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A New Paradox of the Digital Economy
- Structural Sources of the Limitation of GDP Statistics

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Abstract

The Internet has dramatically changed the way we conduct business and our daily lives by provided us with unprecedented services and conveniences. However, contrary to such accomplishments, productivity in industrialized countries is now experiences an apparent decline. This has raised the question of a possible productivity paradox in the digital economy. The limitation of GDP statistics in measuring the advancement of the digital economy has thus become an important subject.

This paper analyzed the structural sources of this problem.

Utilizing the results of empirical analyses of national, industrial, and individual behavior in the digital economy, solutions to these critical issues were investigated.

Based on the two-faced nature of information and communication technology (ICT) and the fact that people's preferences extend beyond economic value, the concept of uncaptured GDP was postulated and spinoff dynamism to a new co-evolution among advancement of the Internet, increasing dependence on uncaptured GDP, and a shift in people's preferences was reviewed. This provided new insight and suggested a transformative direction to address the limitation of using GDP statistics in the digital economy.

Keywords: Digital economy; productivity decline; limitation of GDP; uncaptured GDP; soft innovation resources

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1. Introduction

1.1 Myth of GDP

The dramatic advancement of the Internet has generated the digital economy, which has changed the way we conduct business and our daily lives (Tapscott, 1994). The further progression of digitized innovation over the last two decades, such as cloud services, mobile services, and artificial intelligence, has augmented this change significantly. This has accelerated permeation of the Internet into information and communication technology (ICT) in general as illustrated in **Fig. 1** (see the details of this phenomenon in **Appendix 1**) and has provided us unprecedented services and conveniences (DBCDE, 2009).

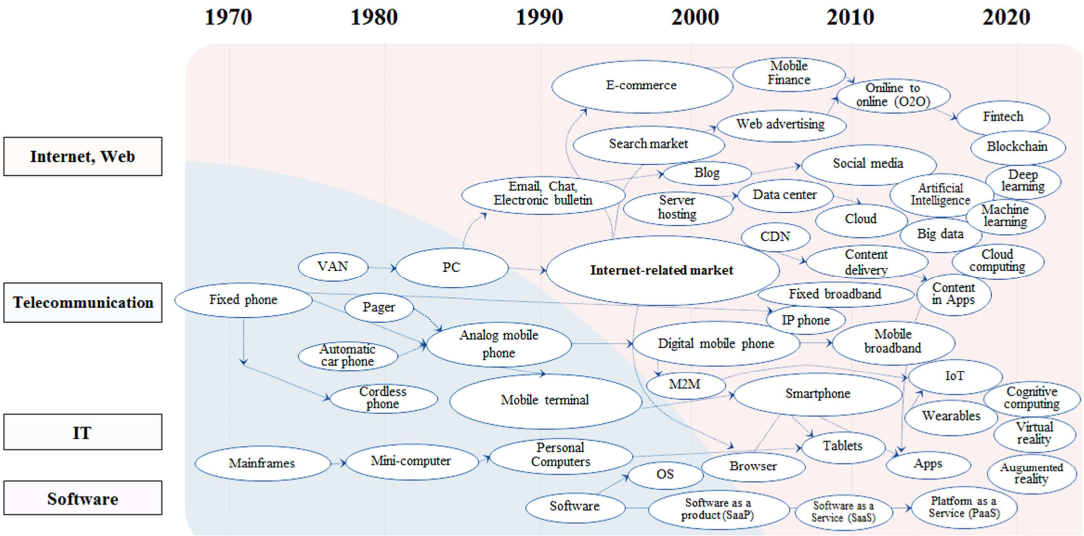

Fig. 1. Illustration of the Digital Innovation Initiated by the Advancement of the Internet.

However, contrary to these accomplishments, productivity in industrialized countries has experienced a structural decline (OECD, 2016; US Council on Competitiveness, 2016), as demonstrated in **Figs. 2** and **3**. These suggest that there may be a productivity paradox in the digital economy.

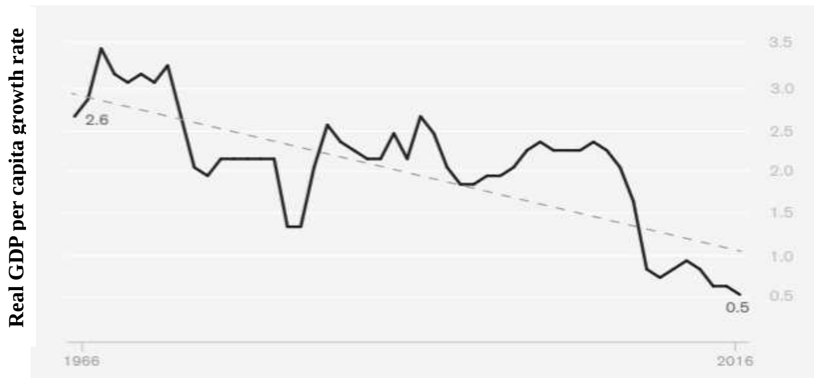

Fig. 2. Trend in Productivity Decline in the US - Real GDP per capita growth rate

(1966-2016).
Source: No Recovery (US Council on Competitiveness, 2016).

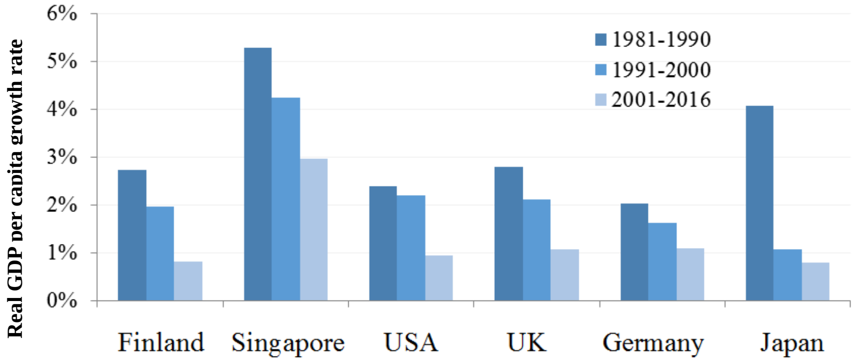

Fig. 3. Trend in Productivity Decline in Six ICT Advanced Countries
- Real GDP per capita growth rate (1981-2016).

Indicate average growth rate in three periods. The country order is world ICT ranking in 2014 (WEF) (see Table 1).
Source: World Economic Outlook Database (IMF, 2017*a*).

Consequently, the limitations of GDP statistics in measuring the advancement of the digital economy have become an important subject (Brynjolfsson et al., 2014; Economist, 2016; US Council on Competitiveness, 2016; IMF, 2017*b*).

OECD has raised the question: "Are GDP and productivity measures up to the challenges of the digital economy?" (Ahmad et al., 2016). The question aims to address seven productivity loop holes that stemd from the advancement of the digital economy: (i) new forms of intermediation of peer-to-peer services, (ii) blurring production boundaries that lead consumers to become producers, (iii) consumer durables and investment, (iv) free and subsidized consumer products, (v) free assets produced by households, (vi) vague transactions through e-commerce, and (vii) mismeasurement of ICT price.

These loop holes can be attributed to the advancement of the digital economy initiated by the Internet and to the role of online intermediaries (OECD, 2010; Copenhagen Economics, 2013).

Furthermore, the social well-being enabled by digitization is feared not to be duly considered in identifying a nation's optimal trajectory. The OECD has explained how the measures of the total value of consumer welfare are at odds with the conceptual basis of measuring GDP and income (Ahmad et al., 2016). This may result in seeking the pseudo optimization in a subsystem. It is definite that the optimal solution in the subsystem does not correspond to the optimal solution in the total system.

Without a reasonable solution to this problem, decision making and policy implementation can become biased and misleading. Given the long stagnation in GDP growth despite its leading position in the world ICT in Finland[1] as demonstrated in **Table 1**, such hopeful interpretation could be justified as "The well-being of the Finnish people

[1] Though Finland has ranked first (2013, 2014) or second (2015, 2016) in the world in terms of ICT, the country' average real GDP growth rates have been 0.57 % pa. (2006-2013) and 0.34% pa. (2014-2016).

has developed in a more positive direction than one might conclude on the basis of the economic development of recent years indicated by GDP data” (Ylhainen, 2017).

Table 1 World ICT Leaders by ICT Rank (2013-2016)

2013	1 Finland	2 Singapore	7 UK	9 USA	13 Germany	21 Japan
2014	1 Finland	2 Singapore	7 USA	9 UK	12 Germany	16 Japan
2015	1 Singapore	2 Finland	7 USA	8 UK	10 Japan	13 Germany
2016	1 Singapore	2 Finland	5 USA	8 UK	10 Japan	15 Germany

Figures indicate world rank by Networked Readiness Index (NRI).

Source: The Global Information Technology Report (WEF, annual issues).

By utilizing the advancement of the digital economy, Finland occupies a leading position in the world regarding ICT advancement and human capital development (Finland is ranked second and top in the world in 2016, respectively) and demonstrates high levels of well-being such as trust, gender parity, happiness, and equality. However, its current economic performance, as indicated by GDP data, is the lowest among countries with advanced ICT, as demonstrated in **Table 2**.

Table 2 Institutional State of Six ICT Advanced Countries in the Digital Economy (2016)

		Finland	**Singapore**	**USA**	**UK**	**Germany**	**Japan**	**References**
Population (million) * 2015		5.5	5.5	321.6	65.1	81.9	126.9	The Global Competitiveness Report 2016-2017 World Economic Forum (WEF, 2016)
ICT (Rank out of 139)		2 <1>	1 <2>	5 <9>	8 <7>	15 <13>	10 <21>	The Global Information Technology Report 2016 (WEF, 2016)
Human capital (Rank out of 130)		1 <2>	13 <3>	24 <16>	19 <8>	11 <6>	4 <15>	The Human Capital Report 2016 (WEF, 2016)
Global competitiveness (Rank out of 138)		10 <3>	2 <2>	3 <5>	7 <10>	5 <4>	8 <9>	The Global Competitiveness Report 2016-2017 (WEF, 2016)
GDP per capita (1000 US$) *2015		42.0	52.9	55.8	43.8	41.0	32.5	The Global Competitiveness Report 2016-2017 (WEF, 2016)
GDP growth rate (% pa at fixed prices) Average	**2006-2013**	0.57	5.85	1.26	0.63	1.46	0.56	World Economic Outlook Database (IMF, annual issues)
	2014-2016	0.34	2.50	2.20	2.36	1.62	0.85	
Trust (Rank out of 21) *2013		2	7	5	12	16	19	Global Teachers Status Index (Varkey Gems Foundation, 2014)
Gender parity (Rank out of 144)		2	55	45	20	13	111	Global Gender Gap Report 2016 (WEF, 2016)
Happiness *2015-2017 (Rank out of 156) <2010-2012>		1 <7>	34 <30>	18 <17>	19 <22>	15 <26>	54 <43>	World Happiness Report 2013, 2018 (The Earth Institute, Columbia University. et. al., 2013, 2018)
Inequality (GINI index) *2010 state		19	45	47	39	35	34	Distribution of Household Income Source (ILO, 2012)

Figures in < > indicate the state in 2013.

We now confront the third productivity paradox, following the earlier computer -initiated productivity paradox (which manifested in the late 1980s to the 1990s and was postulated by Nobel Laureate Solow (1987) but faded with workplace productivity improvement) and the internet-initiated productivity paradox (which manifested in the early 2010s and was postulated by Cowen (2011) and supported by Brynjolfsson et al. (2011)). The third paradox raises a fundamental question regarding the GDP myth in the digital economy.

1.2 New Challenge

As the GDP is considered the most fundamental yardstick in devising economic policies, a large number of studies have attempted to identify the structural sources of the issues stemming from the GDP as a measurement tool in representing the true picture of a digital economy (e.g., Feldstein, 2017; Syverson, 2017; Groshen et al., 2017; US Council on Competitiveness, 2016; Byrne et al., 2016; Dervis et al., 2016). However, no study has provided rational answers to this fundamental question (IMF, 2017*b*).

Authors in previous studies stressed the significance of increasing dependence on uncaptured GDP[2] by postulating that the Internet promotes a free culture that provides utility and happiness to people through its consumption but cannot be captured through GDP data, which measure revenue. This added value of providing people with utility and happiness, which extends beyond economic value, is defined as uncaptured GDP (Watanabe et al., 2015*a*, 2015*b*).

The shift in people's preferences from economic value to the supra-functionality beyond economic value (encompassing social, cultural, and emotional values)[3] induces the further advancement of the Internet, which intensifies the increasing dependence on uncaptured GDP.

Thus, the technological shift from the computer age to the Internet and the abundance of freely available digital products and services in the digital economy have resulted in a new co-evolution among people's shifting preferences, the advancement of the Internet, and the increasing dependence on uncaptured GDP (Watanabe et al., 2015*a*, 2015*b*, 2016*a*, 2016*b*).

