Management Review Quarterly
https://doi.org/10.1007/s11301-019-00173-6

Lessons from three decades of IT productivity research: towards a better understanding of IT-induced productivity effects

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Received: 7 June 2019 / Accepted: 1 October 2019

Abstract
New developments in the fields of artificial intelligence or robotics are receiving considerable attention from businesses, as they promise astonishing gains in process efficiency—sparking a surge of corporate investments in new, digital technologies. Yet, firms did not become per se more productive, as labor productivity growth in various industrial nations has decelerated in recent years. The fact that the adoption of innovative technologies is not accompanied by productivity increases has already been observed during the dawn of the computer age and became known as Solow's Paradox. Thus, this paper takes stock of what is known about the Solow Paradox, before incorporating the findings into the debate of the current productivity slowdown. Based on an in-depth review of 86 empirical studies at the firm level, this paper uncovers various reasons for the emergence of the Solow Paradox, debates its following reversal marked by the occurrence of excess returns and deduces a model of factors influencing the returns on IT investments. Based on these insights, four overarching explanations of the modern productivity paradox namely adjustment delays, measurement issues, exaggerated expectations and mismanagement are discussed, whereby mismanagement emerges as a currently neglected, but focal issue.

Keywords IT investment · Information technology · Productivity · IT productivity paradox · Solow Paradox · Industry 4.0

JEL Classification A12 · O31 · O33

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Published online: 14 October 2019

1 Introduction

Advances in modern technologies like robotics, 3D printing, internet of things (IOT), artificial intelligence (AI), blockchain, virtual reality (VR) or augmented reality (AR) are creating furor among individuals and firms. They promise a so-called fourth industrial revolution with disruptive innovations that could change not only everyday life, but also entire industries forever (Obermaier 2019). Due to the enormous potential of these technologies, companies are afraid to end up on the losing side of a digital revolution if they do not adopt these disruptive technologies themselves. As a result, global business expenditure on AI, machine learning and robotic process automation is, for instance, expected to reach $232 billion in 2025, which marks a 18-fold increase from the estimated spending of $12.4 billion in 2018 (KPMG 2018).

Despite these efforts of companies to digitize their operations, they are struggling to become more productive. In fact, US labor productivity growth fell from an average of 2.73% per year from 2000 through 2010 to an average of 1.06% per year between 2010 and 2018 (BLS 2019). A similar trend can be observed in other industrialized economies. The OECD member states recorded a decline in labor productivity growth from an average of 1.46% per year from 2001 through 2010 to an average of 0.98% per year between 2010 and 2017 (OECD 2019). Brynjolfsson et al. (2019b) refer to this conundrum as a so-called modern productivity paradox, since companies are constantly increasing the investment volume in highly praised digital technologies such as AI or IOT, but on average fail to achieve substantial productivity gains.

A glance at the past reveals that a similar phenomenon was already encountered some 30 years ago. With respect to the beginning of the computer age, Solow (1987, p. 36) remarked that productivity growth was slowing down in many industrialized countries: “what everyone feels to have been a technological revolution, a drastic change in our productive lives, has been accompanied everywhere, including Japan, by a slowing down of productivity growth, not by a step up. You can see the computer age everywhere but in the productivity statistics.” Since this illustrious quote the productivity paradox of information technology (IT) is known as Solow’s Paradox and marks the onset of numerous studies addressing the impact of IT on productivity, profitability or market value of firms (see Brynjolfsson and Yang 1996; Schryen 2013).

Notwithstanding the enormous amount of academic publications, the Solow Paradox remains a mystery to this day, with researchers either proposing its resolution or arguing for its continued existence. While Brynjolfsson and Hitt (1996) conclude that the Solow Paradox disappeared by 1991, Acemoglu et al. (2014) state that only the IT-producing sector might have been able to achieve a considerable increase in productivity due to IT investments and therefore regard the proposed resolution of the Solow Paradox as premature. According to their results, an IT-induced productivity revolution is improbable, as a “race against machines” (Brynjolfsson and McAfee 2012) had indeed taken place, in which productivity gains of IT-intensive manufacturing firms were achieved only at times and when present, were caused by declining relative output in conjunction with an even sharper decline in employment. Thus, the often claimed improvements in productivity due to IT investments are empirically only partially verifiable, which calls for a more in-depth investigation. Therefore, we try to answer the research question:

> What are reasons for the absence or emergence of IT-induced productivity effects?

Moreover, in the light of the widely discussed modern productivity paradox (Acemoglu and Restrepo 2019; Aghion et al. 2019; Agrawal et al. 2019a; Brynjolfsson et al. 2018, 2019b; Crafts 2018), the question arises whether there are parallels between a current productivity slowdown which is accompanied by the adaptation of new, digital technologies and the lack of productivity improvements during the onset of the computer age. Thus, we attempt to elaborate the following research question:

> To what extent can insights from the review of IT productivity research contribute to the explanation of lacking productivity gains from investments in modern technologies?

To answer our research questions, we conduct an in-depth analysis and discussion of empirical literature regarding the Solow Paradox at the firm level. Although several literature reviews and meta-analyses already exist in this research field (Brynjolfsson and Hitt 2000; Brynjolfsson and Yang 1996; Cardona et al. 2013; Dedrick et al. 2003; Dehning and Richardson 2002; Kohli and Devaraj 2003; Kohli and Grover 2008; Melville et al. 2004; Polák 2017; Sabherwal and Jeyaraj 2015; Schryen 2013; Wade and Hulland 2004), the Solow Paradox itself has become more of a side note in recent years and the focus has shifted towards information systems business value (Schryen 2013), market value and accounting measures (Dehning and Richardson 2002), the sustainable competitive advantage of IT (Kohli and Grover 2008; Melville et al. 2004; Wade and Hulland 2004), or a (quantitative) assessment of IT elasticities (Cardona et al. 2013; Kohli and Devaraj 2003; Polák 2017; Sabherwal and Jeyaraj 2015). Reviews with a primary focus on the Solow Paradox are more than a decade old (Brynjolfsson and Hitt 2000; Brynjolfsson and Yang 1996; Dedrick et al. 2003). Therefore, we place the Solow Paradox and thus productivity back at the center of the debate.

