978; Japan Science and Technology Agency, 1985; Mitsubishi Research Institute, 1991; Watanabe, 1992; Watanabe, 1999; OECD, annual issues), the rate of obsolescence of technology in UPM over the 1990-2017 period was estimated, as illustrated in **Fig. 17** (see the details of the estimation approach and estimated values in **Appendices 3 and 4**).

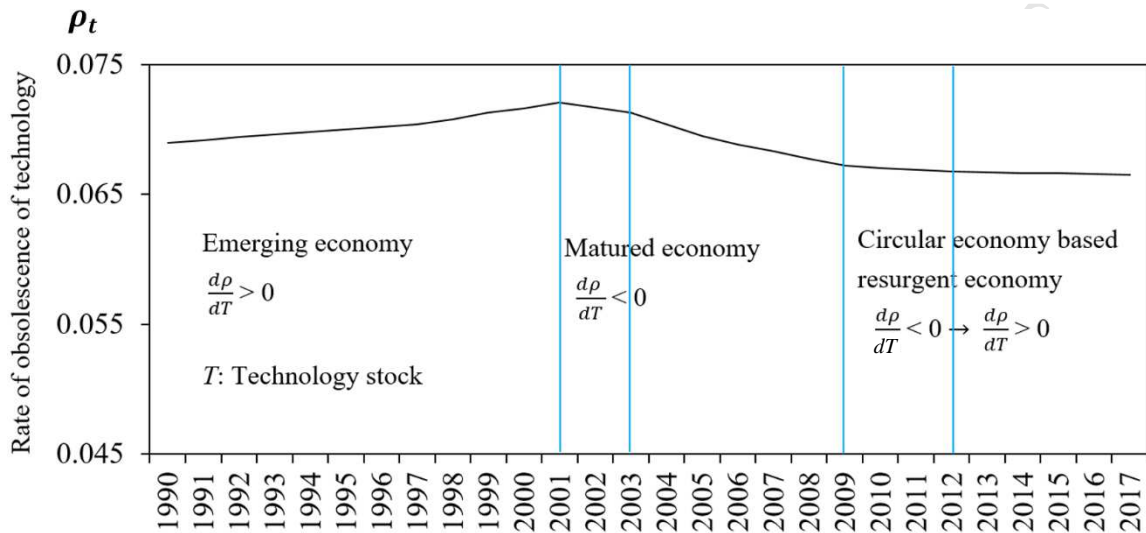


Fig. 17. Trend in the Rate of Obsolescence of Technology in UPM (1990-2017).

Dynamic change in rate of obsolescence of technology, as reviewed in **Fig. 12**, evidence the capacity of firms to change lead time between R&D and commercialization (m), as illustrated in **Fig. 18** (see the details of estimated values in **Appendix 4**). This dynamic change in lead time was reflected in the measurement of the technology knowledge stock.

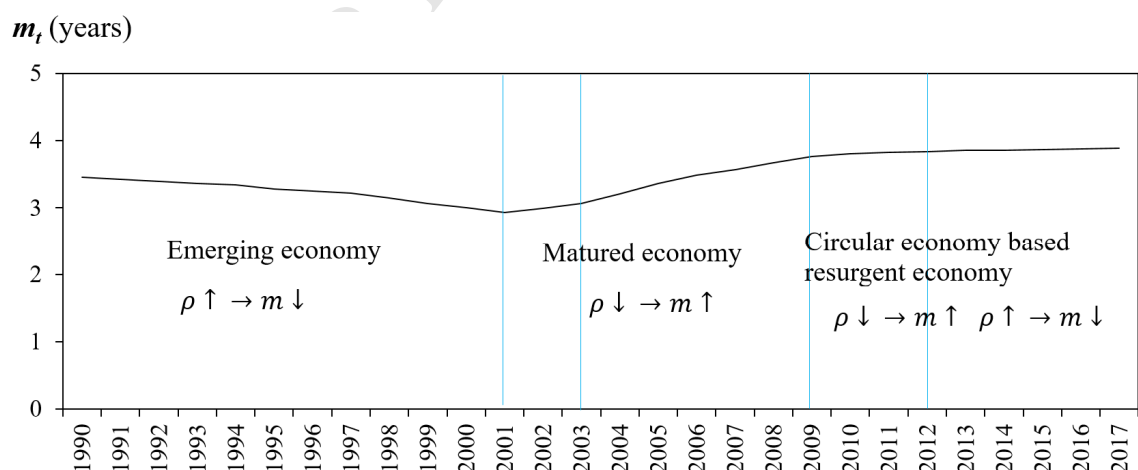


Fig. 18. Trend in Lead Time between R&D and Commercialization (1990-2017).

2) Rate of Depreciation of Sold Goods and Services

In principle, the strategy of firms for the planned depreciation of market value is based on the similar strategy of planned obsolescence of technology (Keeble, 2013). However, it largely depends on external obsolescence and is more sensitive to factors other than digital solutions (Disney et al., 2003; Obeng et al., 2014). It is subject to the advancement of the Internet, similar to ρ , yet it is also subject to the sales trend (S) or, specifically, the popularity of sold goods and services in the market. Yet notably, it is decisive factor of firms' planned depreciation strategy (Rodriguez et al., 2015). In addition, technology knowledge stock (T) cannot be overlooked as it may produce new goods and services that substitute existing ones. Furthermore, advancement of the internet accelerates dissemination of goods and services in new emerging markets and extends their life cycle leading, to decreasing δ .

Hence, the rate of depreciation of sold goods and services δ can be depicted by a function describing dependence on the Internet, the sales trend and technology knowledge stock.

Contrary to rate of obsolescence of technology, the depreciation of sold goods and services is primarily governed by traditional mortality forces, such as wear and tear and deterioration. These forces are typically a constant function of the age of the assets and do not change with the passage of time (Barreca, 2000)⁵.

In addition, compared to technological obsolescence, which increases the mortality rate over time, leading to a higher rate of obsolescence, the rate of depreciation of sold goods and services is considered to be much lower as it stems from traditional mortality forces.

Based on the foregoing review in addition to the lifecycles of UPM's leading products, the rate of depreciation of goods and services sold by UPM over the 1990-2017 period was estimated, as illustrated in **Fig. 19** (see the details of the estimation approach and estimated values in **Appendices 3 and 4**).