Based on these findings, the authors attempted to compare the spin-off dynamism from traditional computer-initiated ICT innovation in the era of the Product of Things (PoT) with internet-initiated ICT innovations in the Internet of Things (IOT)[4] by using their

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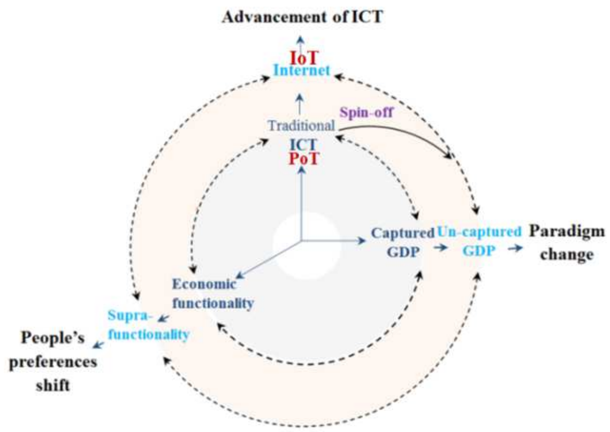
[2] The Internet promotes a free culture that provides utility (satisfaction of consumption) and happiness to people through its consumption but this culture cannot be captured through GDP data which measure revenue. Such utility and happiness constituted uncaptured GDP. This can be defined as added value that provides utility and happiness beyond economic value to people but cannot be measured by traditional GDP accounts (captured GDP) which measure economic value.

[3] Supra-functionality beyond economic value illustrates peoples' shifting preferences which encompass *social* (e.g., creation of and contribution to social communication), *cultural* (e.g., brand value, cool and cute), *aspirational* (e.g., aspiration of traditional beauty), *tribal* (e.g., cognitive sense, fellow feeling), and *emotional* (e.g., perception value, five senses) values (McDonagh, 2008). (See the detail in Fig. 11).

[4] IoT is a system of interrelated computing devices, mechanical and digital machines, objects, animals, or people that are provided with unique identifiers and the ability to transfer data over a network without

framework of co-evolutional among the advancement of ICT, a paradigm change, and a shift in people's preferences as illustrated in **Fig. 4**.



Under the digital economy the innovation stream has spun-off from traditional co-evolution among PoT (Product of Things), GDP increase and economic functionality to IoT (Internet of Things), uncaptured GDP and supra-functionality beyond economic value.

Fig. 4. Spin-off Dynamism Scheme
- Co-evolution among the Internet, Uncaptured GDP, and Supra-functionality.

This concept of spin-off dynamism toward a new co-evolution may shed light on the current critical issues related to the measurement of GDP in the digital economy.

Inspired by this expectation, this study uses the framework of co-evolutionary dynamism and empirical analyses of national, industrial, and individual behaviors in the digital economy to determine solutions to the issues of the measurement of GDP.

First, based on this framework and the results of the above empirical analyses, structural sources of the productivity decline in the digital economy was analyzed (Section 2).

Second, utilizing the findings obtained from this analysis and using intensive reviews of the results of the above empirical analyses, transformation into GDP diminishing structure as a consequence of the above co-evolutionary dynamism was identified as structural sources of the limitation of GDP (Sections 3 and 4).

Third, inspired by the above identification and utilizing the development trajectories of 500 global ICT firms, the transformative challenge against such diminishing structure was investigated (Section 5).

It was identified that the structure of the limitation of GDP measurement in the digital economy could be attributed to the emergence and increase in activities that cannot be captured by GDP including the emergence of new business and blurring of production boundaries, and also to a transformation into GDP diminishing structure encompassing misleading ICT prices and shift to non-monetary consumption. Against such circumstances, global ICT leading firms have been endeavoring to harness soft innovation resources that activate ICT indigenous self-propagating function leading to inducing supra-functionality beyond economic value.

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requiring human-to-human or human-to-computer interaction. PoT transfers products through semi-conductor-to-computer, and computer-to-human interactions.

The structure of this paper is as follows: Section 2 discusses the structural sources of productivity decline in the digital economy. Section 3 analyzes the two-faced nature of ICT. The shift to non-monetary consumption is analyzed in Section 4. Transformative challenges in the digital economy are investigated in Section 5. Section 6 summarizes the noteworthy findings, policy suggestions, and future research.

2. Structural Sources of the Productivity Decline in the Digital Economy

Based on the framework of co-evolution among the advancement of ICT, a paradigm change, and a shift in people's preferences, structural sources of the productivity decline in the digital economy is analyzed in this section.

2.1. Measuring the Digital Economy Scheme

Fig. 5 presents the scheme of measuring the digital economy focusing on the dramatic advancement of the Internet. The advancement of the Internet creates new and unique identical services that include the provision of freebies, easy replication, and mass standardization through the development of online intermediaries (OECD, 2010).

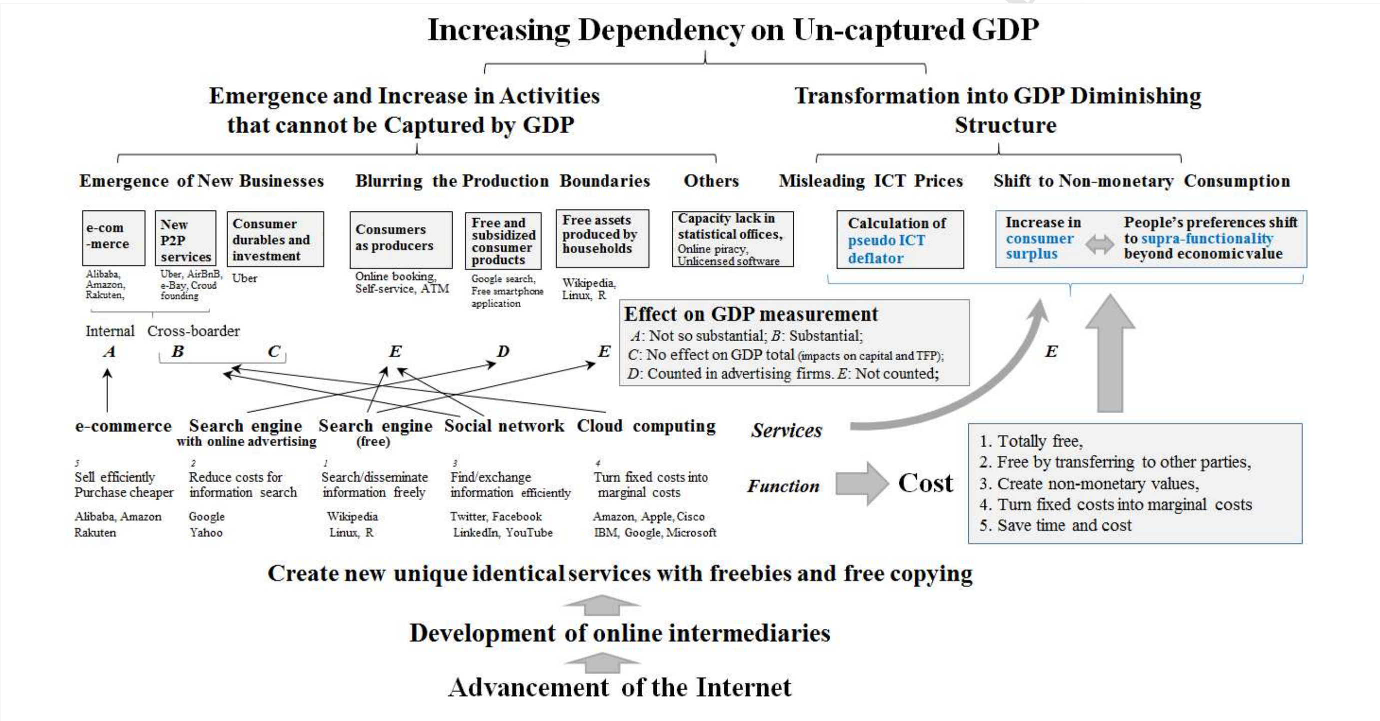

Fig. 5. Scheme of Measuring the Digital Economy.

Original sources:
The Economic and Social Role of Internet Intermediaries (OECD, 2010),
The Impact of Online Intermediaries on the EU Economy (Copenhagen Economics, 2013),
Are GDP and Productivity Measures Up to the Challenges of the Digital Economy? (Ahmad et al., OECD, 2016),
Operationalization of Un-captured GDP (Watanabe et al., 2016*a*).

New and unique identical services include (i) e-commerce as initiated by Alibaba, Amazon, and Rakuten, which sells efficiently and offers inexpensive services; (ii) search engine with online advertising such as Google and Yahoo, with reduced costs for information search services; (iii) free search engines such as Wikipedia, Linux, and R, with free information search and dissemination; (iv) social networks such as Twitter, Facebook, LinkedIn, and YouTube, with services of finding and exchanging information efficiently; and (v) cloud computing platforms such as Amazon, Apple, Cisco, IBM, Google, and Microsoft, with services of turning fixed costs into marginal costs.

These services are provided for free, are free by transferring to other parties, create non-monetary value, turn fixed costs into marginal costs, and save on time and cost.

2.2. Increasing Dependence on Beyond GDP Measurement

2.2.1. Emergence of and Increase in Activities that Cannot be Captured by GDP

This service creation leads to the emergence and increase in activities that cannot be captured by GDP, which include (i) emergence of new businesses such as e-commerce-based transactions, new P2P services (e.g., Uber, AirBnB, e-Bay, and crowd founding), and consumer durables and investment (e.g., Uber); (ii) blurring the production boundaries such as consumers as producers (“prosumers”), free and subsidized consumer products, and free assets produced by householders; and (iii) increasing the capacity lacking in statistical officers, online piracy, and unlicensed software.

2.2.2. Transformation into a GDP-diminishing Structure

The transformation into a GDP-diminishing structure could stem from (i) misleading ICT prices by calculating a pseudo ICT deflator in evaluating the real value of an ICT-driven digital economy and (ii) shifting to non-monetary consumption. This type of consumption results in increased consumer surplus and stems from people’s preferences shifting to supra-functionality, which extends beyond economic value by encompassing social, cultural, and emotional values (see footnote 3).

2.3. Effect on GDP Accounting

As reviewed earlier, because GDP is considered the most fundamental yardstick in devising economic policies, the identification of the loop holes of GDP measurement and the extent of the resultant bias has become a crucial subject under the digital economy. The OECD has been taking a leading role in this identification. It has classified the above effects into *A)* not so substantial, *B)* substantial, *C)* no effect on the GDP total, *D)* counted in certain parties, and *E)* not counted by the GDP frame, as illustrated in Fig. 5 (Ahmad et al., 2016).

Although we expect people to enjoy the well-being that is enabled by the advancement of the digital economy, this well-being is excluded from the GDP accounting and is considered at odds with the conceptual basis of measuring the GDP. This treatment causes fear, which leads to the pseudo optimization of a nation’s trajectory management.

The above analysis on the structural sources of the productivity decline in the digital economy reveals that the two-faced nature of ICT (which leads to ICT price decline) and the shift to non-monetary consumption are critical sources of the productivity decline in the digital economy.

Therefore, the subsequent sections of this paper focus on the analysis of these two issues by utilizing the results of the preceding empirical analyses of national, industrial, and individual behaviors in the digital economy.

3. Two-faced Nature of ICT

Inspired by the preceding analysis of the structural sources of the productivity decline in the digital economy, dynamism leading to the ICT price decrease and its subsequent impacts on GDP measurement are analyzed in this section.

3.1. Calculation of the Pseudo ICT Deflator

By realizing the two-faced nature of ICT as a consequence of a trap in ICT advancement (Watanabe et al., 2015*b*), it was identified that while advancement of ICT generally contributes to enhancing the prices of technology through new functionality development (as demonstrated by the advancement of Apple's iPhones: **Fig. 6)**, the dramatic advancement of the Internet has resulted in the decline of ICT prices because of the characteristics of digital content, including provision of freebies, easy replication, and mass standardization.

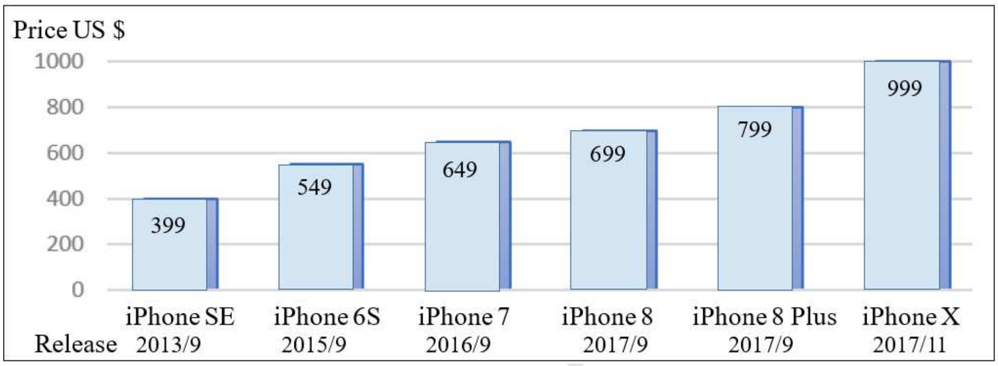

Fig. 6. Trend in iPhone Prices by Function (2013-2017).
Source: Apple press release library.

The continued drop in ICT prices results in the declining marginal productivity of ICT in leading ICT firms (see ***Note***). With such price decrease and intense competition, ICT firms endeavor to introduce new and unique features in their products and services to fulfill preferences of consumers. However, these efforts are not necessarily captured by the GDP, which measures economic value (uncaptured GDP). Mismeasurement of ICT price can be attributed to this phenomenon.

Fig. 7 illustrates this dynamism. Uncaptured GDP, which is illustrated in the top right of the figure, is produced efforts such as outsourcing price decreasing factors and utilization of soft innovation resources (for more details, see Section 5).

Fig. 8 supports this dynamism by illustrating the trends in ICT price decline and its sources, namely, Internet dependence and the ICT stock[5] increase in world ICT leaders Finland and Singapore[6] in the period of 1994-2011.