Based on an in-depth review of 86 empirical firm-level studies, we make three important contributions to the literature. First, we show that the literature on the Solow Paradox can be divided into two groups: studies with an observation period prior to the late 1980s, which predominantly found no significant effects, and those with a later observation period, which indicated mostly significant positive effects, even revealing excess returns on IT investments. Second, although the origin of the Solow Paradox has been discussed intensively (e.g. Brynjolfsson 1993; Triplett 1999; Brynjolfsson and Hitt 1998), less is known about the reasons for the following reversal of the paradox and the appearance of excess returns. Thus, we provide a comprehensive overview of this issue, whereby we also deduce a model of factors influencing the return on IT investments. Third, we apply these insights to the modern productivity paradox and discuss adjustment delays, measurement issues, exaggerated expectations and mismanagement as potential reasons for the recent deceleration in productivity growth. Thereby, mismanagement emerges as a mostly neglected issue that could be a relevant contributor to the current productivity slowdown. Furthermore, it appears that many aspects, which were discussed as a cause of the Solow Paradox, are re-examined in the debate of the modern productivity paradox.

The remaining part of the work is structured as follows: First, we describe the relationship of IT and productivity from a theoretical perspective. Following is a detailed explanation of our systematic literature review process. Subsequently, we synthesize the key findings. Building on these insights, we discuss reasons for the emergence of the modern productivity paradox. Finally, we illustrate potential areas for future research.

2 IT and productivity

2.1 The economic relation between IT and productivity

In order to analyze the contribution of IT investments on productivity, it is necessary to understand the functional relation between inputs and output. The most common approach to model the production process of an economic system is the use of production functions. To measure the impact of IT on productivity empirically, either parametric or non-parametric techniques are employed. Because of their underlying properties, non-parametric approaches such as growth accounting (Solow 1957) are primarily utilized in studies at the industry and country level, while parametric approaches are mainly applied in studies at the firm level (Cardona et al. 2013). Since this study is focused on the firm level, the parametric approach will be outlined in the following.[1]

The Cobb–Douglas function is the starting point for most empirical productivity estimations which characterizes the relationship between inputs and outputs as follows (Brynjolfsson and Hitt 1996; Cardona et al. 2013):

$$Y = A \cdot K^{\alpha} \cdot L^{\beta} \tag{1}$$

where Y is output, A total factor productivity (TFP), K capital and L labor input. TFP is a residual factor that is usually interpreted as a measure of technological progress, but basically just describes the variation in the efficiency of output creation due to unobservable factors (Syverson 2011). Labor input can be represented by the number of employees, employee hours or quality-adjusted employee hours (labor services), which additionally take into account deviations within the skill composition of the workforce. For capital, either the capital stock or the quality-adjusted capital stock (capital services), which takes productivity differences between the different

[1] For an excellent discussion of parametric and non-parametric approaches, see Cardona et al. (2013).

asset classes into account, can be utilized (Cardona et al. 2013). α and β are the output elasticities of capital and labor input, respectively. They indicate by which percentage the output changes if the use of an input factor is increased by one percent.

In order to assess the effect of IT, the input factor capital can be divided into IT capital and non-IT capital. IT capital broadly defined includes the stock of hardware, software, telecommunications and IT-related services (Dedrick et al. 2003),[2] although most studies just cover the stock of hardware (e.g. Brynjolfsson and Hitt 2003; Chwelos et al. 2010). Non-IT capital comprises all other forms of capital, leading to the following equation:

$$Y = A \cdot K_{IT}^{\gamma} \cdot K_{Non-IT}^{\alpha} \cdot L^{\beta} \tag{2}$$

To calculate the parametric approach, Eq. (2) is to be log-linearized:

$$\ln Y_{it} = \beta_1 \ln K_{IT,it} + \beta_2 \ln K_{Non-IT,it} + \beta_3 \ln L + control\,variables + \varepsilon_{\mathrm{it}} \tag{3}$$

where Y is output, K_{IT} IT capital, K_{Non-IT} non-IT capital and L labor input. β_{1-3} indicate the output elasticities of the input factors. The marginal product of IT capital is determined by multiplying the output elasticity β_1 with the ratio of output to IT capital input. Index i denotes the unit of observation and t the time period. Control variables at the firm level are, for example, industry affiliation or firm size. ε represents the disturbance term.

The most common measure of productivity is labor productivity, i.e. the quotient of output (gross output or value added) and labor input (Syverson 2011). Dividing both sides by labor input, Eq. (3) can be transformed to:

$$\ln y_{it} = \beta_1 \ln k_{IT,it} + \beta_2 \ln k_{Non-IT,it} + control\,variables + \varepsilon_{\mathrm{it}} \tag{4}$$

where y is output per hour worked (labor productivity), k_{IT} IT capital per hour worked and k_{Non-IT} non-IT capital per hour worked (Stiroh 2005).

2.2 IT in the production process

The question that still remains is, why an increase in IT investments (and the resulting increase in IT capital) should lead to productivity gains. An improvement in labor productivity (ln(*Y/L*)) can occur on the input side, through a decrease in labor input (ln *L*), as well as on the output side, through an increase in sales (ln *Y*). Table 1 gives an overview of the possible effects of IT capital on labor productivity, which are outlined in the following.

A common application of IT is to automate business processes. This procedure is known as capital deepening and indicates that capital input increases relative to labor input (Corrado et al. 2009). For example, routine bookkeeping tasks are performed by computer programs instead of accountants. In this case, labor is directly substituted for the comparatively more productive input factor IT capital, which leads to an increase in capital intensity and ultimately to an improvement

[2] Because of this broad definition, the terms IT and information and communication technology (ICT) are used interchangeably within this work.

Table 1 Possible mechanisms through which IT capital can increase labor productivity

	Mechanism	Objective	Area of effect
Input side	Capital input increases relative to labor input	Cost savings through a relative reduction of labor input without a detrimental effect on output	Process
Output side	More efficient combination of labor and capital	Improvement in output quantity without increasing labor input or capital input	Process
	Price premium due to superior or innovative products and services	Improvement in output quality without increasing labor input or capital input	Product

in labor productivity. This only applies, of course, if the reduction in labor input is not offset by an equal or even greater reduction in output due to a smaller work force. Moreover, automatization can lead to a more reliable production process, resulting in a reduction of deficient products or poor services.

Additionally, IT has the potential to improve the flow of information within and between firms or customers and thereby reduces the cost of coordinating economic activities (Gurbaxani and Whang 1991). This enables not only incremental improvements of the workflow, but a radical transformation of business processes. As such, IT has not only a direct impact on labor productivity like for example in accelerating the process of financial transactions in banks, but exhibits a dual role, in serving as a catalyst for the fundamental transformation of organizational structures and processes (Dedrick et al. 2003). This allows companies to achieve a higher output level without altering the level and quality of inputs (reflected by an increase in the TFP). To achieve this objective, firms can either increase the quantity of the output (e.g. through process innovations) or improve the quality of the output (e.g. through product innovations).