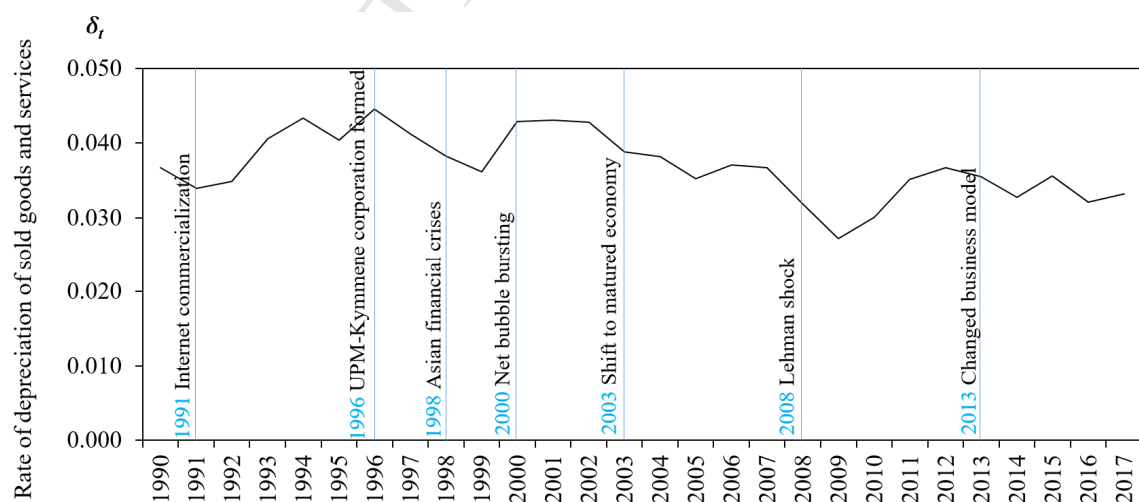


Fig. 19. Trend in the Rate of Depreciation of Sold Goods and Services (1990-2017).

⁵ Barreca (2000) demonstrated as follows:

5 years ago, 10 year old assets may have had a 3% retirement rate (depreciation rate); today, 10 year old assets would still have a 3% retirement rate; and 30 years from now, 10 year old assets would still have a 3% retirement rate.

4.3.3 Technology-Driven Market Value Development Trajectory

Utilizing the estimated rate of obsolescence of technology, the lead-time between R&D and commercialization and the estimated rate of depreciation of sold goods and services, the technology knowledge stock and market value of UPM over the 1990-2017 period were estimated, as illustrated in **Fig. 20** (see **Appendix 4** for estimated values).

Market value V - 200 (Bil. Eur.)

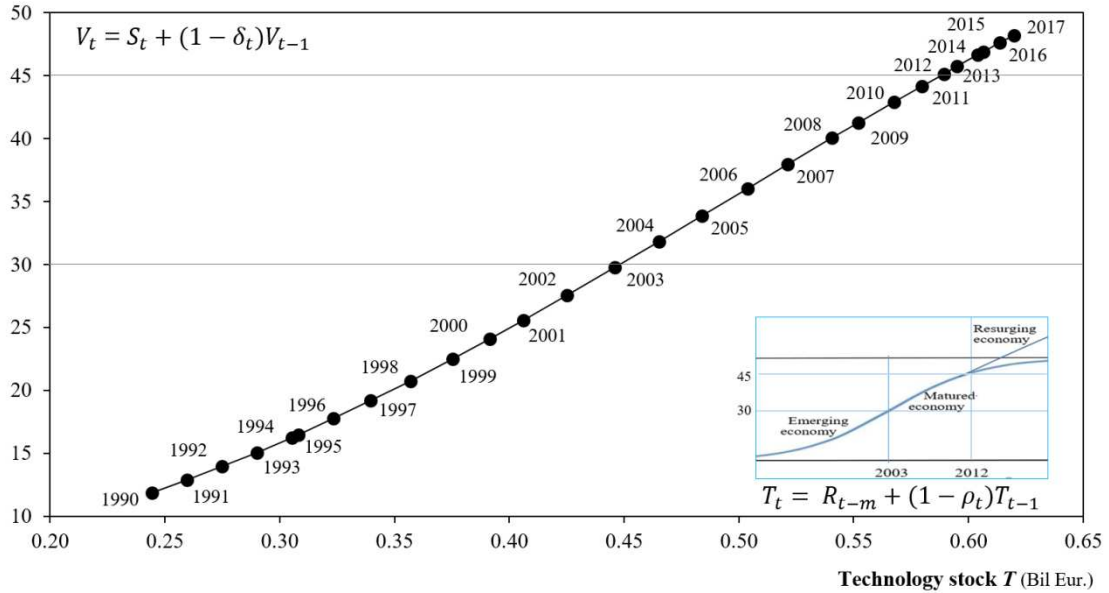


Fig. 20. Trends in Technology Knowledge Stock and Market Value of UPM (1990-2017).

Based on these values, UPM's technology-driven development trajectory over the 1990-2017 period was estimated.

Table 3 summarizes the estimated trajectory by comparing the trajectory of simple logistic growth (*SLG*) and logistic growth given the trajectory of dynamic carrying capacity (*LGDC*) (see the details of mathematical development in Fig. 12). While the former saturates at a certain upper limit (carrying capacity), the later continues to increase, as it is supported by a self-propagating function and led by a dynamically changing upper limit that is induced by the incorporation of new innovations during the development process (Watanabe et al., 2004).

Table 3 UPM's Technology-Driven Development Trajectory (1990-2017)

$$V^* = \frac{N_k}{1 + be^{-aT} + \frac{b_k}{1 - a_k/a} e^{-a_k T}} \quad V^* = V - 200$$

	N_k	a	b	a_k	b_k	$adj. R^2$
<i>SLG</i>	61.15 (10.82)	6.30 (9.08)	16.54 (8.05)			0.986
<i>LGDC</i>	83.31 (4.45)	7.35 (8.36)	27.98 (2.64)	3.11 (1.05)*	1.72 (1.04)*	0.999

The figures in parenthesis indicate t-statistics: Significant at the 1% level except * (15% level).

Upon examining Table 3, we noted that *LGDC* demonstrated a statistically better fit to the development trajectory, with a significant self-propagating function represented by the ratios of a_k/a and b_k/b which had substantial values of 0.42 and 0.06, respectively.

4.3.4 Circular-Economy-driven Restructuring

Utilizing the results of the above estimate, **Fig. 21** illustrates the trend and prospect of UPM's trajectory of technology-driven increase in market value. Upon examining Fig. 21 we noted that UPM continued along its trajectory of technology-driven increase in market value based on *SLG* and shifted from an emerging development trajectory to a matured trajectory from 2003 onwards, as demonstrated by the inflection point of *SLG* ($\ln b/a = 0.45$), which corresponds to the technology knowledge stock level in 2003. This timing corresponds inflection point of the firm's planned obsolescence strategy (shifting from $\frac{d\rho}{dT} > 0$ to $\frac{d\rho}{dT} < 0$) to achieve profitable R&D with minimum R&D investment (see the details of this inspection in **Appendix 5**).