[5] ICT stock encompasses capital services provided by assets derived from the advancement of ICT, including digital innovations such as computer hardware and equipment, telecommunication equipment, and computer software and services as illustrated in Fig. 1 into which the Internet has been permeating, as illustrated in Fig. A1 in Appendix 1 (for more details on this structure, see Watanabe et al., 2015*a*).

[6] Finland and Singapore shared the top and second position in the world ICT rankings as shown in Tables 1 and 2.

Both ICT leaders demonstrated clear evidence of the two-faced nature of ICT. That is, the advancement of ICT (represented by ICT stock increase) leads to increased prices of ICT, whereas the advancement of the Internet leads to decreased prices of ICT.

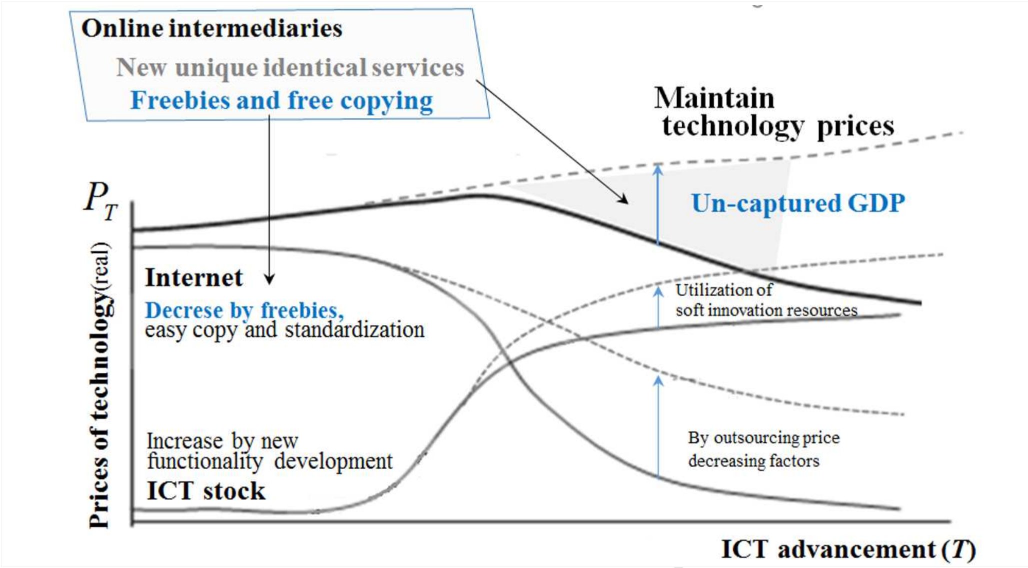

Fig. 7. Dynamism of ICT Price Decrease as a Consequence of Its Two-faced Nature.

Original source: New Paradigm of ICT Productivity – Increasing Role of Uncaptured GDP and Growing Anger of Consumers (Watanabe et al., 2015*a*).

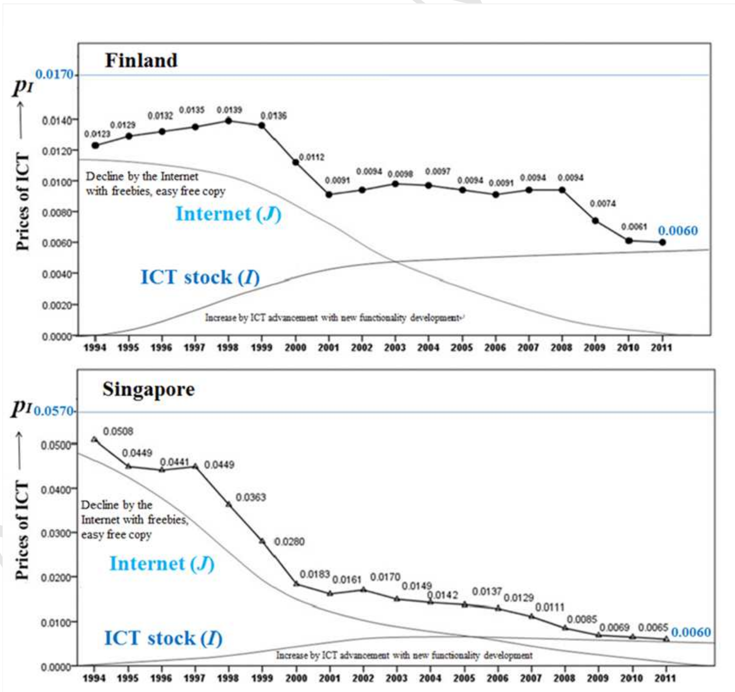

Fig. 8. Trends in ICT Prices in World ICT Leaders: Finland and Singapore *(1994-2011)*.

Original source: New Paradigm of ICT Productivity – Increasing Role of Uncaptured GDP and Growing Anger of Consumers (Watanabe et al., 2015*a*).

Given that firms seek profit maximization in a competitive market, their marginal ICT productivity corresponds to the relative price of ICT, and the contribution of ICT to the growth rate can be attributed to the product of this productivity and R&D intensity (R&D expenditure per sales) (see ***Note***). Therefore, the decrease in ICT price results in the stagnation of growth, as postulated by Cowen (2011) (see Section 3.2).

Under this dynamism, ICT prices (ICT deflator) calculated without uncaptured GDP lead to a pseudo deflator, which increases as uncaptured GDP increases, thus resulting in the devaluation of the actual (real) value of the digital economy. The actual deflator should be calculated using gross utility, which considers the uncaptured GDP. This deflator decreases as ICT advances and the subsequent uncaptured GDP increases, which leads to the appreciation of the actual (real) value of the digital economy. **Fig. 9** explains how this confusion results in the miscalculation of the ICT deflator.

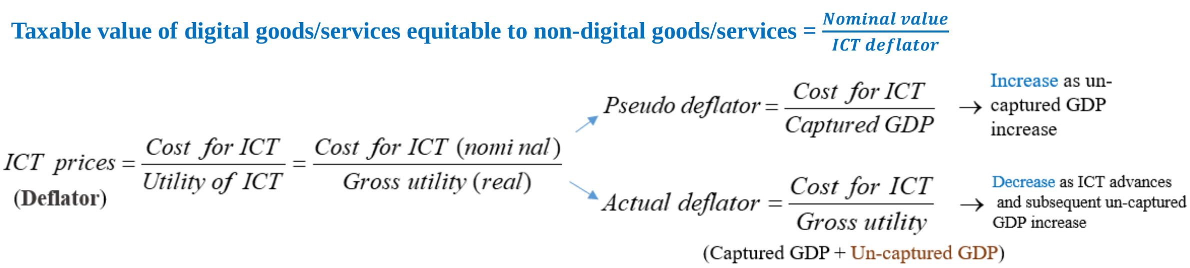

Fig. 9. Scheme in Calculating the Pseudo ICT Deflator.

Given the fairness principle for taxation, digital goods/services should be assessed in an equitable way to non-digital goods/services.

3.2. Two Faces of ICT in 500 Global ICT Firms: Bipolarization

The preceding analysis demonstrates clear evidence of the two-faced nature of ICT, but it depends on national-level macro analysis that uses aggregated data. To confirm this result using micro data, which represent actual competitive behavior in the digital r

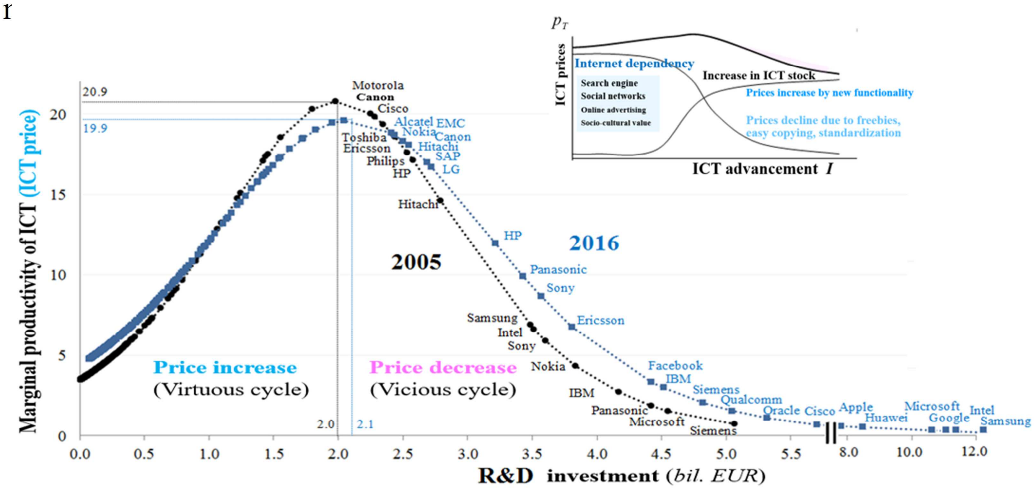

Fig. 10. Bipolarization of ICT Price Increase and Decrease in 500 Global ICT Firms (2005, 2016).

Original source: The Transformative Direction of Innovation toward an IoT-based Society: Increasing Dependency on Uncaptured GDP in Global ICT Firms (Naveed et al., 2018).

Fig. 10 illustrates the trends in the decrease of ICT prices due to ICT advancement of 500 global ICT firms in 2005 and 2016 (see **Appendix 2** the details of the analytical framework).

Provided that global ICT firms seek the profit maximum strategy in the competitive global market, their ICT prices are represented by the marginal productivity of ICT. In addition, given that the Internet has been permeating into ICT in general, the ICT advancement efforts of global ICT firms are represented by their gross R&D investment (incorporating all ICT advancement R&D, including the internet-relevant R&D) (see Figs. 1 and A1).

Fig. 10 shows the bipolarization between highly R&D-intensive firms and relatively non-intensive firms. The former experiences a price decrease as a consequence of ICT advancement through R&D investment increase, and the latter maintains a virtuous cycle as prices increase with the increase in R&D investment.

This bipolarization can be attributed to the logistic growth nature of this ICT-driven trajectory[7]. The former's behavior demonstrates productivity decline as ICT advances, a consequence of the digital economy.

Fig. 10 demonstrates how the two-faced nature of ICT advances over time and during the development of digitization. The price decrease firms are only 16 out of the 500 global ICT firms in 2005, but they increase to 25 in 2016, as shown in **Table 3**.

Table 3 R&D-intensive Global ICT Firms Confronting to Productivity Decline (2005, 2016)

		2005	2016
Productivity declining firms	1	**Siemens** (Germany)	**Samsung Electronics** (South Korea)
	2	**Microsoft** (USA)	**Intel** (USA)
	3	**Panasonic** (Japan)	**Google** (USA)
	4	**IBM** (USA)	**Microsoft** (USA)
	5	**Nokia** (Finland)	**Huawei** (China)
	6	**Sony** (Japan)	**Apple** (USA)
	7	**Intel** (USA)	**Cisco Systems** (USA)
	8	**Samsung Electronics** (South Korea)	**Oracle** (USA)
	9	**Hitachi** (Japan)	**Qualcomm** (USA)
	10	**Hewlett-Packard** (USA)	**Siemens** (Germany)
	11	**Philips Electronics** (Netherlands)	**IBM** (USA)
	12	**Ericsson** (Sweden)	**Facebook** (USA)
	13	**Toshiba** (Japan)	**Ericsson** (Sweden)
	14	**Cisco Systems** (USA)	**Sony** (Japan)
	15	**Canon** (Japan)	**Panasonic** (Japan)
	16	**Motorola** (USA)	**Hewlett-Packard** (USA)
	17		**LG Electronics** (South Korea)
	18		**SAP** (Germany)
	19		**Hitachi** (Japan)
	20		**Canon** (Japan)
	21		**Nokia** (Finland)
	22		**EMC** (USA)
	23		**Alcatel-Lucent** (France)
	24		**Toshiba** (Japan)
	25		**Amazon** (USA)

[7] The indigenous and unique features of ICT include a logistic growth nature and a two-faced nature.

		Productivity increasing firms **484** (out of 500)	**Productivity increasing firms** **475** (out of 500)

Furthermore, highly R&D-intensive firms are confronting the stagnation of sales, as their sales growth rate decreases over time, while relatively non-intensive firms enjoy sales increases as the sales growth rate increases, as shown in **Table 4.** Given that stagnation of sales in highly R&D-intensive firms can be attributed to R&D investment centered by the internet-relevant R&D, this contrast corresponds to Cowen's notion of the internet-oriented productivity paradox (Cowen, 2011).

Table 4 Contrast of Sales Growth Rate between Highly R&D-intensive and Non R&D-intensive Global ICT Firms (2005-2016) - Average of sales growth rate (% *p.a*)

Highly R&D-intensive firms

	Samsung	Google	Microsoft	Apple	Amazon
2005-2008	14.5	72.6	13.3	38.5	25.5
2009-2012	14.2	27.5	8.8	53.5	38.7
2013-2016	9.7	24.0	8.7	27.5	28.0

Relatively non R&D-intensive firms

	Electronic Arts	Taiwan Semiconductor	Accenture	Kyocera	Free Scale
2005-2008	1.9	9.7	0.8	0.1	-1.5
2009-2012	7.4	15.9	5.8	12.4	0.8
2013-2016	8.0	21.6	14.6	18.6	4.0

Data sources: Same as Fig. 10.

All these results support the supposition of the two-faced nature of ICT, which is one of the critical structural sources of productivity decline in the digital economy as analyzed in Section 2.