Alterations of business processes in conjunction with IT investments allow the input factors to be combined more efficiently and thus achieve permanent increases in productivity (Davenport 1993). For example, if a firm introduces an enterprise resource planning (ERP) system, it can process and store a variety of operational data in a single application. First, managers or employees can make faster and more profound decisions based on the additional information available. Second, the system enables firms to get a better understanding of the different actions that take place within the firm and plan the workflow across all company levels and divisions accordingly. In order to realize this potential, firms must restructure existing processes and redefine established workflows. These restructuring measures embody the knowledge of how production factors can be optimally combined. This knowledge is neither measurable nor tangible. It is intangible and cannot simply be modeled as a separate input factor. Rather, it ensures that existing input factors are combined more efficiently, which leads to an increase in labor productivity.

IT can also be utilized to equip products or services with digital functions or even to launch new innovative digital products and services (Porter and Heppelmann 2014, 2015). If customers are willing to pay a price premium for the additional value created by digital features or innovations (innovation premium), this is reflected by an increase in sales (Bresnahan et al. 2002). An example is the Kindle e-book reader released in 2007, which allows users to download e-books, newspapers and magazines and read them directly on the device. The benefit of using Kindle is that consumers can access their electronic books anytime and anywhere without having to physically transport them. This convenience provides additional value for the customer, which can culminate in a price premium. In addition, improved internal communication as well as the faster and more comprehensive transfer of information by means of IT reduce coordination costs and, thereby, facilitate new service and product innovations (Brynjolfsson and Saunders 2009).

3 Research methodology

After presenting the role of IT in the production process and its effects on productivity, we analyze the Solow Paradox on the basis of the existing literature. To identify relevant studies, we carried out a six-step systematic search process based on Webster and Watson (2002), Tranfield et al. (2003) and Fisch and Block (2018).

First, in order to ensure the relevance of the collected studies, we made certain restrictions. Studies which monetarily measured or estimated some form of IT investment or IT capital were included, but no articles that utilized IT usage as an independent variable (e.g. Arvanitis and Loukis 2009; Black and Lynch 2001; Greenana and Mairesse 2000), since the investment in IT and usage of IT represent fundamentally different variables (see Devaraj and Kohli 2003; Soh and Markus 1995). In addition, studies that focused exclusively on the effects of IT investments on costs, innovation, consumer surplus, wages, employment, profitability or market value were not considered (e.g. Bharadwaj et al. 1999; Brynjolfsson et al. 2002). Studies investigating the impact of IT on productivity only via a series of mediating variables as well as studies considering solely intermediate variables such as efficiency were not included (e.g. Alpar and Kim 1990; Barua et al. 1995; Chang and Gurbaxani 2013; Mitra and Chaya 1996; Shao and Lin 2002). Besides, the sample was limited to empirical studies at firm or business unit level to avoid biased results due to the potential redistribution and dissipation of revenue between firms, which go unnoticed by studies at a more aggregated level (for an extensive discussion see Brynjolfsson 1993). Based on these constrains and a prior reading of relevant articles in the research field, the following search formula was derived:

(computer OR information technology OR information and communication technology OR Information & communication technology OR ict OR IT investment OR IT expenses OR IT expenditure OR IT capital OR IT spending OR IT stock OR IT purchases OR IT budget) AND (productivity OR output OR value added) AND (firm OR microeconomic OR business unit)

In a second step, we used the search formula to conduct a keyword search (in title, subject headings and abstract) using the Business Source Premier Database, which is one of the most comprehensive databases of articles in the business field. We limited the search to academic, peer-reviewed journal articles in English language from 1987 to 2018. We chose 1987, as it marks the year of Solow's famous quote, which was the triggering point for various academic studies.[3]

This led to a preliminary sample of 1384 articles. Following an initial screening of titles and abstracts, 1307 articles were excluded. The high number of exclusions was due to: studies analyzing the effects of IT adoption, IT diffusion or IT use on productivity, the investigation of other performance indicators like profitability, a primary focus on the industry or country level and the use of non-empirical methodologies. After full reading, we sorted out 28 additional papers, as they did not fulfill our requirements. Thus, we obtained 49 studies by keyword search.

In a third step, we checked similar to prior reviews (e.g. Schryen 2013) the table of contents of each of the eight Journals belonging to the IS Senior Scholars' Basket of Journals: *European Journal of Information Systems, Information Systems Journal, Information Systems Research, Journal of the Association for Information Systems, Journal of Information Technology, Journal of Management Information Systems, Journal of Strategic Information Systems, and MIS Quarterly*. We performed this step to ensure that no relevant article published in any of these outlets was omitted from the review, as this selection represents the official canon of the top journals in the information system field according to the Association for Information Systems (AIS 2011). This resulted in the addition of eleven studies.

In a fourth step, we performed a backward search by systematically scanning the bibliographies of studies in our current sample for further relevant sources. Working papers, book or conference papers were not considered. An exception were the books or book chapters by Strassmann (1985, 1990) and Loveman (1994), as they had substantial influence on the research field, which is evidenced by their high number of google scholar citations (858, 1147 and 926 as of 20 February 2019, respectively) and their inclusion in various previous reviews (e.g. Brynjolfsson and Yang 1996; Dedrick et al. 2003). In total, we identified 16 additional studies. In a fifth step, we conducted a forward search. To retrieve articles quoting the studies discovered so far, we used the Web of Science database. Thereby, we obtained six additional studies.

In a sixth step, we examined previous literature reviews in this research field by Brynjolfsson and Yang (1996), Dedrick et al. (2003) and Schryen (2013) as well as the meta-analyses by Sabherwal and Jeyaraj (2015) and Polák (2017) to look for relevant articles we might have missed. This led to the inclusion of four additional articles and an overall sample of 86 studies.

[3] The search process was last updated on 20 February 2019.

4 Implications of the systematic literature review

An overview of the collected studies shows that there are mixed results regarding the effects of IT investments on productivity at the firm level (see Table 2). Therefore, the subsequent chapter is structured as follows: We start by analyzing studies that found a negative or insignificant effect of IT investments on productivity and discuss potential reasons for the emergence of the Solow Paradox, before we evaluate studies that exhibited a positive effect of IT investments on productivity. Afterwards, we discuss a number of phenomena, which are likely to affect all studies, such as complementary and environmental factors influencing the returns of IT investments, the time lag between IT investments and possible productivity improvements as well as the often debated measurement problems in this research field. Thereby, we try to identify reasons for the absence or emergence of IT-induced productivity effects.