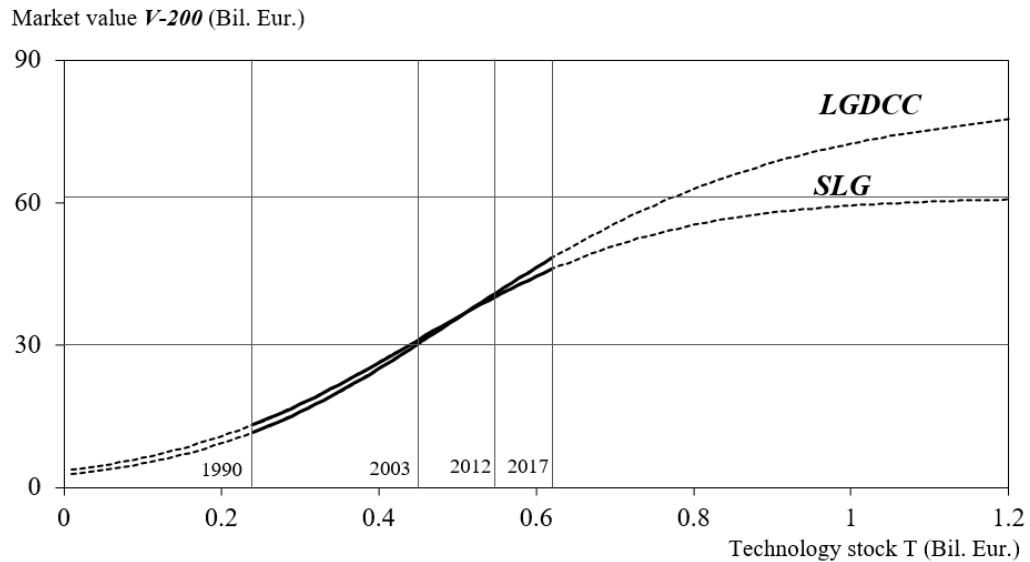
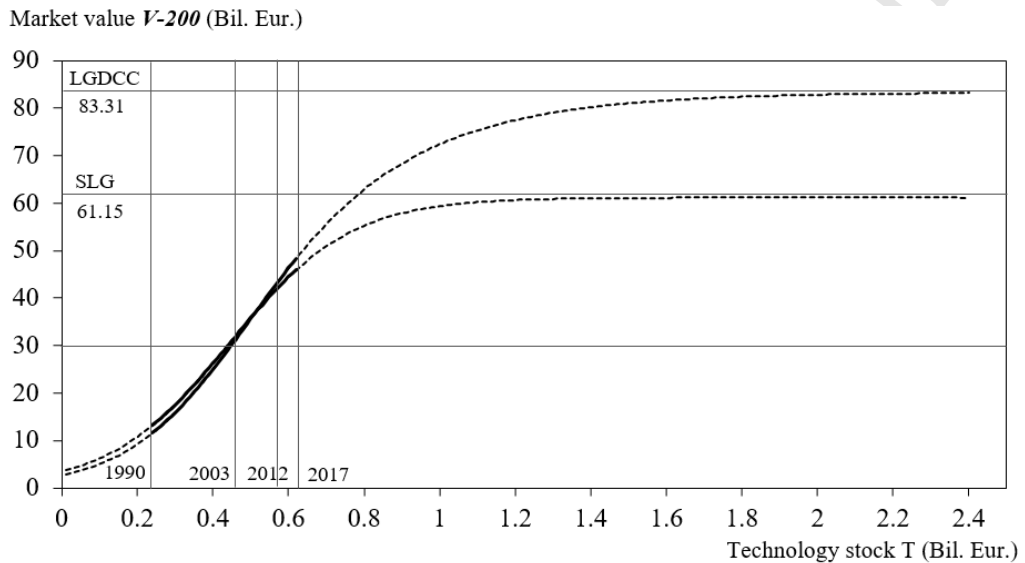


Fig. 21. Trend in UPM's Trajectory of Technology-Driven Increase in Market Value
(1990-2017).

UPM continued its efforts to increase market value yet suffered a saturation trend as a consequence of its of matured trajectory in *SLG*, which has been common among all

forest industries in Europe (Hetemaki et al., 2014) since the beginning of this century.

Confronting full-fledged advancement of digitalization and worldwide overproduction of paper products since the beginning of this century, UPM was not an exception in shifting from an emerging to a matured state. It was obligated to close several paper mills in the first decade of this century. Because of these circumstances, UPM accelerated a circular economy-based business model in the beginning of the second decade of this century, leading to a restructuring into six business groups in 2013.

4.3.5 Planned Obsolescence-Driven Circular Economy

The newly formulated business groups are connected by a common idea: to create value from renewable and recyclable raw materials, synthesizing them based on know-how and technology. Such circular economy-driven restructuring enabled UPM to incorporate new functionality and to shift towards new development trajectory, as outlined in Fig. 8. Specifically, this shift correspond to one from a *SLG* trajectory to a *LGDC* trajectory in 2012, as illustrated in **Fig. 22**. This is also reflective of UPM's circular economy-driven restructuring, which had a full-fledged start in 2013 enabling UPM to resurge through reframing itself within an emerging economy, as outlined in Fig. 7.

This metabolic cycle corresponds to the planned obsolescence management cycle initiated by effective utilization and advancement of the internet. Notably, a higher obsolescence rate is frequent in emerging economies (rapid substitution to new technology), whereas a lower obsolescence rate is present in matured economies (technology life is extended in accordance with the principles of a circular economy). So, the trajectory of UPM transformed to that of an emerging economy and once again resurged, as reviewed in **Fig. 7**.

Such a resurgence was enabled by the co-evolution of the coupling of bio-economy and digitalization and of upstream and downstream operations. The dynamism of a trajectory of planned obsolescence-driven circular economy, enabled by the co-evolution of the coupling of bio-economy and digitalization and of upstream and downstream operations, can be definitely considered as the structural source of resurgence of UPM amidst the new industries in the digital economy. This present analysis similarly provides new insights common to all industries in the digital economy.