Note Price, Productivity and Growth

Contribution by traditional factors | technology (TFP) | TFP

$$Y = F(X,T) \qquad \frac{\Delta Y}{Y} = \Sigma\left(\frac{\partial Y}{\partial X}\cdot\frac{X}{Y}\right)\frac{\Delta X}{X} + \left(\frac{\partial Y}{\partial T}\cdot\frac{T}{Y}\right)\frac{\Delta T}{T} \approx \Sigma\left(\frac{\partial Y}{\partial X}\cdot\frac{X}{Y}\right)\frac{\Delta X}{X} + \frac{\partial Y}{\partial T}\cdot\frac{R}{Y}$$

Elasticity | Elasticity

$$Since\ \frac{\partial Y}{\partial T} = \frac{p_T}{p_Y},\ TFP = \frac{p_T}{p_Y}\cdot\frac{R}{Y}$$

$$\frac{p_T}{p_Y}\cdot\frac{R}{Y} \rightarrow p_T\ decrease \rightarrow \frac{\Delta Y}{Y}\ decrease$$

Y: GDP, X: traditional production factors (labor and capital), T: technology stock ($\Delta T \approx R$), R: R&D investment, p_T, p_Y : prices of technology and products

Elasticity is the measurement of how responsive an economic variable (e.g., T) is to a change in another (e.g., Y). The elasticity of T to Y (T elasticity to Y) ε_{YT} implies a 1% increase in T increases ε_{YT} % increase in Y and represents the efficiency of Y in the inducement of T.

Since $\epsilon_{YT} = \frac{\partial lnY}{\partial lnT} = \frac{\partial Y}{\partial T}\cdot\frac{T}{Y}$, Productivity $\frac{Y}{T} = \frac{1}{\epsilon_{YT}}\cdot\frac{\partial Y}{\partial T}$ Therefore, given the certain period with stable elasticity, T productivity is proportional to marginal productivity of T.

4. Shift from Monetary to Non-monetary Consumption

Similar to Section 3, inspired by the findings identified in Section 2, dynamism leading to shift to non-monetary consumption and its impacts on GDP measurement are analyzed in this section.

4.1. Shift from Economic Functionality to Supra-functionality

Fig. 5 illustrates the significance of the shift from monetary to non-monetary consumptions in the digital economy as one of the source of transforming economy into a GDP-diminishing structure.

As a consequence of historical change in the experience of nations and in accordance with the general shift from a commodity-oriented society to a service-and information-oriented society, consumer preference is generally assumed to steadily shift from an economic functionality-driven preference (captured by the GDP) to supra-functionality preference, which extends beyond economic value-driven preference. Here, supra-functionality encompasses social, cultural, aspirational, tribal, and emotional values as illustrated in **Fig. 11**. These values are not necessarily captured by the GDP (McDonagh, 2008). This shift seems to have a significant relevance to consumer surplus, as shown in Fig. 5, and an increasing dependence on uncaptured GDP as illustrated in Fig. 4.

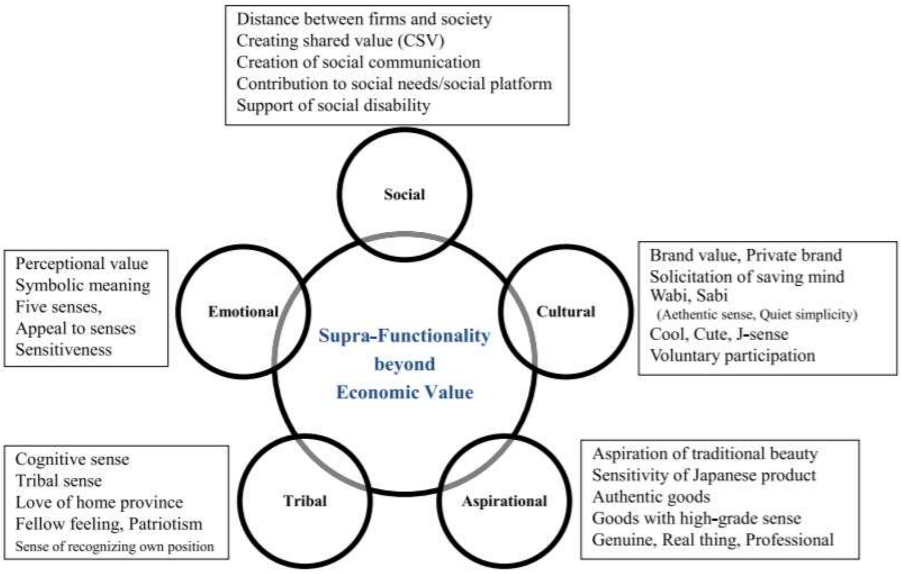

Fig. 11. Basic Concept of Supra-functionality beyond Economic Value.
Original source: New Paradigm of ICT Productivity – Increasing Role of Uncaptured GDP and Growing Anger of Consumers (Watanabe et al., 2015*a*).

This shift can be clearly observed in Japan, which is extremely sensitive to institutional innovation against external shocks and crises (Hofstede, 1991, Watanabe, 2009). **Fig. 12** illustrates this shift as demonstrated by Japan's *Public Opinion Survey Concerning People's Lifestyles*[8] which is conducted annually by Japan's Cabinet Office (see **Appendix 3**).

[8] In this survey, personal preference for future life is chosen from three options: (i) Richness of the heart-spiritual happiness (*because a reasonable level of material affluence has been achieved, future emphasis should be put on spiritual happiness and a comfortable life.*), (ii) Wealth of things – material affluence (*emphasis should still be put on material affluence for future life.*), or

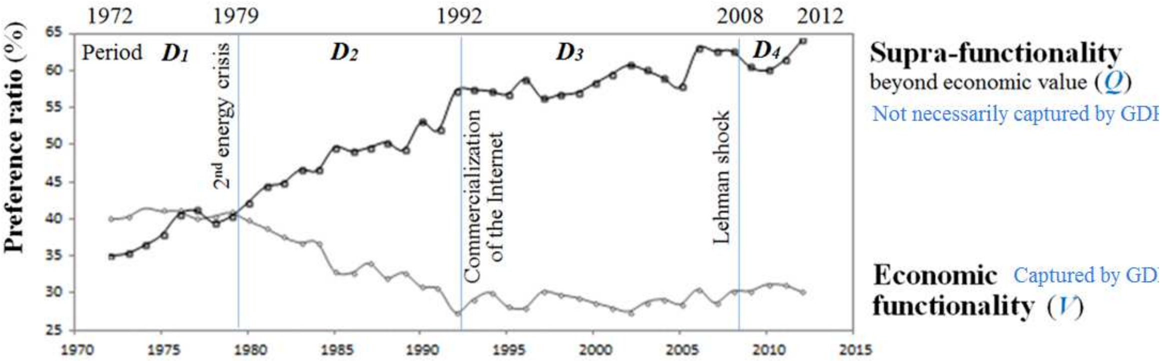

Fig. 12. Trends in the Shift of Preferences in Japan *(1972-2012).*

Source: National Survey of Lifestyle Preferences, annual issues (Japan Cabinet Office, 2012).

As shown in Fig. 12, contrary to the steady decline in people's preference in economic functionality (*V*), supra-functionality beyond economic value (*Q*) steadily increases and exceeds *V* in 1979, which is the year of the second energy crisis. Whereas *Q* continues to increase steadily, *V* declines to its lowest level in 1992, which is the year that immediately follows the commercialization of the Internet in 1991. It has remained at the same level since then. A decline in *Q* due to the Lehman shock in 2008 is followed by a sharp recovery. Consequently, a shifting trend from *V* to *Q* can be classified into four phases: *Phase 1* (1972-1979), *Phase 2* (1980-1992), *Phase 3* (1993-2008), and *Phase 4* (2009-2012) as indicated by D_1 - D_4 in Fig.12, respectively.

This shift in people's preference induces the advancement of the Internet, which, in turn, accelerates the shift in people's preferences. Therefore, the advancement of the Internet and the shift to supra-functionality lead to a co-evolutionary dynamism, as illustrated in Fig. 4. Under this co-evolutionary dynamism, conflict occurs between captured GDP and uncaptured GDP during this shift. This conflict leads to growing anger among consumers (Watanabe et al., 2015a), thus resulting in the decline of consumption. This situation is a source of great stagnation (Cowen, 2011) from the demand side.

During the great stagnation due to the conflict in ICT advancement, which has a two-faced nature of ICT on the supply side, the only possible option for sustainable growth comes from enhancing utility (satisfaction of consumption) through the Internet inducement of ICT stock, as both the marginal propensity of consume and marginal productivity of ICT decline (Watanabe et al., 2015*a*).

Consequently, the effective enhancement of utility as a function of the Internet and ICT stock can be the key for sustainable growth under the productivity decline and subsequent economic stagnation in the digital economy.

Furthermore, because consumption constitutes a major part of GDP (55-70% of GDP in five countries in Table 2 while 40 % in Singapore), the extent to which GDP effectively reflects utility to consumption would be a key measure for assessing the state of uncaptured GDP dependence[9].

(iii) Cannot identify explicitly. While the second option corresponds to a preference for economic functionality, the first option corresponds to that of supra-functionality beyond economic value (Watanabe et al., 2011).

[9] A lower level of utility reflection to consumption suggests a higher level of uncaptured GDP

4.2. Shift in Consumer Preferences
- Measurement of Elasticity of Utility to Consumption

Utility is governed by ICT stock and Internet dependence in the digital economy. Therefore, the elasticity of utility to consumption[10] can be measured by the sum of elasticity of ICT stock to consumption and that of Internet dependence to consumption. **Table 5** compares the elasticity of consumption in six countries in 2013.

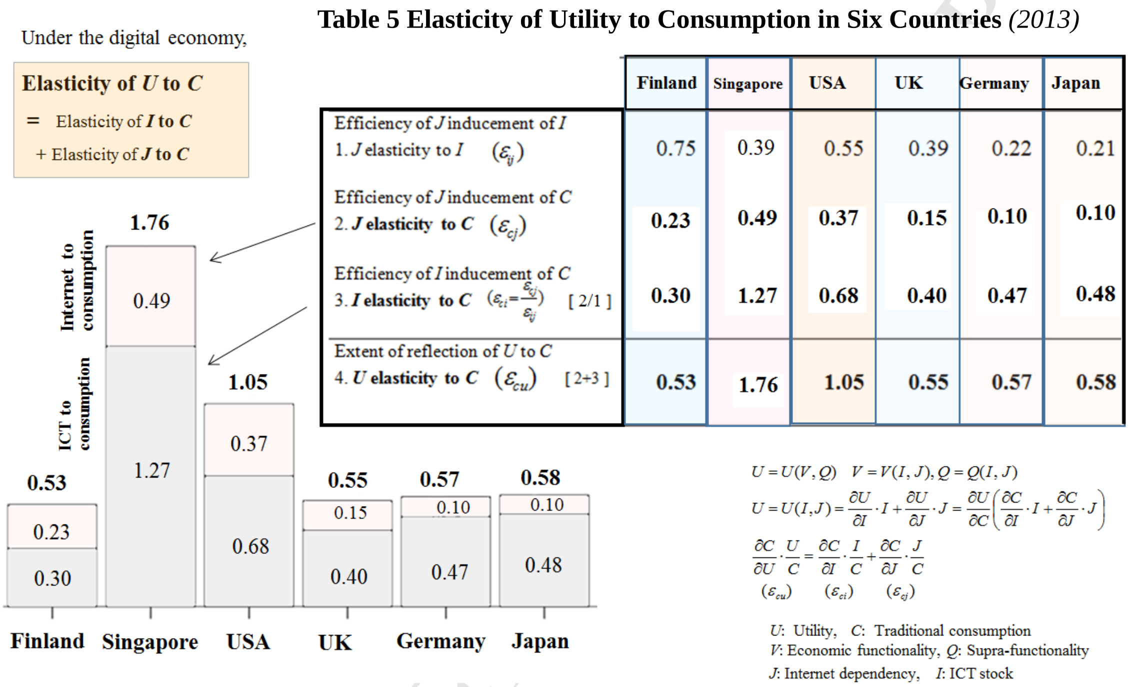

Fig. 13. Elasticity of Utility to Consumption in Six Countries *(2013).*

Original source:
Dependence on Uncaptured GDP as a Source of Resilience beyond Economic Value in Countries with Advanced ICT Infrastructure: Similarities and Disparities between Finland and Singapore (Watanabe et al., 2015*a*).

Fig. 13 presents the contrast of this elasticity in six countries. Singapore demonstrates conspicuously high elasticity, whereas Finland demonstrates the opposite: it has the lowest level among the six countries.

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dependence.
[10] Elasticity is the measurement of how responsive an economic variable (X) is to a change in another (W). The elasticity of X to W (X elasticity to W)
ε_{WX} implies a 1% increase in X increases ε_{WX} % increase in W and represents the efficiency of X in the inducement of W (see ***Note*** in Section 3).

With this observation in mind, **Fig. 14** illustrates the contrast in the development trajectories between these world ICT leaders. This figure clearly demonstrates the difference between Finland and Singapore with respect to development trajectory. Finland effectively utilizes the Internet (*J*) in inducing ICT stock (*I*), as demonstrated by its highest Internet elasticity to ICT stock. Its induced ICT stock contributes significantly to satisfying consumer preference for supra-functionality beyond economic value rather than economic functionality only. Consequently, increased ICT does not reflect increased consumption, which is measured by the GDP value, thus resulting in a low GDP growth rate. Although its ICT significantly contributes to supra-functionality beyond economic value, it cannot necessarily be captured by GDP.