4.1 Reasons for the absence of IT-induced productivity effects

4.1.1 Small sample sizes and shortcomings in the research design of early studies

Reviewing the literature it became apparent that particularly early studies did not find a significant relation between IT investments and productivity (Loveman 1994; Mahmood 1993; Mahmood and Mann 1993; Strassmann 1985, 1990; Weill 1992). This can potentially be attributed to the small sample sizes of these studies. Strassmann (1985, 1990) considered 38 service firms, Weill (1992) 33 valve manufacturers, Mahmood (1993) 81 firms and Loveman (1994) 60 strategic business units (of 20 firms). As smaller sample sizes tend to produce less significant results, this may be one reason for the absence of noteworthy effects. Though, also later studies such as Tam (1998), Francalanci and Galal (1998a, b) or Ko and Osei-Bryson (2008) are possibly affected by small sample sizes.

Moreover, some of the early studies seem to have shortcomings in their research design. Barua and Lee (1997) as well as Lee and Barua (1999) analyzed the same data set as Loveman (1994) but arrive at a different conclusion. Barua and Lee (1997) indicated that large manufacturing firms achieved significant productivity gains from IT investments, revealing that the insignificant results of Loveman (1994) can be attributed to the choice of the deflator employed for IT capital as well as modeling issues. Similarly, taking into account different behavioral assumptions, functional forms, capitalization methods and methodologies, Lee and Barua (1999) demonstrated that IT investments had a significant positive impact on the productivity of the business units under consideration.

Furthermore, Mahmood (1993, p. 198) and Mahmood and Mann (1993, p. 120) labeled their studies as exploratory and, noted that their results "should be interpreted carefully" due to the cross-sectional research design. In addition, the data used to measure IT investments during this period were potentially inadequate, due to the difficulty of collecting data in an era of limited digital databases (Dedrick et al. 2003).

Table 2 Summary of the collected studies

Author	Sample size	IT data source	Observation period	Region	Results
Studies indicating a negative or insignificant effect of IT investments on productivity					
Strassmann (1985, 1990)	38 Firms	MPIT	1977–1987	USA	o
Weill (1992)	33 Valve manufacturers	–	1982–1987	USA	o
Mahmood (1993)	81 Firms	CW	1988	USA	o
Mahmood and Mann (1993)	~100 Firms	CW	1989	USA	o
Loveman (1994)	60 SBUs	MPIT	1978–1984	USA	o
Byrd and Marshall (1997)	350 Firms	IDG	1990–1993	USA	–
Francalanci and Galal (1998a)	34 Life insurers	LOMA	1986–1995	USA	–
Francalanci and Galal (1998b)	52 Life insurers	LOMA	1986–1995	USA	–
Tam (1998)	88 Firms	ACD	1983–1991	Pacific Rim	o
Dasgupta et al. (1999)	162 Firms	IW	n.a.	USA	–
Licht and Moch (1999)	791 Firms	MIP-S & IDC	n.a.	Germany	o
Lee and Menon (2000)	~60 Hospitals	WADOH	1976–1994	USA	o
Hu and Plant (2001)	n.a.	IW	1990–1995	USA	o
Dunne et al. (2004)	n.a.	ASM	1977 and 1992	USA	o
Ko and Osei-Bryson (2004)	63 Hospitals	WADOH	1975–1994	USA	o
Osei-Bryson and Ko (2004)	370 Firms	IDG	1988–1992	USA	o
Chowdhury (2006)	300 SMEs	–	2000	Kenya & Tanzania	–
Ko and Osei-Bryson (2006)	370 Firms	IDG	1988–1992	USA	o
Ko and Osei-Bryson (2008)	~60 Hospitals	WADOH	1976–1994	USA	o
Badescu and Garcés-Ayerbe (2009)	341 Firms	ESI	1994–1998	Spain	o
Menon et al. (2009)	Hospitals	WADOH	1979–2006	USA	o
Baker et al. (2017)	1236 Healthcare firms	HIMSS	1998–2004	USA	o
Studies indicating a positive effect of IT investments on productivity					
Brynjolfsson and Hitt (1995)	~300 Firms	IDG	1988–1992	USA	+

Table 2 (continued)

Author	Sample size	IT data source	Observation period	Region	Results
Lichtenberg (1995)	n.a.	IDG & IW	1988–1991	USA	+
Brynjolfsson and Hitt (1996)	367 Firms	IDG	1987–1991	USA	+
Hitt and Brynjolfsson (1996)	370 Firms	IDG	1988–1992	USA	+
Rai et al. (1996)	210 Firms	IW	n.a.	USA	+
Barua and Lee (1997)	47 SBUs	MPIT	1978–1984	USA	+
Dewan and Min (1997)	~300 Firms	IDG & CW	1988–1992	USA	+
Rai et al. (1997)	n.a.	IW	1994	USA	+
Lehr and Lichtenberg (1998)	44 Federal agencies	CII	1987–1992	USA	+
Yorukoglu (1998)	380 Firms	IDG	1987–1991	USA	+
Lee and Barua (1999)	47 SBUs	MPIT	1978–1984	USA	+
Lehr and Lichtenberg (1999)	500 Firms	ES & CII	1977–1993	USA	+
Devaraj and Kohli (2000)	8 Hospitals	–	n.a.	USA	+
Menon et al. (2000)	~60 Hospitals	WADOH	1976–1994	USA	+
Sircar et al. (2000)	624 Firms	IDC	1988–1993	USA	+
Bresnahan et al. (2002)	300 Firms	CII	1987–1994	USA	+
Hitt et al. (2002)	~350 Firms	CII	1986–1998	USA	+
Kudyba and Diwan (2002)	~350 Firms	IW	1995–1997	USA	+
Ross (2002)	51 Firms	IW	1999	USA	+
Becchetti et al. (2003)	n.a.	MCU	1995–1997	Italy	+
Brynjolfsson and Hitt (2003)	527 Firms	IDG & CII	1987–1994	USA	+
Bertschek and Kaiser (2004)	411 Firms	SSBS	n.a.	Germany	+
Doms et al. (2004)	Retail firms	AES	1992–1997	USA	+
Kim and Davidson (2004)	n.a.	–	1990–1998	Korea	+
Zhu (2004)	114 Retail firms	CII	n.a.	USA	+
Hempell (2005a)	1222 Firms	MIP-S	1994–1999	Germany	+

Table 2 (continued)