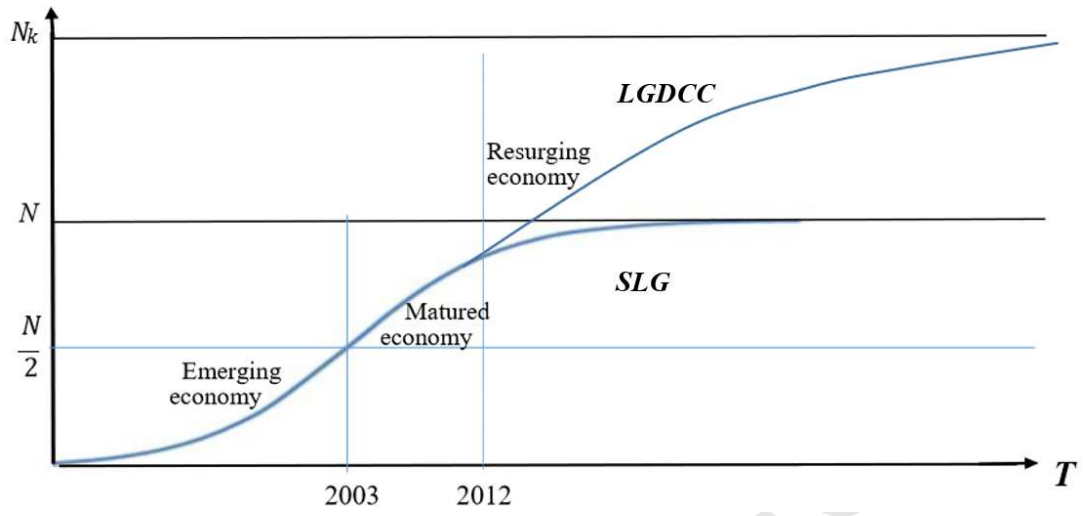


Fig. 22. UPM's Circular Economy Initiative within a Resurgent Economy.

5. Conclusion

In light of the increasing significance of the transformation of a forest-based bioeconomy into a digital platform industry, a pioneer challenge initiated by UPM's planned obsolescence-driven circular economy was analyzed. A model explaining this transformation dynamism was developed and its reliability was demonstrated based on an empirical analysis of UPM's development trajectory.

The noteworthy findings described as following:

- (i) Driven by digital solutions, the bioeconomy has taken major steps forward in recent years, leading to the realization of the long-lasting goal of shifting from a traditional fossil economy towards a bioeconomy-based circular economy.
- (ii) The coupling of two streams, digitalization and bioeconomy, has led to the emergence of a digitalized bioeconomy that satisfies the downstream shift in consumers' preferences and that additionally induces further coupling in upstream of the value chain.
- (iii) Hence, the co-evolution of the coupling of bioeconomy and digitalization and of upstream and downstream operations has transformed the forest-based bioeconomy into a digital platform industry.
- (iv) This co-evolution-driven restructuring enabled UPM to incorporate new functionality and to shift towards a new development trajectory in line with a circular economy.
- (v) This shift corresponds with a long-lasting societal preference shift, leading UPM to resurge within the emerging economy.
- (vi) UPM's planned obsolescence management strategy additionally enabled this metabolic shift.
- (vii) Hence, the trajectory of a planned obsolescence-driven circular economy enabled by the co-evolution of the coupling of bioeconomy and digitalization and of upstream and downstream operations can be considered the structural source of the resurgence of UPM within the digital economy.

These findings give rise to the following insightful suggestions for other industries confronting a similar stream of transformation:

- (i) A circular economy-seeking metabolism should be applied when operating within a matured economy, confronting stagnation.
- (ii) Planned obsolescence management should be incorporated to achieve sustainable development.

- (iii) Co-evolutionary coupling of bioeconomy and digitalization and of upstream and downstream operations should be sought.
- (iv) Shifting trends in the co-evolution of megatrends initiated by a bioeconomy-based circular economy should be learned.
- (v) A consolidated platform ecosystem should be further developed.

This research thus developed a new practical approach, comprehensive dimensions such as the co-evolution of the coupling of bioeconomy and digitalization and of upstream and downstream operations in addition to the planned strategy of obsolescence and the shift in trajectory from a fossil economy to a circular economy.

This approach is expected to provide new insights into the forest-based bioeconomy as well as to industries that are embracing digital solutions. However, since this approach focused on digital solutions, not taking other factors as natural resources, subsequent limitations of this analysis should be carefully recognized.

Furthermore, because of constraints stemming from the reliability of data, particularly data on technological obsolescence and rate of depreciation of sold goods and services, successive monitoring and empirical surveys are strongly recommended. In addition, since the abovementioned transformation has been still in its infancy, diversified possibilities should be carefully watched.

Further work should focus on addressing these constraints and performing further in-depth analyses of success and failure trajectories with respect to shifts in trajectories towards a circular economy. In addition, given the dynamic advancement of platform ecosystems amidst the digital economy, the comparison of noteworthy business models in the digital economy at large is another subject that should be addressed on a priority basis.

Acknowledgement

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Authors are grateful to invaluable advices provided by reviewers.

Appendix 1. Model Constructed for the Analysis

Market value created by firms in a competitive environment can be described as follows:

$$V = F(X, T) \quad (1)$$

where V : market value; X : traditional production factors; and T : technology knowledge stock.

Given the emphasis on internet-driven digital solutions, the internet permeates T as follows:

$$V = F(X, T(I)) \quad (2)$$

where I : internet dependence.

Furthermore, I embodies X in an internet of things (IoT) society as follows:

$$V = F(X(I), T(I)) \quad (3)$$

Thus, the market value of firms seeking digital solutions in an IoT society is governed by the following function:

$$V \approx F(T(I)) \quad (4)$$

Technology knowledge stock at time t , T_t can be depicted as follows:

$$T_t = R_{t-m} + (1 - \rho)T_{t-1}, \quad T_0 = R_{1-m}/(\rho + g) \quad (5)$$

where R_t : R&D expenditure at time t ; m : time lag between R&D to commercialization; ρ : rate of obsolescence of technology; and g : increasing rate of R&D expenditure at the initial period.

Given the creative disruption caused by embracing digital solutions, these solutions can be represented by the decreasing rate of obsolescence of technology (i.e. prolongment of the life time of technology) initiated by the advancement of the internet as follows:

$$\rho_t = \rho_0 I_t^\lambda \quad (6)$$

where λ : learning coefficient for digital R&D.

Corresponding to change in ρ , m also changes as follows (Watanabe, 1999):

$$m_t = \frac{\ln R_0/T_0 - \ln(\rho_t + g)}{\ln(1+g)} + 1 \quad (7)$$

Similarly, market value at time t V_t can be depicted as follows:

$$V_t = S_t + (1 - \delta)V_{t-1}, \quad V_0 = S_1/(\delta + k) \quad (8)$$

where S_t : sales at time t ; δ : rate of depreciation of sold goods and services; and k : growth rate of sales at the initial period.