Singapore's behavior is contrary to that of Finland. Although Singapore's ICT inducement by the Internet is smaller than that of Finland, it contributes largely to consumer preference for economic functionality, which is captured by the GDP value, thus leading to a high GDP growth rate (5.85 % in Singapore vs 0.57 % in Finland on average for 2006-2013 as compared in Table 2).

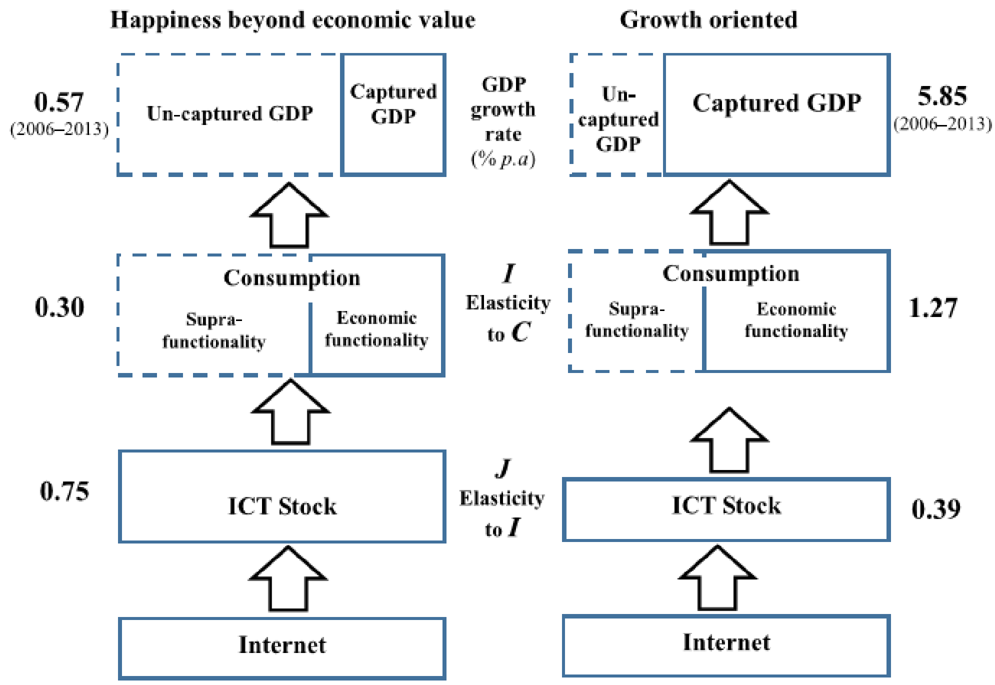

Fig. 14. Contrasting the Development Trajectories of the World ICT Leaders Finland and Singapore (2013)**.**

J: Internet dependency, *I*: ICT stock, *C*: Consumption. GDP growth rate is an average between 2006 and 2013.

Original source:
Dependence on Uncaptured GDP as a Source of Resilience beyond Economic Value in Countries with Advanced ICT Infrastructure: Similarities and Disparities between Finland and Singapore (Watanabe et al., 2015*a*).

4.3. Measurement of Uncaptured GDP

In the spin-off dynamism that leads to the co-evolution among the Internet, uncaptured GDP, and supra-functionality beyond economic value, as illustrated in Fig. 4, stimulation from both Internet advancement and the inducement of the shift of people's preferences drives the uncaptured GDP dependence. The equilibrium of both inertia leads to a rising power emerging uncaptured GDP.

With this understanding, the uncaptured GDP of the world ICT leaders Finland and Singapore is measured. Here, the inducement of the shift of people's preference depends on the elasticity of utility to consumption.

Fig. 15 compares the trends in captured and uncaptured GDP between both countries over the period of 1994-2013.

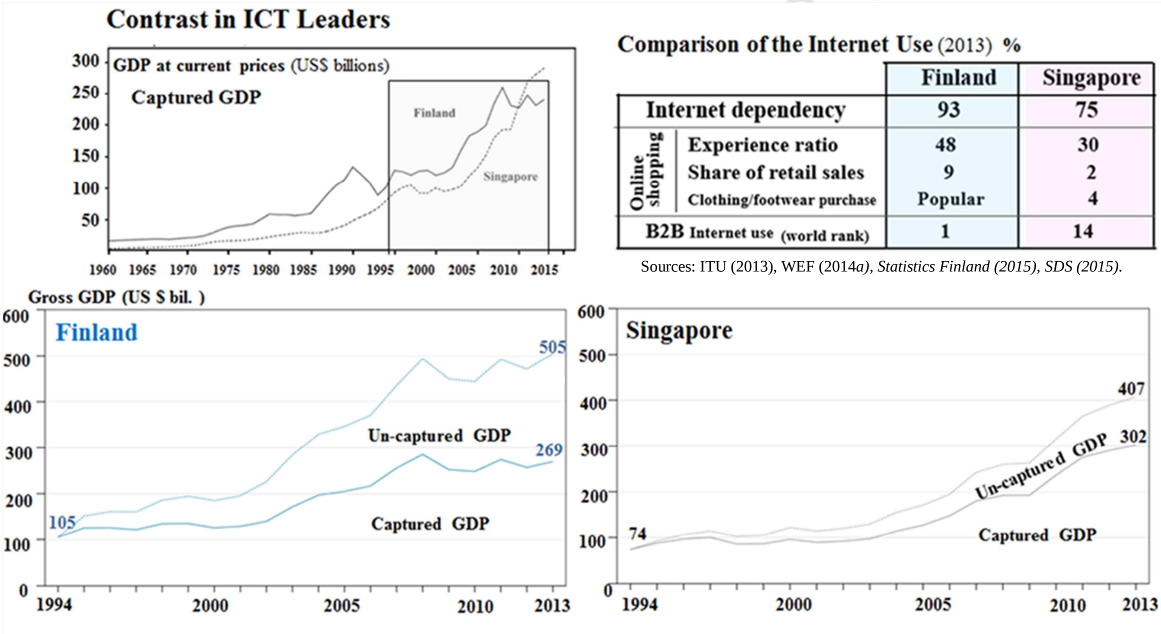

Fig. 15. Comparison of Captured and Un-captured GDP between Finland and Singapore (1994-2013).

Original source:
Operationalization of Un-captured GDP: Innovation Stream under New Global Mega-trends (Watanabe et al., 2016*a*).

As shown in the figure, although Finland's captured GDP is lower than that of Singapore after 2010, Finland has a higher gross GDP (the sum of captured and uncaptured GDP) than Singapore does. This result agrees with the previous estimate comparing the elasticity of utility to consumption and suggests that Finland has shifted largely to uncaptured GDP dependence, whereas Singapore has maintained its traditional GDP dependence.

5. Transformative Challenges in the Digital Economy

Inspired by the findings obtained from Sections 3 and 4 identifying the transformation into GDP diminishing structure, transformative challenge initiated by the forefront of global ICT firms against such structure is investigated in this section. An empirical analysis utilizing the development trajectories of 500 global ICT firms is conducted.

5.1 Key Features of the Digital Economy

As analyzed in the preceding sections of the paper, key features of the digital economy can be highlighted as follows:

(i) Expanding at a tremendous pace,

(ii) Value can be provided free of charge,

(iii) ICT prices decrease and productivity declines,

(iv) Digital goods are mobile and intangible, thus leading to a substantially different business model,

(v) The boundary between consumer and producer is thin and creates a "prosumer,"

(vi) Barriers of entry are low which makes companies innovate seamlessly,

(vii) Companies can fully enjoy network externalities and subsequent self-propagation,

(viii) Companies are bipolarized between those enjoy network externality and not,

(ix) Digital companies have a tendency towards gigantic monopoly, and

(x) Contrary to traditional monopoly, this new monopoly can enhance convenience.

These features remind us of growing significance of the analysis of the transformative innovation stream in the new co-evolution spinning off from traditional co-evolution among PoT, GDP and economic functionality to IoT, uncaptured GDP and supra-functionality beyond economic value, as illustrated in Fig. 4 for overcoming the current crucial problem in the digital economy: the limitation of GDP.

Analyses in the preceding sections identified that structural sources of this crucial problem can be attributed to ICT price decrease and subsequent marginal productivity decline in supply side, and a shift in people's preferences to supra-functionality beyond economic value in demand side.

These features prompt us to envision transformative direction to address this crucial problem in the digital economy which can be expected in the forefront endeavor of highly R&D-intensive global ICT firms for the above new co-evolution.

5.2 Transformative Direction of Leading Global ICT Firms

(1) Transformative Direction of Highly R&D-intensive Firms

While advancement of the digital economy has been largely depend on the strong initiative of highly R&D-intensive global ICT firms, they are confronting to the dilemma of R&D investment at the forefront of the digital economy, that is marginal productivity declines as R&D investment increases as revealed in Fig. 10.

Given the shift in people's preferences to supra-functionality beyond economic value in the foregoing co-evolution, possible solution to this unanswered question can be expected by exploring supra-functionality by means of new sophisticated innovation not depending on tough R&D investment.

Since such functionality can be induced by ICT indigenous self-propagating function (Watanabe et al., 2004), a key to this solution depends on how to activate this self-propagating function as illustrated in **Fig. 16**. Fig. 16 illustrates a dynamism activating self-propagating function by means of effective utilization of sleeping resources (not commercially operating cars and drivers) initiated in ridesharing revolution by Uber.

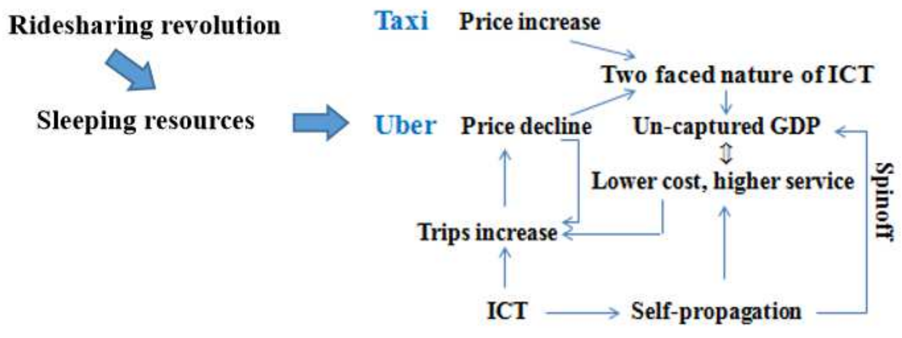

Fig. 16. Activation of self-propagating Function by Means of Effective Utilization of Sleeping Resources – A Case of Ridesharing Revolution by Uber.

Confronting to productivity decline in the digital economy, highly R&D-intensive global ICT firms have been endeavoring to transform into a new business model that creates supra-functionality by not largely depending on R&D investment.

Key of this this business model is how effectively induce functionality that leads to creating supra-functionality by activating potential self-propagating function.

Fig. 17 demonstrates transformative trajectories of highly R&D-intensive 25 global ICT firms in 2016 toward a new business model. These firms have been confronting to productivity decline as illustrated in Fig. 10 and tabulated in Table 3. In order to address such critical circumstances, these firms have been endeavoring to effectively create new functionality that leads to exploring supra-functionality beyond economic value corresponding to a shift in people's preferences as reviewed in Section 4.1.

Aiming at accomplishing such endeavor without depending largely on R&D investment which may accelerate productivity decline, these firms have been making every effort in activating their potential self-propagating function which induces functionality development (Watanabe et al., 2004).

Given the logistic growth nature of ICT[11], development trajectories of global ICT firms can be depicted by R&D-driven logistic growth function (see the details of

[11] ICT in which network externalities function to alter the correlation between innovations and institutional systems which creates new features of the innovation leading to exponential increase. Schelling (1998) portrayed an array of logistically developing and diffusing social mechanisms stimulated by these interactions.

mathematical explanation in **Appendix 2**). While development trajectory based on simple logistic growth (*SLG*) saturates at certain upper limit of development (carrying capacity) which is assumed constant through the development process, in particular innovations, the correlation of the interaction between innovation and institutional systems (encompassing not only business but also socio-cultural environments governing people's preferences) displays a systematic change in the process of growth and leads to the creation of a new carrying capacity in the process of the development. Mayer and Ausbel (1999) introduced an extension of the widely used logistic model of growth by allowing it for a sigmoidally increasing carrying capacity (see the mathematical details in **Appendix 2**). They stressed that, "evidently, new technologies affect how resources are consumed, and carrying capacity would change." This explains unique development process of ICT, which develops and diffuses by altering the carrying capacity or creating a new carrying capacity in the process. They then proposed logistic growth within a dynamic carrying capacity (*LGDCC*) to model these behaviors.

This dynamism can be considered corresponding to ICT indigenous self-propagating function incorporation (Watanabe et al., 2004). Therefore, the magnitude of the self-propagating function can be estimated by the ratio of dynamic carrying capacity that leads development trajectory after incorporating the self-propagating function and development trajectory estimated by *SLG* that demonstrates development level when no self-propagating function incorporates (Watanabe et al., 2017*c*).

Fig. 17 demonstrates trends in marginal productivity of ICT and this magnitude in highly R&D intensive global ICT firms in 2016 (see the details of analysis in **Appendix 2**).