Author	Sample size	IT data source	Observation period	Region	Results
Hempell (2005b)	1222 Firms	MIP-S	1994–1999	Germany	+
Huang (2005)	34 Banks	–	1996–2003	Taiwan	+
Mahmood and Mann (2005)	239 Firms	CW	1991–1993	USA	+
Shu and Strassmann (2005)	12 Banks	–	1989–1997	USA	+
Stare et al. (2006)	n.a.	SORS	1996–2002	Slovenia	+
Dewan et al. (2007)	~500 Firms	CII	1987–1994	USA	+
Gargallo-Castel and Galve-Górriz (2007)	1225 Firms	SBS	1998	Spain	+
Melville et al. (2007)	933 Firms	CII	1987–1994	USA	+
Neirotti and Paolucci (2007)	30 Insurance firms	ANIA	1992–2001	Italy	+
Loukis et al. (2007)	176 Firms	–	2004	Greece	+
Baker et al. (2008)	Healthcare firms	HMISS	2006–2007	USA	+
Giuri et al. (2008)	680 SMEs	MCU	1995–2003	Italy	+
Sircar and Choi (2009)	n.a.	IDC	1988–1993	USA	+
Wilson (2009)	1651 Firms	ACES	1998	USA	+
Chwelos et al. (2010)	800 Firms	CII	1987–1998	USA	+
Ramirez et al. (2010)	228 Firms	CII	1996–1999	USA	+
Commander et al. (2011)	968 Firms	–	2001–2003	Brazil & India	+
Lee et al. (2011)	48 Firms	MIIT	2005–2007	China	+
Bloom et al. (2012)	n.a.	ABI & BSCI & FAR & QICE	1995–2003	United Kingdom	+
Bloom et al. (2012)	720 Firms	CiDB	1999–2006	Europe	+
Chang and Gurbaxani (2012)	386 Firms	CII	1987–1994	USA	+
Mithas et al. (2012)	452 Firms	–	1998–2003	USA	+
Tambe and Hitt (2012)	1800 Firms	JSW & CITDB	1987–2006	USA	+
Tambe et al. (2012)	253 Firms	JSW	1999–2006	USA	+

Table 2 (continued)

Author	Sample size	IT data source	Observation period	Region	Results
Vinekar and Teng (2012)	948 Firms	IW	1991–1997	USA	+
Hall et al. (2013)	9850 Firms	MCU	1995–2006	Italy	+
Lee et al. (2013)	309 Hospitals	OSHPD	1997–2007	USA	+
Castiglione and Infante (2014)	n.a.	MCU	1995–2006	Italy	+
Liu et al. (2014)	1114 Firms	DGBAS	1991	Taiwan	+
Tambe and Hitt (2014a)	n.a.	JSW & CITDB	1987–2006	USA	+
Tambe and Hitt (2014b)	n.a.	IDG & CII	1987–1994	USA	+
Luo and Bu (2016)	6236 Firms	WBES	2007	Emerging countries	+
Huang et al. (2017)	1165 Firms	DGBAS	1991	Taiwan	+
Kılıçaslan et al. (2017)	n.a.	TURKSTAT	2003–2012	Turkey	+
Aboal and Tacsir (2018)	2302 Firms	SIS & MIS	2004–2009	Uruguay	+
Khanna and Sharma (2018)	900 Firms	CHMIE	2000–2016	India	+
Wang et al. (2018)	Hospitals	DH	2011–2016	USA	+
Wu et al. (2018)	6442 Firms	JSW	1987–2007	USA	+

Results refer solely to the relationship between IT investments and productivity or output, where: − negative effect; o insignificant effect or mixed results; + positive effect; – indicates the data have been collected independently or were marked as proprietary

ABI, Annual Business Inquiry; ACES, Annual Capital Expenditures Survey; AES, Assets and Expenditure Survey; ANIA, Italian Association of Insurance Enterprises; ASM, Annual Survey of Manufactures; ACD, Asian Computer Directory; BSCI, Business Survey into Capitalized Items; CEP, Center for Economic Performance Management survey; CMIE, Centre for Monitoring Indian Economy (Prowess database); CII, Computer Intelligence Infocorp; CITDB (formerly CII), Computer Intelligence Technology Database; CW, Computerworld; DH, Definitive Healthcare; ES, Enterprise Survey; ESI, Entrepreneurial Strategy Inquiry; CiDB, European Ci Technology Database; HIMSS, Healthcare Information and Management Systems Society Analytics Database; DGBAS, Industry, Commerce, and Service Census survey conducted by Directorate-General of Budget, Accounting and Statistics; IDC, International Data Corporation; IDG, International Data Group; IW, InformationWeek; JSW, anonymous Job-Search Website; FAR, Fixed Asset Register; LOMA, Life Office Management Association; MPIT, Management Productivity and Information Technology; MIP-S, Mannheim Innovation Panel for the Service Sector; MIS, Manufacturing Innovation Surveys; MCU, Mediocredito-Capitalia-Unicredit Survey; MIIT, Ministry of Industry and Information Technology; OSHPD, Office of Statewide Health Planning and Development; QICE, Quarterly Inquiry into Capital Expenditure; SIS, Service Innovation Surveys; SME, Small and Medium-Sized Enterprise; SBS, Survey on Business Strategies; SSBS, Service Sector Business Survey; SIS, Service innovation surveys; SORS, Statistical Office of the Republic of Slovenia; SBU, Strategic Business Unit; TURKSTAT, Turkish Statistical Institute; WADOH, Washington State Department of Health; WBES, World Bank's Enterprise Surveys

4.1.2 Adjustments delays and managerial challenges as a result of technological change

What appears to be the key factor in explaining the mixed results in this research field, however, is the period under investigation. Most articles that exhibited a negative or insignificant relationship between IT investments and productivity considered at least in part a period before the late 1980s (e.g. Dunne et al. 2004; Ko and Osei-Bryson 2008; Loveman 1994; Menon et al. 2009; Strassmann 1985, 1990; Weill 1992), whereas studies with a subsequent observation period indicated mostly a significant positive relationship between IT investment and productivity. The importance of the observation period is, for instance, highlighted by Kudyba and Diwan (2002), who noted slightly increasing returns on IT investments between 1995 and 1997 as well as Tambe and Hitt (2012), who indicated that the returns on IT investments between 2000 and 2006 are higher than in any previous period.

Learning-curve effects A reason for this circumstance could be the innovative nature of IT in the 1970s and 1980s and the associated difficulty of learning and adjusting to a new technology. The lagged occurrence of productivity effects can be explained by S-curves. A disproportionate improvement in the performance of a technology only occurs after a certain time, which is attributed to learning-by doing effects (Arrow 1962). Given the high level of complexity and the low level of IT expertise at the time, the learning phase for many early IT users was probably fairly extensive. Especially, since IT had not yet reached its current omnipresence in everyday life and the utilization of IT at the workplace was a complete novelty for many employees. This meant that, on the one hand, employees had to be trained to use the new technology correctly and, on the other hand, companies had to identify productivity-enhancing applications for IT (Brynjolfsson 1993).