Given the logistic nature of the growth of internet, equation (4) can be developed by the following T -driven logistic growth function:

$$V_t \approx F(T(I)), \quad \frac{dV}{dT} = \frac{\partial V}{\partial T} \cdot \frac{dT}{dT} = \frac{\partial V}{\partial T} = aV(1 - \frac{V}{N}) \quad (9)$$

where N : carrying capacity and a : velocity of diffusion.

Equation (9) develops the following simple logistic growth function (SLG):

$$V_t(T_t) = \frac{N}{1 + be^{-aT_t}} \quad (10)$$

where b : coefficient indicating the initial level of diffusion.

The critical level informing firms' decision to undertake R&D should satisfy the following balance (see *Note*):

$$\frac{\partial V}{\partial T} = (1 + mr)(r + \rho) \quad (11)$$

where r : interest rate.

Similar to ρ as a function of internet-driven learning for digital solutions, δ can be depicted as a function of the internet-driven learning in an IoT society as follows:

$$\delta_t = \delta_0 I_t^\mu \quad (12)$$

where μ : learning coefficient for sales promotion.

This rate is also subject to the trends in sales (S) and technology stock (T). In addition, advancement of the internet expands the market leading to the extension of the life time of goods and services. Thus, δ is governed by $\Phi(S, T, I)$ as depicted in equation (13).

$$\delta_t = \delta_0 I_t^\mu \cdot \Phi(S, T, I) \quad (13)$$

Note: Internal rate of return of R&D investment

The critical level that informs firms' decision to undertake R&D is defined by the following discount rate (r : internal rate of return [*IRR*] of R&D investment), which should not be lower than the interest rate (Watanabe et al., 1997).

$$V = F(X, T) \quad T_t = R_{t-m} + (1 - \rho)T_{t-1} \quad \text{where } V: \text{production (value added); } T: \text{technology stock; } R: \text{R\&D investment; } m: \text{lead time between R\&D and commercialization; and } \rho: \text{rate of obsolescence of technology.}$$

Present value of one unit R&D investment ($R = 1$) at the initial year of the commercialization:

$$1 / (1 + r)^{-m} = (1 + r)^m \approx e^{mr} \quad \text{where } r: \text{discount rate.}$$

The return of one unit R&D investment at the initial year of the commercialization:

$$\frac{\partial V}{\partial T}; \text{ its value at time } t: \frac{\partial V}{\partial T} \cdot (1 - \rho)^t; \text{ and its present value at the initial year of commercialization (} t = 0 \text{):}$$

$$\frac{\frac{\partial V}{\partial T} \cdot (1 - \rho)^t}{(1 + r)^t} = \frac{\partial V}{\partial T} \cdot (1 - \rho)^t (1 + r)^{-t} \approx \frac{\partial V}{\partial T} \cdot e^{-\rho} \cdot e^{-t} = \frac{\partial V}{\partial T} \cdot e^{-(r + \rho)}; \text{ and whole value in its total life is:}$$

$$\int_0^\infty \frac{\partial V}{\partial T} e^{-(r + \rho)t} dt$$

Discount rate r which equilibrates present values of investment and its return can be identified as *IRR* to R&D investment.

$$e^{mr} = \int_0^\infty \frac{\partial V}{\partial T} e^{-(r + \rho)t} dt = \frac{\partial V}{\partial T} \frac{1}{(r + \rho)}$$

$$1 + mr = \frac{\partial V}{\partial T} \frac{1}{(r + \rho)}$$

Thus, the critical level informing firms' decision to undertake R&D should satisfy the following balance given marginal technology productivity:

$$\frac{\partial V}{\partial T} = (1 + mr)(r + \rho)$$

Appendix 2. Planned Obsolescence in a Matured Industry Shifting Toward Digital Solutions

From equation (1) firms' technology productivity can be developed as follows:

$$\frac{dV}{dT} = \frac{\partial V}{\partial X} \cdot \frac{dX}{dT} + \frac{\partial V}{\partial T} \cdot \frac{dT}{dT} = \frac{\partial V}{\partial X} \cdot \frac{dX}{dT} + \frac{\partial V}{\partial T} \quad (14)$$

$$\Phi \equiv \frac{\partial V}{\partial X} \cdot \frac{dX}{dT} = \frac{dV}{dT} - \frac{\partial V}{\partial T} \quad (15)$$

From equations (9) and (11), the components of equation (15) can be provided as follows:

$$P \equiv \frac{dV}{dT} = aV(1 - \frac{V}{N}) \quad (9)$$

$$Q \equiv \frac{\partial V}{\partial T} = (1 + mr)(r + \rho) \quad (11)$$

Provided that firms seek profitable R&D with minimum R&D investment and maximum utilization of digital solutions, the planned obsolescence strategy can be depicted as follows⁶:

$$\frac{d\Phi}{d\rho} = 0 \quad (16)$$

$$\frac{d\Phi}{d\rho} = \frac{dP}{d\rho} - \frac{dQ}{d\rho} = a \left[\frac{dV}{d\rho} \left(1 - \frac{V}{N} \right) - \frac{V}{N} \cdot \frac{dV}{d\rho} \right] - \frac{dQ}{d\rho}$$

$$= a \cdot \frac{dV}{d\rho} \left(1 - \frac{2V}{N} \right) - \frac{dQ}{d\rho}$$

$$= a \cdot \frac{dV}{dT} \cdot \frac{dT}{d\rho} \left(1 - \frac{2V}{N} \right) - \frac{dQ}{d\rho} = a \cdot aV \left(1 - \frac{V}{N} \right) \left(1 - \frac{2V}{N} \right) \frac{dT}{d\rho} - \frac{dQ}{d\rho} = 0$$

$$\frac{d\rho}{dT} = \frac{a^2 V \left(1 - \frac{V}{N} \right) \left(1 - \frac{2V}{N} \right)}{\frac{dQ}{d\rho}} \quad (17)$$

Provided that interest rate r is given by an external market independent from ρ management, the following holds true:

$$\frac{dQ}{d\rho} = \frac{d}{d\rho} (1 + mr)(r + \rho) = r \cdot \frac{dm}{d\rho} (r + \rho) + (1 + mr)$$

$$= \frac{-1}{\ln(1+g)} \cdot \frac{r(\rho+r)}{(\rho+g)} + (1 + mr) \approx -\frac{r(\rho+r)}{g(\rho+g)} + (1 + mr)$$

In the case that $H \equiv \frac{g(\rho+g)}{r(\rho+r)}(1 + mr) > 1$, $\frac{dQ}{d\rho} > 0$, then $\frac{d\rho}{dT} < 0$. The numerator of equation (17) is negative in a matured economy ($N > V > N/2$) whereas the opposite occurs in an emerging economy ($V < N/2$).