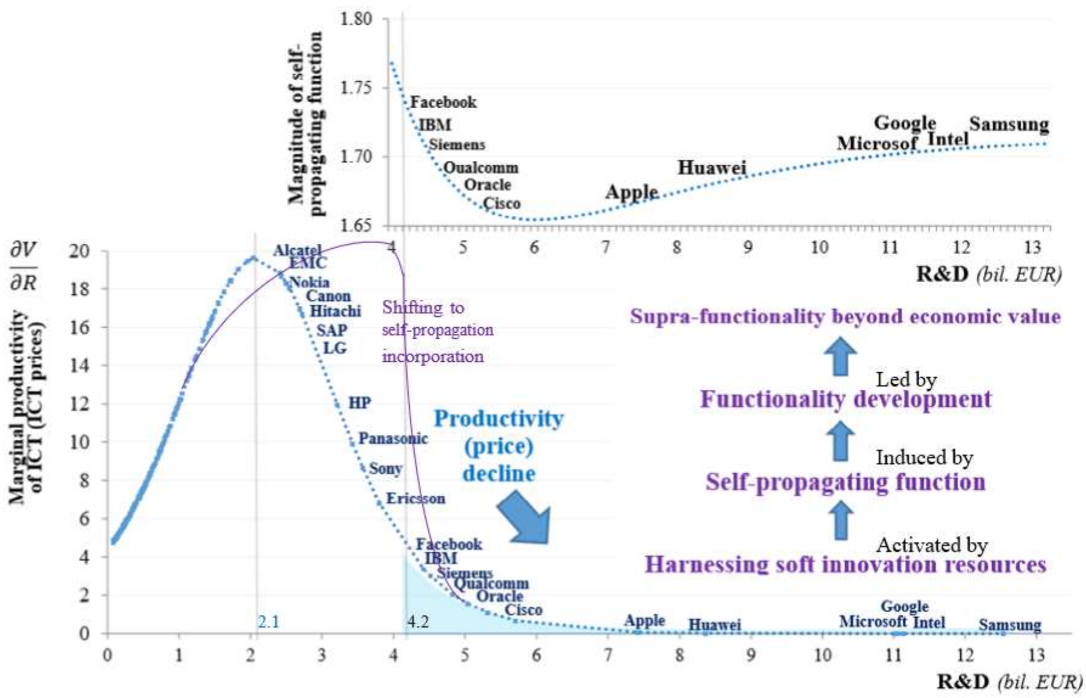

Fig. 17. Transformative Direction of Highly R&D-intensive Global ICT Firms (2016).

Looking at Fig. 17 we note that activation of self-propagating function enables to maintain marginal productivity increase with higher level of R&D investment by shifting the inflection point of R&D investment that changes a virtuous cycle between R&D investment and marginal productivity to a vicious cycle (marginal productivity declines as R&D investment increases) as illustrated by purple line in the lower left in Fig. 17. However, notwithstanding such effect, extremely highly R&D-intensive firms (12 firms out of 25 firms) cannot avoid marginal productivity decline stream.

Consequently, they depend on soft innovation resources like sleeping resources in Fig. 16. Since effective utilization of these soft innovation resources activate self-propagating function indigenous to ICT (Watanabe, 2013. Watanabe et al., 2016*b*, 2017*a*, 2017*b*, 2017*c*; Naveed et al., 2017), this utilization induces functionality development leading to developing supra-functionality beyond economic value without depending on R&D investment increase.

These resources can be attained in reaction to the marginal productivity of ICT decline due to the high dependence on ICT, which has a two-faced nature. Thus, survival strategy of extremely highly R&D-intensive global ICT firms depends on the construction of the platform which demonstrates the above dynamism.

(2) Transformative Direction of ICT-driven Business Model

Confronting to such dilemma of R&D investment and productivity decline while sustainable R&D investment is essential for new innovation, highly R&D-intensive global ICT firms have been endeavoring to transform into a new business model that creates optimal balance of self-propagating function creation and sustainable R&D investment.

Fig. 17 demonstrates that while top R&D 6 firms as Samsung, Intel, Google, Microsoft, Huawei and Apple have succeeded in constructing a virtuous cycle between sustainable R&D investment and magnitude of self-propagating function increase despite marginal productivity decline, another 6 firms out of extremely high-R&D intensive 12 firms are not necessary succeful in constructing such a cycle.

Given such a tough challenge, learning from a successful virtuous cycle accomplished by top R&D 6 firms may provide insightful suggestion in finding the solution of current crucial problem in the digital economy, the limitation of GDP by solving two structural questions as ICT price decrease and subsequent marginal productivity decline in supply side, and a shift in people’s preferences to supra-functionality beyond economic value in demand side.

Effective utilization of soft innovation resources leads a way in satisfying both demands simultaneously. Soft innovation resources activate self-propagating function by awaking its potential incorporating in ICT firms, which induces functionality development and this induced functionality explores supra-functionality beyond economic value. Thus, simultaneous solution to satisfying demands from both supply side and demand side can be provided.

Fig. 18 demonstrates significant direction of ICT-driven disruptive business models which leading global ICT firms have been endeavoring by harnessing the vigor of soft innovation resources.

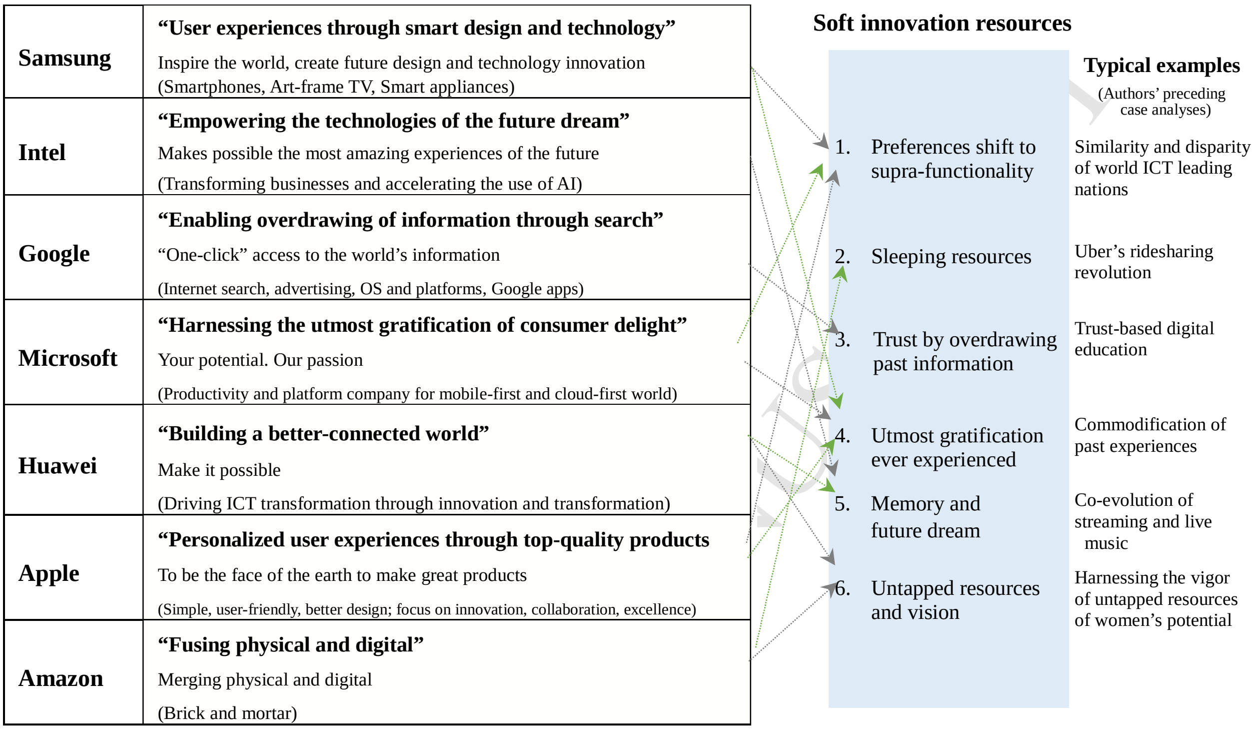

Fig. 18. Significant Direction of ICT-driven Disruptive Business Models.

While Amazon was not included in top R&D intensive firms in 2016, given its conspicuous R&D investment growth rate which changed it top R&D firm in 2017, it was included in this comparison.

Source: Authors' elaboration based on Naveed et al. (2018).

Soft innovation resources harnessed by these firms can be highlighted as follows majority of them are beyond the GDP counting (Japan Cabinet Office, 2012; Watanabe et al., 2015*a*).

- Driving force of a shift in people's preferences from economic value to supra-functionality (MacDonagh, 2008; Watanabe et al., 2015*b*)
- Sleeping resources, such as the ridesharing revolution (Watanabe et al., 2016*b*)
- Trust by overdrawing past information (Watanabe et al., 2017*b*)
- Utmost gratification ever experienced (Watanabe, 2014)
- Memory and dreams (Naveed et al., 2017)
- Untapped resources and vision (Watanabe et al., 2017*c*)

(3) Spin-off Dynamism to Increase Dependency on Uncaptured GDP

These accomplishments in the forefront of the leading global ICT firms are based on harnessing soft innovation resources identified as a soft value addition corresponding to uncaptured GDP and that are essential for the spin-off from traditional co-evolution among PoT, GDP and economic functionality to new co-evolution among IoT, uncaptured GDP and supra-functionality beyond economic value.

Based on the preceding confidence, **Fig. 19** illustrates a platform that demonstrates spin-off dynamism to increase dependence on uncaptured GDP, which leads to a new trajectory to sustainable growth in the digital economy.

This shift accelerates a shift from a PoT society to an IoT society by inducing further advancement of the Internet which increases further dependency on uncaptured GDP. At the same time, supra-functionality beyond economic value also accelerates uncaptured GDP dependence as illustrated in **Fig. 20**.

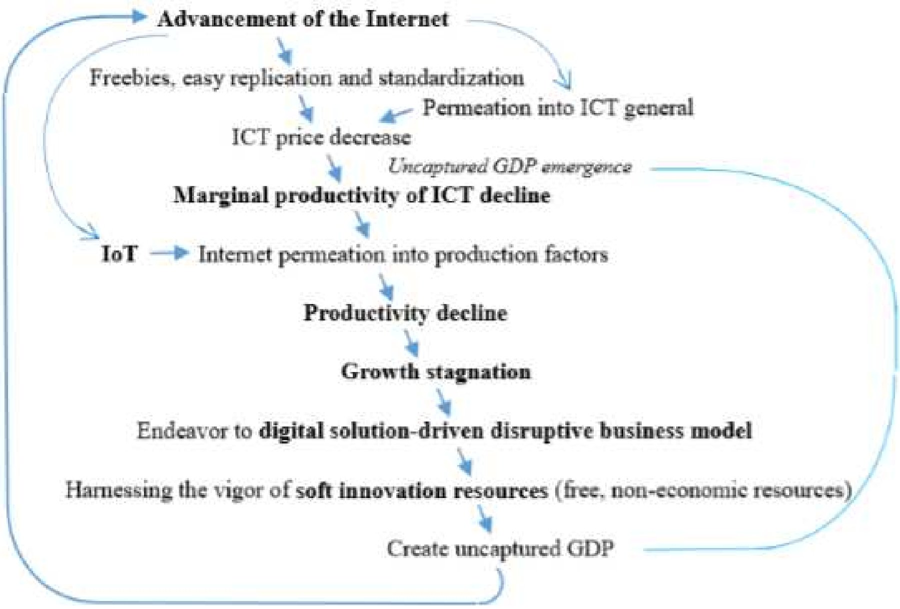

Fig. 19. Scheme of the Platform which Demonstrates Spin-off Dynamism to Increase Dependence on Uncaptured GDP.

Furthermore, effective utilization of soft innovation resources which triggered the above dynamism contributes to removing structural impediments in captured GDP growth such as conflict between public, employers and labour union, and also disparity of gender. Thus, spontaneous creation of uncaptured GDP through effective utilization of soft innovation resources contributes to overcoming economic stagnation by its hybrid functions as illustrated in Fig. 20.

Such endeavour toward transformative direction towards an IOT society leads to a new stream of digital solution-driven disruptive business model that creates uncaptured GDP spontaneously not merely depending on it passively.

Locomotive power of this stream can largely be attributed to effective utilization of soft innovation resources which activates self-propagating function identical to ICT and induces functionality development leading to supra-functionality beyond economic value corresponding to a shift in people’s preferences.

This shift accelerates a shift from a PoT society to an IoT society which increases further dependency on uncaptured GDP. At the same time, supra-functionality beyond economic value also accelerates uncaptured GDP dependence as illustrated in Fig. 20.

Thus, spontaneous creation of uncaptured GDP through effective utilization of soft innovation resources plays a hybrid role in accelerating new co-evolution among IoT, uncaptured GDP and supra-functionality beyond economic value while contributing to overcoming economic stagnation.