Changes in skill requirements and emergence of new jobs After all, the introduction of IT into the workplace severely altered the tasks of employees. Autor et al. (2003) found that from the 1970s onwards, the share of routine cognitive and manual tasks in the US economy declined, whereas the share of non-routine analytical and interactive tasks increased. This shift in assigned tasks may have led to a temporary decline in the productivity of employees, as they had to adapt to modified skill requirements. Moreover, the adaption of IT did not only lead to a shift of tasks, but to the emergence of completely new jobs (Spitz-Oener 2006). Since such jobs require a novel skill set, most workers are likely lacking the necessary qualifications. At the same time, the labor market and educational institutions had to adapt to the new skill requirements, leaving a period with a potential shortage of adequately qualified workers. The hype about IT back then may have also resulted in pre-emptive investments, creating situations in which companies have owned IT capital but had a workforce that could not utilize it (Kwon and Stoneman 1995).

Insufficient capital stock of IT and compensatory effects Also, at the early stages of IT adoption, most companies might just not have enough IT capital to affect productivity in a meaningful way. Especially, since computers can only be used effectively for communication and information distribution if a large portion of the workforce is equipped with them. When computers were introduced in companies, they were still relatively expensive and therefore not yet widespread in all areas of a company. In 1977, only 10% of the plants analyzed by Dunne et al. (2004) stated that they were investing in computers. By 1992, this figure had surged to over 60%. While IT investments grew by about 300% during the 1980s to $1 trillion (Mahmood and Mann 2005), in 1992 alone the total investment in IT amounted to nearly 160 billion in constant 1987 US$ (Lee and Barua 1999). The impact of the initially low IT capital stock may therefore have been too modest to be measurable. Only as the IT capital stock grew over the years as a result of rising IT expenditure, the potential of computers and the associated network effects were unlocked (Brynjolfsson and Hitt 1998). Dewan and Min (1997) address another important issue. They discovered that IT capital is a net substitute for other forms of capital in all economic sectors. This suggests that the slow increase in labor productivity may be due to the compensatory effect of a reduction in non-IT capital per employee coupled with an increase in IT capital per employee. As the IT capital stock rose the non-IT capital stock might have declined, leading to an offsetting effect.

IT as general purpose technology David (1990) and Simon (1987) offer a different explanation, arguing that IT might be a General Purpose Technology (GPT). Also according to Bresnahan and Trajtenberg (1995), a technology must be pervasive, improve over time and lead to numerous complementary innovations to be considered as a GPT. Consequently, such technologies are typically key components in a multitude of machines or applications and serve as the basis for the development of innovations. The steam engine, for example, was an important GPT that fulfilled these criteria. It had been used in a wide range of new applications, from powering spinning looms in mechanized factories to the propulsion of locomotives, enabling a new and innovative transportation system. Almost a 100 years passed, however, between the innovation of the steam engine and its deployment as productivity-enhancing technology (Crafts 2004). Thus, the more far-reaching and profound the potential restructuring associated with the introduction of a new technology is, the greater the time lag between its invention and its ultimate impact on the economy, which is especially true for GPTs (Brynjolfsson et al. 2018). While the steam engine was the backbone of the economy in the eighteenth century and electricity triggered a second industrial revolution in the nineteenth century, IT was seen by many as a technology of similar magnitude and the foundation of a third industrial revolution. But only through the transformation of work processes and complementary innovations in the wake of the steadily increasing IT investments the "true" potential of IT could be realized, resulting in a delay until productivity gains materialized. Triplett (1999) cautions, however, that historical analogies are often misleading. Particularly the high degree of individuality of steam engines, electricity or IT and the resulting heterogeneous applications and implications should be taken into account. Thus, just because it took extensive time for other GPTs to lead to productivity gains, it cannot be assumed that IT will follow a similar pattern.

Exaggerated expectations In a similar vein, Carr (2003) and Gordon (2000) noted that the expectations regarding IT may have been exaggerated, as its strategic and economic impact is considerably less far-reaching than commonly assumed, particularly when compared to the disruptive innovations of the past. IT may have just not provided companies with the competitive edge they desired, as a multitude of IT applications became readily available for purchase on the market (Clemons and Row 1991; Mata et al. 1995). If every company can simply buy IT applications, then the development or purchase of those no longer offers a competitive advantage, as there is no barrier for competitors to do the same (Barney 1991; Clemons and Row 1991). So even though IT investments were potentially valuable to companies, as they could increase efficiency, every competitor could just buy a similar type of software. It therefore made little sense from a strategic point of view to invest huge sums to develop an IT application in-house if one could simply buy a similar, state-of-the-art application on the market for a fraction of the cost. The more companies began to buy off-the-shelf applications, the more the competitive the market became, which in turn led to falling prices, making the technologies widely accessible and affordable. The result was an increasing homogenization of applications as more and more companies replaced self-developed applications with generic ones. This may have cumulated in IT becoming "essential to competition but inconsequential to strategy" (Carr 2003, p. 6). Basically, IT became a commodity. Based on this premise, the strategy for companies also changed significantly. Instead of being one of the first to develop and implement an IT application, it may have been better to be one of the last in adopting them, buying best practice, ready-to-use solutions at a reasonable price (Carr 2003). Thus, companies may have in the beginning overspent on IT. Only as time progressed and companies started to change their expectations regarding IT, thereby altering their strategy from spending huge sums to be one of the first to lower spending on ready-made solutions, IT investments started to pay off.

Mismanagement There is also the possibility that IT did not lead to productivity gains because managers were unaware of how to properly implement and use IT. They may have misunderstood IT as a mere tool to increase efficiency instead of recognizing its true potential. Dos Santos and Sussman (2000, p. 431) summed this circumstance up strikingly: "An emphasis on IT to improve current efficiencies assumes that the future will be the same, only more so. Firms operating from this perspective strive to do the same things only do them faster and cheaper. […] [T]hey try to increase their speed in the race they have entered rather than questioning whether they have entered the right race." This failure in strategic thinking may have led to the underwhelming productive gains by IT early on. Likewise, managers may have struggled to align IT strategy and business strategy leading to dysfunction and underwhelming performance effects of IT investments (Henderson and Venkatraman 1993; Chan and Reich 2007).