In the case that $g > r$, $\frac{g(\rho+g)}{r(\rho+r)}(1 + mr) > \frac{r(\rho+r)}{r(\rho+r)}(1 + mr) = (1 + mr) > 1$, $\frac{d\rho}{dT} < 0$.

⁶ The internal rate of return of R&D investment r in equation (11) should be no lower than the interest rate, and maximum digital substitution for traditional production factor X should be sought.

Appendix 3. Rates of Obsolescence of Technology and Depreciation of Sold Goods and Services

A3.1 Rate of Obsolescence of Technology

On the basis of a historical review comparing different countries which is tabulated in **Table 4**, the rate of obsolescence of technology in the Finnish PPI⁷ in 1995 can be estimated as 7%.

Table A1 Rate of Obsolescence of Technology in the Manufacturing Industry in the 1980s and 1990s

	1980s average (1985)	1995	Average growth rate	References
Japan	9.8 ^{*1}	12.3 ^{*2}	2.5 % <i>p.a</i>	*1 Japan Science & Technology Agency (1985) Watanabe (1992) *2 Watanabe (1999)
USA	6.7 ^{*3}	9.0 ^{*4}	3.0 % <i>p.a</i> ^{*4}	*3 Mitsubishi Research Institute (1991) *4 Higher pace than Japan during a period of new economy
Europe	5-10 ^{*5} 6.5 ^{*6}	8.0 ^{*7}	2.0% <i>p.a</i> ^{*7}	*5 Schott and Bosworth (1978). *6 Pace of technological change is similar to the USA (OECD). *7 Pace of technological change is similar to Japan (OECD) Electronics/machinery 9%, Chemicals 8% Pulp & paper/food 7%

As reviewed in Section 2, UPM's development trajectory over the last quarter century has been shifting from an emerging economy to a matured economy informed by a circular economic strategy within a resurgent economy. This trajectory shift corresponds to the advancement of the digital economy, and the countermeasures to this shift largely depend on digital solutions led by the advancement of the internet (Tieto, 2017).

With this understanding, UPM's rate of obsolescence of technology as part of its planned obsolescence strategy can be considered a function of the advancement of digital innovation represented by internet dependence (I) as follows:

$$\rho_t = \rho_0 \cdot I^\lambda \quad (18)$$

where ρ_0 : the rate of obsolescence of technology of the base year and λ : coefficient.

As reviewed in Section 2, $\frac{d\rho}{dt} > 0$ in an emerging economy, while $\frac{d\rho}{dt} < 0$ in a matured economy. Finally, $\frac{d\rho}{dI} < 0 \rightarrow \frac{d\rho}{dt} > 0$ in circular economy based on a resurgent economy⁸.

In addition, as reviewed in Fig. 13, given firms' planned obsolescence management

⁷ Since pulp and paper industry is non-R&D intensive industry as demonstrated below, its pace of technological change is among the lowest group in the manufacturing industry. R&D intensity in 2014 (Japan's case): Pharmaceutical 7.8%, electronics 6.5%, chemicals 3.9%, machinery 3.7%, textiles 2.4%, pulp & paper 0.7%, food 0.6%.

⁸ $\frac{d\rho}{dT} = \frac{d\rho}{dI} \cdot \frac{dI}{dT}$ and $\frac{dI}{dT} > 0$ in a digital economy.

strategy, the rate of obsolescence of technology is also subject to the long-term interest rate (r).

Taking all these factors into account, UPM's rate of obsolescence of technology over the 1990-2017 period was estimated by the following equation. The coefficient was identified by a heuristic approach, satisfying all conditions necessary for the planned obsolescence strategy, as illustrated in Fig. 13.

$$\rho_{1995} = 0.07, \rho_t = \rho_{1995} \cdot I^{0.1} \text{ (1990-2001)}, \rho_t = \rho_{2001} \cdot I^{-0.1} \text{ (2002-2017)}$$

A3.2 Rate of Depreciation of Sold Goods and Services

While firms' strategy for planned depreciation of market value is based on the similar strategy of planned obsolescence of technology in principle (Keeble, 2013), it is more sensitive to factors other than digital solutions (Disney et al., 2003; Obeng et al., 2014).

As reviewed in Section 4, it is subject to the advancement of the internet, similar to ρ , yet it is also subject to the trends in sales (S) and technology stock (T). Both generally react to saturate and/or substitute goods and services, leading to an increase in the rate of depreciation of market value δ (Bosworth, 1978). In addition, advancement of the internet reacts by extending the life cycle, leading to decreasing δ . Therefore δ_t can be depicted by the following equation:

$$\delta_t = \delta_0 I_t^\mu \cdot \Phi(S, T, I) \quad (13)$$

$$\phi_t = A \cdot S^\alpha T^\beta I^\gamma \quad (19)$$

where A : scale factor and α, β and γ : coefficients.

Following the estimated rate of obsolescence of technology, the primary governing factor $\delta_0 I_t^\mu$ can be estimated as follows⁹:

$$\delta_{1995} = 0.04, \delta_t = \delta_{1995} \cdot I^{0.1} \text{ (1990-2001)}, \delta_t = \delta_{2001} \cdot I^{-0.1} \text{ (2002-2017)}$$

By means of a heuristic approach satisfying all conditions necessary for the planned obsolescence strategy, as illustrated in Fig. 12, the coefficients of equation (19) were identified as follows:

$$\Phi_t = 0.25 \cdot S^{0.76} T^{0.32} I^{-0.16} \text{ (1990-2001)}, \Phi_t = 0.29 \cdot S^{0.76} T^{0.32} I^{-0.19} \text{ (2002-2017)}$$

Consequently, δ_t was estimated as follows:

$$\delta_t = 0.01 \cdot I^{-0.06} S^{0.76} T^{0.32} \text{ (1990-2001)}, 0.013 \cdot I^{-0.29} S^{0.76} T^{0.32} \text{ (2002-2017)}$$

⁹The resurgence of the forest industry has been expected to disseminate goods and services in existing industries through innovation (Technology Strategy Board, 2014): Formable plywood (developed by UPM) and wood-based casting plaster (developed by Onbone) are typical examples in the 2010s, with lifetimes of 30 years (Finnish Forest Industries Federation, 2012). Accordingly, their δ_{2010s} was estimated as 0.033. Given the decreasing trend in δ_t since the early 1990s, δ_{1995} was estimated to be 0.04.