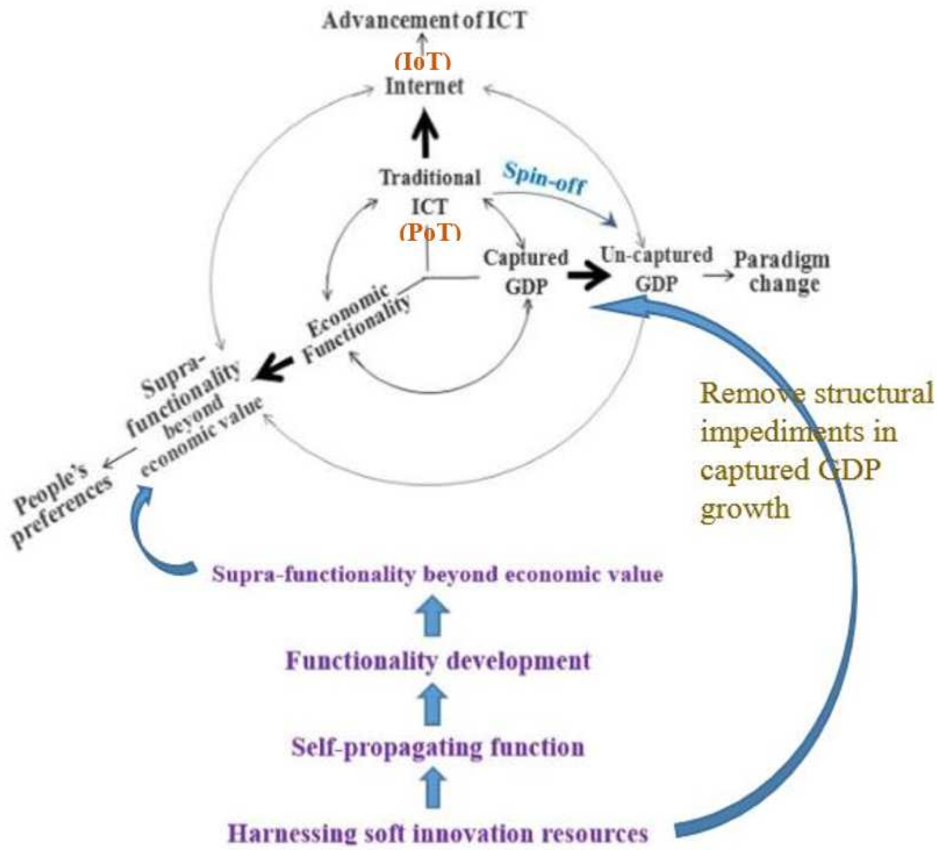

Fig. 20. Hybrid Role of Soft Innovation Resources Removing Structural Impediments in GDP Growth.

These findings provide new insight and constructive suggestions to a transformative direction to address the limitation of GDP in the digital economy.

6. Conclusion

Considering the increasing significance of measuring GDP in the digital economy because of growing concern regarding the limitation of GDP, a practical new solution was examined. The problem was investigated based on the results of intensive empirical analyses of the national, industrial, and individual behavior in the digital economy.

Given the two-faced nature of ICT and that people's preferences extend beyond economic value, the concept of uncaptured GDP was postulated and spinoff dynamism to a new co-evolution among advancement of the Internet, increasing dependence on uncaptured GDP, and a shift in people's preferences to supra-functionality beyond economic value was reviewed. Structural sources of the limitation of GDP in the digital economy were thus identified and a transformative direction to address the problem was suggested based on investigation of the forefront endeavor of leading global ICT firms.

The following findings outline the structural sources of the problem:

- ICT prices have continued to decline because of a trap in ICT advancement that stems from the two-faced nature of ICT. That is, the advancement of ICT generally contributes to enhanced prices of technology through new functionality development, whereas the dramatic advancement of the Internet decreases prices of technology because of the following characteristics: provision of freebies, easy and free replication, and mass standardization. Therefore, the marginal productivity declines in leading ICT firms.
- To compensate for decreases in prices, new and unique services have been introduced that are not necessarily captured by the GDP, which measures economic value, thus leading to increased dependence on uncaptured GDP.
- Mismeasurement of ICT price (dependence on a pseudo deflator) can be attributed to this phenomenon.
- The new services that have been introduced correspond to a shift in people's preferences from economic functionality to supra-functionality beyond economic value, which encompasses social, cultural, and emotional values.
- This shift induces further advancement of the Internet, which intensifies increasing dependence on uncaptured GDP. Therefore, a new co-evolution among Internet advancement, increasing uncaptured GDP, and a shift in people's preferences has emerged.

In addition, the following noteworthy findings provide constructive insight on the above issues:

- Under such circumstances in the digital economy, leading global ICT firms have been endeavoring to create supra-functionality by harnessing soft innovation resources.
- This trajectory is a way to achieve sustainable growth by means of the gross GDP, including uncaptured GDP.

- The survival strategy of global ICT firms depends on the construction of a platform that demonstrates above dynamism.
- The transformative direction of highly R&D-intensive firms may provide a constructive suggestion for identifying where a company's real economic activity is taking place.

These findings give rise to the following insightful suggestions for optimal countermeasures to these critical issues:

- Spinning off to new co-evolution among advancement of the Internet, increasing dependence on uncaptured GDP, and a shift in people's preferences to supra-functionality beyond economic value should be realized.
- Sustainable growth in gross GDP, including uncaptured GDP, should be targeted.
- Management system harnessing soft innovation resources should be further explored.
- Optimal national accounting based on gross GDP should be developed.
- Comprehensive uncaptured GDP measurement should be developed.
- The higher well-being that a nation actually enjoys should be demonstrated rather than merely assessed through captured GDP.

Thus, this analysis provides new insights for measuring the digital economy.

Future works should focus on international and historical reviews of success stories of gross GDP management both at national and industrial levels. The development of public policies based on the gross GDP concept should also be prioritized.

In addition, given the increasing significance of minimizing tax evasion, development of a tax principle for prosumers, taxation of uncaptured GDP, and precise evaluation of digital value to be taxed, tax challenges in the digital economy should also be investigated.

An optimal balance between new revenues for public policy through taxation of uncaptured GDP and reasonable incentive with the aim of encouraging the harnessing of soft innovation resources should be carefully considered.

Acknowledgement

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Authors are grateful to Dr Kashif Naveed and Dr Shino Iwami (University of Jyvaskyla) for their data construction and bibliometric analysis.

Appendix 1 Permeation of the Internet into Broad ICT

Fig. A1 traced the trend in the sum of $\rho + g$ in ICT related 27 key scientific research consisting of (i) Internet R&D, (ii) Internet related peripheral R&D, and (iii) other ICT R&D over the period 1980-2015.

Fig. A1 demonstrates that while the sum of $\rho + g$ values were diverged by 2005, they have been converging toward 2010-2015 thereby technology stock both of the Internet and other ICT can be treated as a sum of both R&D. This demonstrates the permeation trend of the Internet into broad ICT.

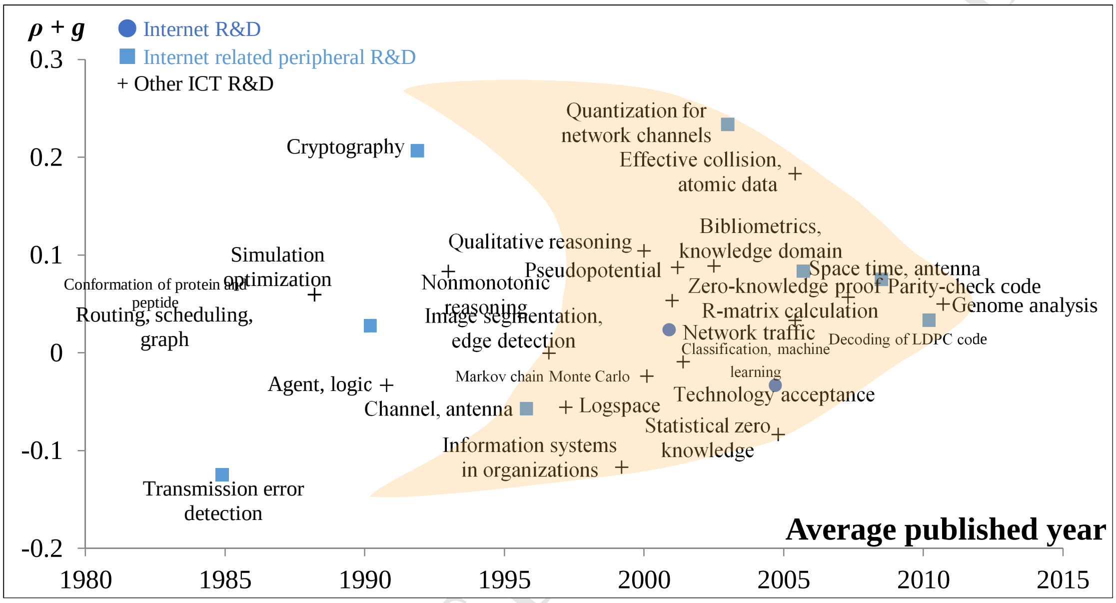

Fig. A1. Trend in the Sum of Rate of Obsolescence of Technology and Growth Rate of R&D at the Initial Stage in Internet R&D and Other ICT R&D (1980-2015).

Analysis of Fig. A1 was based on the following bibliometrics approach:

The top 1% scientific paper in "*Computer Science*" and "*Information Science & Library Science*" over the period 1960 -2015 was traced (altogether 14,438 scientific papers retrieved from the Web of Science provided by Clarivate Analytics were examined).

First, by using Academic Landscape System (Kajikawa et al., 2007; Innovation Policy Research Center, 2013) a citation network was constructed. Second, by means of Newman method (Newman, 2004), the citation network was divided into 27 clusters. Each respective cluster contains more than 100 papers. Thus, top 1% scientific papers highlight 27 scientific fields in the broad ICT as illustrated in Fig. 2 which can be classified as (i) Internet R&D (2 clusters), (ii) Internet related peripheral R&D (8 clusters), and (iii) other ICT R&D (17 clusters).

ρ can be estimated by calculating a reciprocal of the forward half-life after the peak with negative value, while g can be estimated by calculating a reciprocal of the backward half-life before the peak with positive value as illustrated in **Fig. A2**.

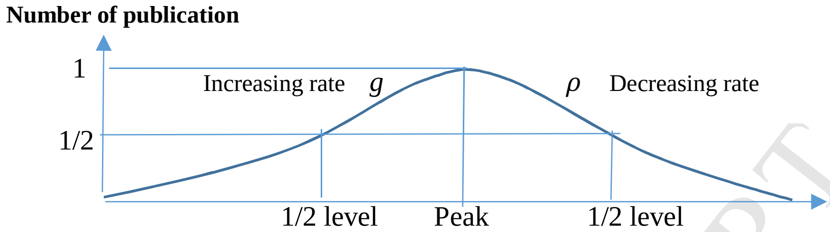

Fig. A2. Calculation Method.

Furthermore, driven by the IoT, the physical world is becoming an ecosystem composed of physical objects embedded with sensors and actuators connected to applications and services through a wide range of networks. Consequently, the Internet has been permeating into not only ICT general but also all production factors (McKinsey Global Institute, 2015) toward an IoT-based society.

Appendix 2 Analytical Framework

1. Trends in ICT Prices in Finland and Singapore

New Paradigm of ICT Productivity – Increasing Role of Uncaptured GDP and Growing Anger of Consumers (Watanabe et al., 2015*a*).

2. Bipolarization of ICT Prices in 500 Global ICT Firms

The Transformative Direction of Innovation toward an IoT-based Society: Increasing Dependency on Uncaptured GDP in Global ICT Firms (Naveed et al., 2018).

3. Elasticity of Utility to Consumption in Six Countries

Dependence on Uncaptured GDP as a Source of Resilience beyond Economic Value in Countries with Advanced ICT Infrastructure: Similarities and Disparities between Finland and Singapore (Watanabe et al., 2015*a*).

4. Development Trajectories of Finland and Singapore

Dependence on Uncaptured GDP as a Source of Resilience beyond Economic Value in Countries with Advanced ICT Infrastructure: Similarities and Disparities between Finland and Singapore (Watanabe et al., 2015*a*).

5. Measurement of Uncaptured GDP in Finland and Singapore

Operationalization of Un-captured GDP: Innovation Stream under New Global Mega-trends (Watanabe et al., 2016*a*).

6. Development Trajectory of Global ICT Firms

(1) Model Construction

Following techno-economic analysis approach was used for the numerical analysis.
Digital value V created by the global ICT firms in an IoT society can be depicted as follows:

$$V = F(X, I_g) \tag{1}$$

where I_g: gross ICT stock = I (ICT stock) +J (internet dependence); X: other production factors.
Taylor expansion on the first term:

$$\ln V = p + q \ln X + r \ln I_g \tag{2}$$

where p, q, and r: coefficients.
I_g embodies into X in an IoT society as follows:

$$X = F(I_g) \qquad \ln X = p_x + r_x \ln I_g \tag{3}$$

where p_x and r_x: coefficients.
Synchronizing equations (2) and (3):

$$\ln V = p + q(p_x + r_x \ln I_g) + r \ln I_g = (p+q\cdot p_x) + (q\cdot r_x + r)\ln I_q \equiv \alpha + \beta \ln I_g \tag{4}$$

where $\alpha = p + q\cdot P_x$, $\beta = q\cdot r_x + r.$

This demonstrates that V is governed by I_g under the above circumstances.

As the Internet permeates into ICT in general (see Fig. 1 and Appendix 1), I_g increases proportional to gross R&D represented by gross R&D expenditure (see ***Note 1***)

$$I_g = I + J \approx \frac{R_i}{\rho_i + g_i} + \frac{R_j}{\rho_j + g_j} \approx \frac{R_i}{\rho + g} + \frac{R_j}{\rho + g} = \frac{R_i + R_j}{\rho + g} = \frac{R}{\rho + g} \tag{5}$$

where R_j: R&D related to the Internet, and R_i: R&D related to other ICT; ρ: rate of obsolescence of ICT, and g: R&D growth rate at initial stage.