Moreover, managers themselves probably had difficulties in measuring the contribution of IT to the success of the business and therefore had little indication of how to optimize IT practices (Willcocks and Lester 1996). This problem in assessing the value of IT investments may also have led managers to apply heuristics or personal assessments to determine the optimal level of IT capital instead of rigorously conducting cost–benefit analyses. As a result, managers may have determined the IT budget based on their perceived value of IT and continued to invest in IT because they believed to benefit from it, when in reality no productivity gains were achieved (Brynjolfsson and Yang 1996).

In addition, the introduction of IT has rendered some established management concepts obsolete (Macdonald et al. 2000). In the 1960s and 70s, for example, the premise was to always use all available information for decision-making. In an IT-driven business world, however, this can result in information overload (Ackoff 1967; Eppler and Mengis 2004) and complicate decision-making rather than improve it (Brynjolfsson 1993). This issue may have been reinforced by management's (unconscious) resistance to adapt to the changing environment (Dos Santos and Sussman 2000).

4.1.3 Developing countries and the healthcare sector

Nonetheless, there are some studies with more recent data, which reported an insignificant or even negative effect of IT investments on productivity (e.g. Chowdhury 2006; Menon et al. 2009). This seems to be mainly due to two reasons: the country of data collection and the industrial sector. Although there are hardly any disparities in studies with data from industrial countries and a positive relationship between IT investments and productivity can be observed consistently, studies in developing and newly industrialized countries such as Tanzania and Kenya (Chowdhury 2006), Malaysia (Tam 1998), Taiwan (Huang 2005; Huang et al. 2017; Liu et al. 2014), China (Lee et al. 2011), Brazil (Commander et al. 2011), India (Commander et al. 2011; Khanna and Sharma 2018), Turkey (Kılıçaslan et al. 2017) as well as Uruguay (Aboal and Tacsir 2018) occasionally exhibit insignificant (Tam 1998) or even negative (Chowdhury 2006) effects of IT investments on productivity. The reasons cited for this circumstance include a still relatively small IT capital stock, a low degree of IT diffusion, a lack of public investments in infrastructure and education as well as pre-information age business models (Dewan and Kraemer 2000).

In addition, there are differences between the industrial sectors, whereby insignificant or mixed effects of IT investments on productivity are especially prevalent in the healthcare sector (e.g. Baker et al. 2017; Ko and Osei-Bryson 2004, 2008; Lee and Menon 2000; Menon et al. 2009). An explanation may be that hospitals have a unique structure, where administration and medical staff are two separate entities, which are competing for resources, working under divergent conditions and pursuing different agendas (Menon et al. 2009). In addition, output measurement is particularly challenging in this sector. The key value driver for hospitals is in- and out-patient days, which is a difficult parameter to base productivity estimations on. On the one hand, patients should recover as rapidly as possible while, on the other hand, the hospital generates more revenue if they treat patients for as long as possible. Productivity is also not necessarily the ideal or only parameter to measure the performance of hospitals. Improvement in patient care, reduction in treatment costs, mortality rate or infection rate are all important objectives that are not necessarily related to productivity. Besides, Baker et al. (2008), Lee et al. (2013) and Wang et al. (2018) which utilize larger sample sizes and more recent data than previous studies found a positive interaction between IT expenses and productivity. Thus, the productivity paradox in the healthcare sector may have just endured for a longer time period than in other industries.

4.2 Reversing the paradox: excess returns of IT investments

In contrast to earlier research, studies with an observation period after the late 1980s not only overwhelmingly found a positive relationship between IT investments and productivity, but IT investments even yielded so-called excess returns (e.g. Brynjolfsson and Hitt 1996; Dewan and Min 1997; Hall et al. 2013; Hitt and Brynjolfsson 1996; Lehr and Lichtenberg 1998, 1999; Lichtenberg 1995; Tambe and Hitt 2012; Wilson 2009).[4] If an additional unit of investment in IT does indeed create more value than its costs, the question arises: why are managers not spending more on IT? Thus, a reversal of the initial paradox had potentially occurred, shifting the narrative from a presumable lack of measurable IT returns to abnormally high IT returns (Anderson et al. 2003). Following the economic relation between inputs and output, there seem to be two potential explanations for this new phenomenon: either, there are some hidden forces that prevent or discourage managers from investing more in IT or, the returns of IT are just overstated.

4.2.1 Spillover effects

A possible explanation for the sudden appearance of excess returns could be that, as more and more firms began to invest in and accumulate IT capital, external benefits associated with spillover effects started to occur. Spillovers are generally grouped into either rent spillovers or knowledge spillovers (Griliches 1979). Rent spillovers occur when goods or services are bought by firms for a lower price than their quality-adjusted price. This happens, for instance, when a supplier introduces a new supply-chain system, which simplifies and accelerates the ordering process, thereby reducing transaction cost for buyers, while the supplier cannot capture the rent due to the competitive environment (Chang and Gurbaxani 2012). Knowledge spillovers are external benefits through the dissipation of knowledge from its creator to other parties (Agarwal et al. 2010). For example, when IT workers transfer from one firm to another, knowledge about complementary business practices to IT or IT-related management practices can diffuse across the firm boundaries (Tambe and Hitt 2014a; Wu et al. 2018). Similarly, a firm can obtain spillover benefits if it buys goods electronically from a supplier. This gives the firm insight into the processes and structure of the electronic sales activities. Accordingly, knowledge about the supplier's IT-related sales activities is acquired, which can in turn be implemented in the firm's own system. This knowledge transfer is cost-free and a by-product of the actual order. Thus, the transfer of this knowledge is free of charge and provides firms with know-how for which they do not have to provide anything in return, which can

[4] Rational managers should invest in an input factor until an additional unit of the input creates no more value than its costs, resulting in a net marginal product of zero. Therefore, if the marginal returns outweigh the marginal costs, the difference is referred to as an excess marginal product or excess return (see Lehr and Lichtenberg 1999).

result in an excess return (Chang and Gurbaxani 2012). Taking into account the non-rivalizing properties of IT-related knowledge transfer and the fact that successful IT investments not only depend on the underlying technology, but also the knowledge about its optimal application, IT seems particularly prone to benefit from spillover effects (Wu et al. 2018). At the firm level, there have been relatively few studies on this topic so far, albeit research interest has increased noticeably in recent years (Chang and Gurbaxani 2012; Tambe and Hitt 2014a, b; Wu et al. 2018). For instance, Chang and Gurbaxani (2012) showed that the estimated level of private IT returns is significantly higher if the effects of IT-related spillover effects are not considered. Consequently, they assumed that not taking spillover effects into account is a possible cause of the excess returns on IT investments. Tambe and Hitt (2014b) suggested that productivity gains spill over from other firms' IT investments and contribute 20 to 30% of the productivity growth internal IT investments do. Additionally, they observed that these productivity benefits can be primarily attributed to the proximity of IT-intensive firms and the mobility of skilled IT workers within a region. Taken together, spillover effects may be a substantial contributor to the emergence of excess returns on IT investments.