Appendix 4. Key Data for Analyses (1): Primary Data

Year	UPM Sales (Mil. Euro) (nominal)	UPM Sales (Mil. Euro) (real)	UPM R&D (Mil. Euro) (nominal)	UPM R&D (Mil. Euro) (real)	UPM R&D intensity (R&D/Sales)(%)	UPM market capitalization (Mil. Euro) (nominal)	UPM market capitalization (Mil. Euro) (Real)	GDP deflator (base year 2010)	Internet dependence Finland (%)	Internet price Finland (Real)	UPM energy cost (Mil. Euro) (Real)	Energy price US\$/barrel (Real)
1990	6224.0	8629.5	21.5	29.8	0.35	2002	2776	72.13	0.4	95.83	747.51	30.86
1991	6007.0	8200.7	23.6	32.2	0.39	1894	2586	73.25	1.4	45.19	743.84	25.42
1992	6283.0	8498.6	25.7	34.8	0.41	1968	2662	73.93	1.9	37.62	744.72	24.94
1993	7394.0	9824.1	27.8	37.0	0.38	3852	5118	75.26	2.6	31.17	739.11	21.70
1994	8067.0	10524.3	29.9	39.1	0.37	3948	5151	76.65	4.9	21.31	733.20	20.26
1995	9206.0	11526.7	33.0	41.3	0.36	3690	4620	79.87	13.9	11.40	741.23	21.11
1996	8705.0	10910.3	35.0	43.9	0.40	4340	5439	79.79	16.8	10.18	736.96	25.43
1997	8478.0	10405.3	35.0	43.0	0.41	4957	6084	81.48	19.5	9.30	704.49	23.15
1998	8365.0	9956.8	36.0	42.9	0.43	6630	7892	84.01	25.5	7.92	651.09	14.62
1999	8261.0	9740.7	41.0	48.3	0.50	10663	12573	84.81	32.3	6.87	633.19	20.56
2000	9583.0	11118.3	44.0	51.0	0.46	9502	11024	86.19	37.3	6.31	718.17	32.02
2001	9918.0	11135.7	45.0	50.5	0.45	9681	10870	89.06	43.1	5.78	715.21	25.96
2002	10475.0	11648.1	46.0	51.2	0.44	7960	8851	89.93	62.4	4.63	765.05	27.09
2003	9948.0	11038.5	48.0	53.3	0.48	7917	8785	90.12	69.2	4.35	745.66	31.18
2004	9820.0	10830.6	47.0	51.8	0.48	8578	9461	90.67	72.4	4.24	843.73	39.76
2005	9348.0	10215.7	50.0	54.6	0.53	8665	9469	91.51	74.5	4.16	885.19	55.29
2006	10022.0	10853.2	44.0	47.6	0.44	10005	10835	92.34	79.7	4.00	1012.55	66.06
2007	10035.0	10574.9	50.0	52.7	0.50	7084	7465	94.89	80.8	3.97	916.81	72.75
2008	9461.0	9672.4	49.0	50.1	0.52	4680	4785	97.81	82.5	3.92	858.77	96.20
2009	7719.0	7746.1	48.0	48.2	0.62	4326	4341	99.65	83.7	3.88	818.86	69.10
2010	8924.0	8924.0	45.0	45.0	0.50	6874	6874	100.00	86.9	3.80	836.00	77.38
2011	10068.0	9814.4	50.0	48.7	0.50	4466	4354	102.58	88.7	3.75	965.06	104.75
2012	10492.0	9934.3	45.0	42.6	0.43	4633	4387	105.61	89.9	3.72	885.30	103.63
2013	10054.0	9282.7	38.0	35.1	0.38	6497	5999	108.31	91.5	3.68	839.27	97.75
2014	9868.0	8959.3	35.0	31.8	0.35	7266	6597	110.14	92.4	3.67	892.48	87.42
2015	10138.0	9023.3	37.0	33.0	0.37	9192	8181	112.35	92.7	3.65	704.92	44.05
2016	9812.0	8652.3	40.0	35.4	0.41	12452	10980	113.40	93.4	3.63	589.93	35.87
2017	10010.0	8818.4	51.0	44.9	0.48	13818	12173	113.51	94.0	3.62	523.29	46.26

GDP deflator value for 2017 was estimated based on the growth rate of the last 20 years.

R&D values for 1992-1994 were estimated based on the growth rate of the following 5 years.

The internet dependence value for 2017 was adjusted based on 2013-2015 growth rate.

Internet price p_t was estimated by the following learning equation: $p_t = 55.3 I_t^{-0.6}$ (Tou et al., 2018).

UPM energy cost: UPM's annual reports. Values for 1990-1994 were based on backward estimation.

Energy Price: Average annual OPEC crude oil price (Statista, 2018); energy cost and prices were deflated by GDP deflator.

Appendix 4. Key Data for Analyses (2): Constructed Data

Year	Rate of obsolescence of technology ρ_t	Rate of depreciation of sold goods and services δ_t	UPM technology knowledge stock (Mil. Eur.) T_t	UPM market value (Mil. Eur.) V_t	Lead time between R&D and commerciali- zation m_t	Internet dependence Finland (standardized 1995 = 1) I_t	UPM energy consumption (Barrel) E_t
1990	6.9	0.037	244.4	211857.9	3.5	0.03	24.2
1991	6.9	0.034	259.6	212865.8	3.4	0.10	29.3
1992	6.9	0.035	274.8	213935.1	3.4	0.14	29.9
1993	7.0	0.041	290.0	215065.9	3.4	0.19	34.1
1994	7.0	0.043	305.2	216257.7	3.3	0.35	36.2
1995	7.0	0.040	308.0	216484.6	3.3	1.00	35.1
1996	7.0	0.045	323.4	217759.0	3.2	1.21	29.0
1997	7.0	0.041	339.6	219176.5	3.2	1.40	30.4
1998	7.1	0.038	356.9	220747.7	3.1	1.83	44.5
1999	7.1	0.036	375.3	222496.1	3.1	2.32	30.8
2000	7.2	0.043	391.4	224076.2	3.0	2.68	22.4
2001	7.2	0.043	406.0	225556.6	2.9	3.10	27.6
2002	7.2	0.043	425.3	227549.9	3.0	4.49	28.2
2003	7.1	0.039	446.0	229751.5	3.1	4.98	23.9
2004	7.0	0.038	465.1	231815.9	3.2	5.21	21.2
2005	7.0	0.035	483.9	233867.3	3.4	5.36	16.0
2006	6.9	0.037	503.9	236048.8	3.5	5.73	15.3
2007	6.8	0.037	521.3	237948.0	3.6	5.81	12.6
2008	6.8	0.032	540.6	240038.8	3.7	5.94	8.9
2009	6.7	0.027	551.9	241250.8	3.8	6.02	11.9
2010	6.7	0.030	567.6	242914.3	3.8	6.25	10.8
2011	6.7	0.035	579.8	244180.2	3.8	6.38	9.2
2012	6.7	0.037	589.2	245152.5	3.8	6.47	8.5
2013	6.7	0.035	594.9	245734.2	3.9	6.58	8.6
2014	6.7	0.033	604.0	246650.6	3.9	6.61	10.2
2015	6.7	0.036	606.4	246888.2	3.9	6.67	16.0
2016	6.7	0.032	613.8	247622.4	3.9	6.72	16.4
2017	6.7	0.033	619.8	248217.5	3.9	6.76	11.3

$T_t = R_{t-m} + (1 - \rho)T_{t-1}$, $T_0 = R_{1-m}/(\rho + g)$, where $g = 0.05$ (average of growth rate of 1996-2000). For ρ_t , see Appendix 3, and for m_t , see Appendix 1.