Note 1 **ICT stock at time *t***

ICT stock can be appropriated proportional to gross R&D as follows:

$$I_t = R_{t-m} + (1-\rho)T_{t-1} \ and \ \ I_0 = \frac{R_{t-m}}{\rho+g}, therefore, I_t = \frac{R_{t+1-m}}{\rho+g}, when\ t \gg m-1, I_t \approx \frac{R_t}{\rho+g}$$

where m: time-lag between R&D and commercialization.

Substituting equation (5) for Ig in equation (4):

$$\ln V = \alpha + \beta \ln \frac{R}{\rho + g} = \alpha - \beta \ln(\rho + g) + \beta \ln R \equiv \alpha' + \beta \ln R \tag{6}$$

where $\alpha' = \alpha - \beta \ln(\rho + g)$.

Thus, digital value is governed by gross R&D in the global ICT firms in an IoT society.

Given the logistic growth nature of ICT, V can be developed by an R-driven logistic growth function.

$$V \approx F(R), \quad \frac{dV}{dR} = \frac{\partial V}{\partial R} \cdot \frac{dR}{dR} = \frac{\partial V}{\partial R} = aV\left(1 - \frac{V}{N}\right) \tag{7}$$

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

Equation (7) develops the following simple logistic growth function (*SLG*):

$$V_s(R) = \frac{N}{1+be^{-aR}} \tag{8}$$

where *b*: coefficient indicating the initial level of diffusion.

This function leads to bipolarization as follows:

$$be^{-aR} \equiv \frac{1}{x} \quad \frac{\partial V}{\partial R} = aV\left(1 - \frac{V}{N}\right) = aN \cdot \frac{1}{1 + 1/x}\left(1 - \frac{1}{1 + 1/x}\right) = \frac{aN \cdot x}{(1+x)^2} \tag{9}$$

$$\frac{d\frac{\partial V}{\partial R}}{dx} = \frac{d\frac{\partial V}{\partial R}}{dR} \cdot \frac{dR}{dx} = \frac{d\frac{\partial V}{\partial R}}{dR} \cdot \frac{1}{ax} = aN \cdot \frac{1-x}{(1+x)^3} \qquad \frac{1}{ax} = \frac{b}{a}e^{-aR} > 0 \tag{10}$$

Digitalization exceeding certain R&D level ($R > \ln b/a$) results in productivity decline.

$$\frac{d\frac{\partial V}{\partial R}}{dR} = 0 \iff x = 1 \iff R = \frac{\ln b}{a} \rightarrow R > \frac{\ln b}{a} \Rightarrow \frac{d\frac{\partial V}{\partial R}}{dx} < 0 \tag{11}$$

Thus, $\frac{\ln b}{a}$ indicates inflection point in *SLG* (***Note 2***).

In particular innovation which creates new carrying capacity $N(R)$ during the process of diffusion, equation (7) is developed as follows:

$$\frac{dV(R)}{dR} = aV(R)\left(1 - \frac{V(R)}{N(R)}\right) \tag{12}$$

Equation (12) develops the following logistic growth within a dynamic carrying capacity function (*LGDCC*) which incorporates self-propagating function as carrying capacity increases as $V(R)$ increases as depicted in equation (14) (Watanabe et al., 2004):

$$V_L(R) = \frac{N_k}{1+be^{-aR}+\frac{b_k}{1-a_k/a}e^{-a_kR}} \tag{13}$$

$$N_L(R) = V_L(R)\left(\frac{1}{1-\frac{1}{a}\cdot\frac{\Delta V_L(R)}{V_L(R)}}\right) \qquad \Delta V_L(R) = \frac{dV_L(R)}{dR} \tag{14}$$

Induced by this self-propagating function, functionality (*FD*) spirally increases as $V(R)$ increases as depicted in equation (15):

$$FD = \frac{N_L(R)}{V_L(R)} = \frac{1}{1-\frac{1}{a}\cdot\frac{\Delta V_L(R)}{V_L(R)}} \tag{15}$$

As far as the development trajectory depends on *SLG* trajectory, its digital value ($V_S(R)$) saturates with upper limit depicted by fixed *N* without self-propagating function, once the trajectory shifts to *LGDCC*, it can continue to increase supported by self-propagating function and led by dynamically enhancing upper limit $N_L(R)$. Therefore, the magnitude of self-propagating function (*MSPF*) can be estimated by the ratio of $N_L(R)$ and $V_S(R)$ as follows (Watanabe et al., 2017*c*):

$$MSPF = \frac{N_L(R)}{V_S(R)} = \frac{V_L(R)}{V_S(R)} \cdot \left(\frac{1}{1 - \frac{1}{a} \cdot \frac{\Delta V_L(R)}{V_L(R)}} \right) \quad (16)$$

Note 2 **Inflection point in *LGDCC***

LGDCC function by equation (13) can be approximated by the following *SLG* function (Watanabe et al., 2009):

$$V_L(R) = \frac{N_k}{1 + be^{-aR} + \frac{b_k}{1 - a_k/a} e^{-a_k R}} \approx \frac{N_k}{1 + b' e^{-a'R}} \qquad a' = a\left(1 - \frac{b_k}{b}\right),\; b' = b\left(1 + \frac{b_k}{b} \cdot \frac{1}{1 - \frac{a_k}{a}}\right) \qquad b' e^{-a'R} \equiv \frac{1}{x}$$

$$\frac{\partial V_L}{\partial R} = a' N_k \frac{x}{(1+x)^3},\; \frac{d\frac{\partial V_L}{\partial R}}{dx} = \frac{d\frac{\partial V_L}{\partial R}}{dR} \cdot \frac{1}{a'x} = a' N_k \cdot \frac{(1-x)}{(1+x)^3},\; \frac{d\frac{\partial V_L}{\partial R}}{dR} = 0 \;\; when \;\; x = 1 \; \left(R = \frac{\ln b'}{a'}\right)$$

Therefore, $\frac{d\frac{\partial V_L}{\partial R}}{dR} < 0$ when $R > \frac{\ln b'}{a'} \approx \frac{\ln b\left(1 + \frac{b_k}{b} \cdot \frac{1}{1 - \frac{a_k}{a}}\right)}{a\left(1 - \frac{b_k}{b}\right)} > \frac{\ln b}{a}$

Inflection level in *LGDCC* is higher than that of in *SLG* function without self-propagating function.

(2) Data Construction

Utilizing the EU Industrial R&D Investment Scoreboard (EU) and annual reports of ICT firms, data necessary for the above numerical analyses for top 500 (by R&D level) global ICT firms over the period 2005-2016 were constructed.

Since these data include sales *(S)* and operating income *(OI)* for digital value *V*, together with R&D expenditure *(R)*, in addition to the above analysis, business performance of global ICT firms can be assessed by means of R&D intensity *(R/S)*, profitability *(OI/S)*, and R&D profitability *(OI/R)*.

(3) Empirical Analysis

Table A1 Estimation of Development Trajectory of the 500 Global ICT Firms
(2016 by *SLG*)

$$V_S(R) = \frac{N}{1 + be^{-aR}} + cD$$

N	*a*	*b*	*c*	*adj.R²*	*D*
59.62	1.32	15.91	99.09	0.784	
(17.39)	(10.98)	(21.87)		Samsun, Apple, Hon Hai	

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

Table A2 Estimation of Development Trajectory of the 500 Global ICT Firms
(2016 by *LGDCC*)

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

N_k	a	b	a_k	b_k	$adj.R^2$
102.23	0.77	15.84	0.43	1.32	0.999
(178.83)	(26.13)	(9.72)	(7.06)	(2.53)	

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

Appendix 3 Trends in Japan's Lifestyle Preferences

Table A3 Trends in Percent Ratio of Japan's Preferences Shift (1972-2012)

Year	**Economic-functionality**[1]	**Supra-functionality**[2] beyond economic value	**Others**[3]	**Total**
1972	37.3	40.0	22.7	100
1973	35.3	40.3	24.4	100
1974	36.4	41.5	22.2	100
1975	37.8	41.1	21.1	100
1976	39.9	41.4	18.8	100
1977	40.1	41.1	18.8	100
1978	39.5	40.4	20.1	100
1979	40.3	40.9	18.8	100
1980	39.8	42.2	18.0	100
1981	38.8	44.3	16.9	100
1982	37.6	44.8	17.6	100
1983	36.8	46.4	16.8	100
1984	36.8	46.5	16.7	100
1985	32.9	49.6	17.5	100
1986	32.7	49.1	18.2	100
1987	34.0	49.6	16.4	100
1988	32.0	50.3	17.7	100
1989	32.7	49.3	18.0	100
1990	30.8	53.0	16.2	100
1991	30.5	52.0	17.5	100
1992	27.3	57.2	15.5	100
1993	29.0	57.4	13.6	100
1994	30.0	57.2	12.8	100
1995	28.1	56.8	15.1	100
1996	27.9	58.8	13.3	100
1997	30.1	56.3	13.6	100
1999	29.3	57.0	13.7	100
2002	27.4	60.7	11.9	100
2003	28.7	60.0	11.3	100
2004	29.1	59.0	11.9	100
2005	28.4	57.8	13.8	100
2006	30.4	62.9	6.7	100
2007	28.6	62.6	8.8	100
2008	30.2	62.6	7.2	100
2009	30.2	60.5	9.3	100
2010	31.1	60.0	8.9	100
2011	31.0	61.4	7.6	100
2012	30.1	64.0	5.9	100

[1] Wealth of things: Material affluence (emphasis should still be put on material affluence for future life).
[2] Richness of Heart: Spiritual happiness (because a reasonable level of material affluence has been achieved,
future emphasis should be put on spiritual happiness and comfortable life).
[3] Cannot identify explicitly.

Source: National Survey of Lifestyle Preferences (Japan cabinet office, annual issues).

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TIS1056_Table5_Fig.13

Table 5 Elasticity of Utility to Consumption in Six Countries *(2013)*

	Finland	Singapore	USA	UK	Germany	Japan
Efficiency of *J* inducement of *I* 1. *J* elasticity to *I* (ε_{ij})	0.75	0.39	0.55	0.39	0.22	0.21
Efficiency of *J* inducement of *C* 2. ***J* elasticity to *C*** (ε_{cj})	**0.23**	**0.49**	**0.37**	**0.15**	**0.10**	**0.10**
Efficiency of *I* inducement of *C* 3. ***I* elasticity to *C*** $(\varepsilon_{ci}=\frac{\varepsilon_{cj}}{\varepsilon_{ij}})$ [2/1]	**0.30**	**1.27**	**0.68**	**0.40**	**0.47**	**0.48**
Extent of reflection of *U* to *C* 4. ***U* elasticity to *C*** (ε_{cu}) [2+3]	**0.53**	**1.76**	**1.05**	**0.55**	**0.57**	**0.58**

$$U=U(V,Q) \quad V=V(I,J), Q=Q(I,J)$$

$$U=U(I,J)=\frac{\partial U}{\partial I}\cdot I+\frac{\partial U}{\partial J}\cdot J=\frac{\partial U}{\partial C}\left(\frac{\partial C}{\partial I}\cdot I+\frac{\partial C}{\partial J}\cdot J\right)$$

$$\underset{(\varepsilon_{cu})}{\frac{\partial C}{\partial U}\cdot\frac{U}{C}}=\underset{(\varepsilon_{ci})}{\frac{\partial C}{\partial I}\cdot\frac{I}{C}}+\underset{(\varepsilon_{cj})}{\frac{\partial C}{\partial J}\cdot\frac{J}{C}}$$

U: Utility, *C*: Traditional consumption
V: Economic functionality, *Q*: Supra-functionality
J: Internet dependency, *I*: ICT stock

Original source:

Dependence on Uncaptured GDP as a Source of Resilience beyond Economic Value in Countries with Advanced ICT Infrastructure: Similarities and Disparities between Finland and Singapore (Watanabe et al., 2015*a*).

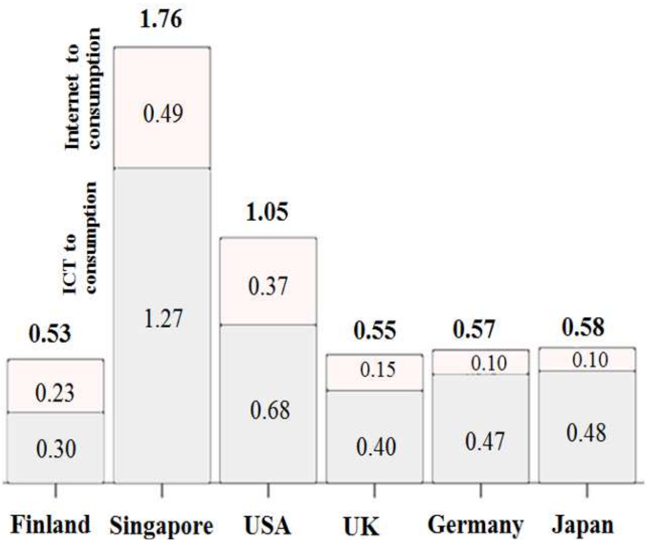

Fig. 13. Elasticity of Utility to Consumption in Six Countries *(2013).*

Original source:

Same as Table 5.

TIS_2017_194_Revised_Highlights

Highlights

A new paradox of the digital economy was discussed.
Structural sources of the productivity decline in the digital economy was identified.
Limitations of GDP in measuring the advancement of the digital economy was identified.
New insights for measuring the digital economy were explored.
Significant role of soft innovation resources was postulated.