$V_t = S_t + (1 - \delta)V_{t-1}$, $V_0 = S_1/(\delta + k)$, where $k = 0.01$ (average growth rate of 1995-2000). For δ_t , see Appendix 3.

Appendix 5. Trend in Marginal Productivity of Technology Corresponding with Internal Rate of Return of R&D Investment (1990-2017)

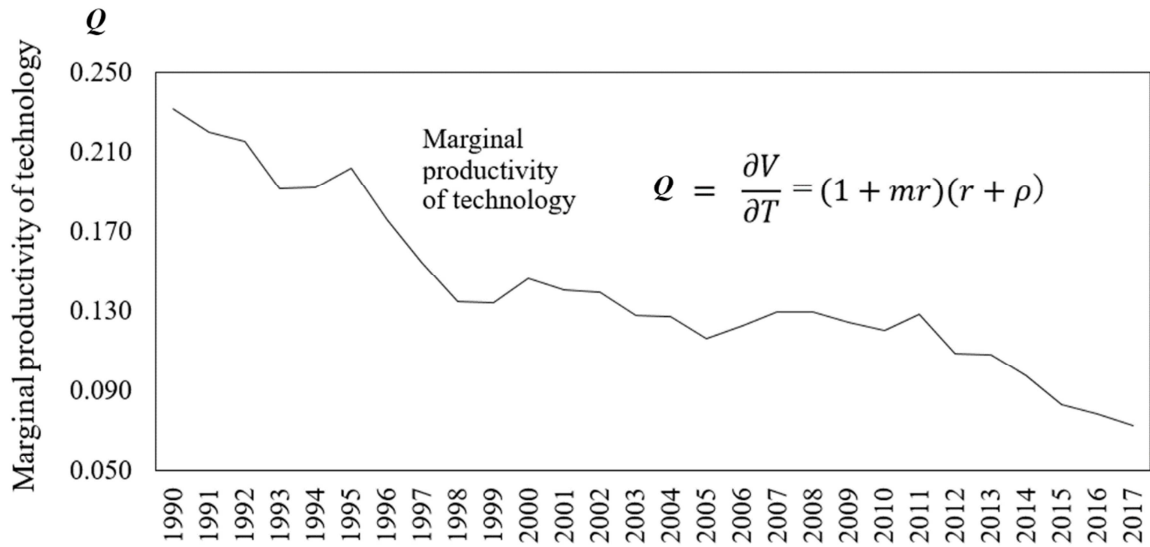


Fig. A1. Trend in UPM's Marginal Productivity of Technology (1990-2017).

Table A2 Trend in Marginal Productivity of Technology Corresponding with Internal Rate of Return of R&D Investment (1990-2017)

Year	r	ρ	m	$Q = (1 + mr)(r + \rho)$	$H = g(\rho + g)(1 + mr)/r(r + \rho)$
1990	0.109	0.069	2.789	0.232	0.401
1991	0.102	0.069	2.835	0.220	0.442
1992	0.098	0.069	2.880	0.215	0.465
1993	0.084	0.070	2.926	0.192	0.576
1994	0.082	0.070	3.284	0.192	0.613
1995	0.087	0.070	3.249	0.202	0.561
1996	0.072	0.071	3.217	0.177	0.720
1997	0.060	0.072	3.145	0.157	0.924
1998	0.047	0.074	3.063	0.139	1.247
1999	0.047	0.076	3.003	0.140	1.257
2000	0.054	0.077	2.933	0.153	1.030
2001	0.050	0.078	2.991	0.148	1.141
2002	0.049	0.060	3.066	0.126	1.178
2003	0.042	0.060	3.214	0.115	1.476
2004	0.041	0.059	3.369	0.115	1.494
2005	0.034	0.059	3.485	0.105	1.899
2006	0.039	0.059	3.573	0.111	1.647

2007	0.043	0.059	3.670	0.118	1.426
2008	0.044	0.059	3.765	0.119	1.419
2009	0.040	0.058	3.803	0.114	1.571
2010	0.038	0.058	3.824	0.110	1.706
2011	0.043	0.058	3.838	0.118	1.444
2012	0.031	0.058	3.857	0.099	2.236
2013	0.030	0.058	3.861	0.098	2.273
2014	0.023	0.058	3.871	0.088	3.190
2015	0.013	0.058	3.879	0.074	6.313
2016	0.009	0.058	3.886	0.070	8.947
2017	0.005	0.058	5.4713	0.064	19.185

$$\frac{dV}{dT} = \frac{\partial V}{\partial T} = aV_t(T_t) \left(1 - \frac{V_t(T_t)}{N}\right) = (1 + m_t r_t)(r_t + \rho_t)$$

r : Long term interest rate¹⁰ for euro area expressed as percent per annum (Source: OECD).

ρ : Rate of obsolescence of technology.

m : Lead time between R&D and commercialization.

g : Increase in rate of R&D at initial stage.

In the case that $H > 1$, $d\rho/dT < 0$ (see Appendix 2). Table 2 demonstrates the stability of H , in which $H > 1$ after 2003.

¹⁰ 'Long-term interest rates refer to government bonds maturing in ten years. Rates are mainly determined by the price charged by the lender, the risk from the borrower and the fall in the capital value. Long-term interest rates are generally averages of daily rates, measured as a percentage. These interest rates are implied by the prices at which the government bonds are traded on financial markets, not the interest rates at which the loans were issued. In all cases, they refer to bonds whose capital repayment is guaranteed by governments. Long-term interest rates are one of the determinants of business investment. Low long-term interest rates encourage investment in new equipment and high interest rates discourage it. Investment is, in turn, a major source of economic growth' (OECD).

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Highlights

Metabolism enabling forest-based ecosystem leader in Europe UPM's resurgence was analyzed.

Dynamism in transforming a forest-based bioeconomy into a digital platform industry was analyzed.

A model tracing the transforming dynamism was developed and its reliability was demonstrated.

Planned obsolescence-driven circular economy initiated by the world leader UPM was analyzed.

Significance of co-evolution between digital-bio and up-down stream coupling was demonstrated.