4.2.2 Risk premium

Another aspect which may not explain the sudden appearance of excess returns, but could shed some light in their continued existence, is the risk associated with IT assets. Dewan et al. (2007) showed that investments in IT are considerably riskier than investments in other types of capital and that firms with a high IT risk have a substantially higher IT marginal product compared to firms with low IT risk. Therefore, firms must earn a substantial risk premium to justify investing in IT. Accordingly, managers will set a higher hurdle rate for IT investments to compensate for the higher risk. Following this assertion, an additional unit of investment in IT does not only need to equal its cost, but also cover the associated risk premium. They concluded that around 30% of the gross returns on IT investments have to be viewed as a risk premium. Disregarding IT risk could therefore lead to an overestimation of IT returns.

4.2.3 Insufficient rental prices for IT

The marginal costs are usually represented by the rental price (which reflects how high the rent of an investment good would be for one period). Therefore, a high marginal return does not necessarily indicate excess returns, but can merely reflect high depreciation rates. For example, the rental price for IT is considerably higher than for other capital investments, since hardware and software become obsolete more rapidly as a result of constant innovations in the IT sector and must therefore be replaced in progressively shorter cycles (Cardona et al. 2013). Rental prices for IT may therefore be set too low, as the ever-shorter innovation cycles in the IT sector are not sufficiently accounted for. Brynjolfsson and Hitt (1996) themselves point to this phenomenon and suggest that the rental prices applied for computer capital may be inadequate. But even if they take a conservative approach and assume that computer capital will be fully depreciated within 3 years, they still get a net marginal product of about 40% for IT capital. In essence, insufficient rental prices for IT alone cannot explain the high excess returns.

4.2.4 Adjustment costs and omission of complementary investments

The most prominent explanation for the appearance of excess returns is the disregard of adjustment costs and the resulting unmeasured complementary investments (Brynjolfsson and Hitt 2000, 2003; Brynjolfsson et al. 2002; Dedrick et al. 2003). IT is often viewed as an asset that creates productivity improvements by itself. To implement an IT system successfully, however, it has to interact with other actors within and outside the firm. This may create a need for additional investments in order to properly integrate an IT system. For example, non-IT workers need to be trained in the use of a new software or consultants may be hired to restructure business processes (Brynjolfsson and Hitt 2003). Consequently, whenever a new IT system is implemented, it requires certain complementary investments. The costs of these complementary investments such as training or consultancy services are, however, immediately expensed and not included as part of the IT investment, even though trained workers or an optimized work flow may improve the productivity effects of a new IT system substantially (Brynjolfsson and Hitt 2000). There may, therefore, be a systematic overestimation of the marginal product of IT, as the IT input is underestimated. In order to determine the true return of IT investments, it would be imperative to take into account not only the actual investment in IT but also the associated costs, since these often amount to a multiple of the initial IT investment (see Brynjolfsson et al. 2002). Various studies examined in this paper, however, measure IT investments solely based on the expenditure for hardware (e.g. Brynjolfsson and Hitt 1996, 2003; Chwelos et al. 2010). Some try to include expenditure on software or IT-related services, but usually measure them very broadly like estimating them based on IT labor (e.g. Dewan and Min 1997; Hitt and Brynjolfsson 1996). If complementary investments were included on the input side, the returns from IT may look much more moderate.

Moreover, even though these adjustment costs may not have been accounted as part of the IT input in the production function, the efforts firms have undergone to fundamentally change their business may still have hampered productivity early on. While the returns from IT during its inception may have been reduced by a fundamental transformation of firms, later on, these massive changes and the build-up intangible assets started to pay off (Brynjolfsson et al. 2019b). Thus, the sudden improvements in productivity may just be a consequence of firms reaping the benefits from the early investments in individual and organizational learning accompanied by a fundamental restructuring phase in late 1970s and early 1980s.

4.3 Factors influencing the returns from IT investments

One particularly interesting finding, which further underlines the importance of complementary investments, is the circumstance that while multiple studies reported a significant positive effect of IT investments on productivity, they also emphasizing a high variance of these returns among firms (e.g. Brynjolfsson and Hitt 1995, 1996; Dunne et al. 2004; Ross 2002). When examining, for example, the scatter plots provided by Brynjolfsson and Hitt (2000) and Brynjolfsson (2003), a strong variance of the data points around the trend line becomes clearly visible, which might cause vanishing IT-induced effects on average. Brynjolfsson and Hitt (1995) stated that firm-specific effects may account for up to 50% of the productivity improvements imputed by IT, but that the relationship between IT investments and productivity remains significant and positive even after accounting for individual firm differences. In other words, the source of the benefit of IT investment is twofold: On the one hand, there are productivity advantages due to the different levels of IT investments and, on the other hand, there are firm-specific effects, which enable some companies to deploy IT more productively than others.

4.3.1 Existing IT resources

Naturally, the success of every IT investment depends on the context surrounding it (Dehning and Richardson 2002). One particularly relevant factor appears to be the IT resources already present within a company (Bharadwaj 2000; Melville et al. 2004). According to Melville et al. (2004) IT resources can be divided into technological IT resources and human IT resources. Technological IT resources can be further grouped into IT infrastructure and business applications. IT infrastructure is described as a shared information delivery base, whereas business applications are certain software like ERP or customer relationship management (CRM) systems that are utilizing the IT infrastructure. Additionally, human IT resources represent the technical skills of employees like programming or system integration and managerial IT skills like the coordination of IT projects. The importance of aligning these IT resources with new IT investments is essential for their success. For instance, IT infrastructure forms the foundation for future business applications. If it is error-prone or inflexible, the benefits of a newly introduced business application will also be limited (Broadbent, Weill and Neo 1999). Likewise, firms with strong human IT resources are able to integrate IT investments more effectively into existing processes, refine acquired applications and tailor them to business needs (Bharadwaj 2000).

4.3.2 Complementary organizational factors

An important component of the value of IT is the ability to enable organizational change and fundamentally transform business processes (Hammer 1990). The introduction of IT without or with insufficient organizational change can lead to a substantial productivity loss as the benefits of IT are potentially offset by negative interactions with existing organizational structures and practices (Brynjolfsson and Hitt 2000). In the past, hierarchical organizational structures were designed to reduce the communication costs and were therefore seen as advantages compared to flat hierarchies (Malone et al. 1987; Radner 1993). Since IT drives communication costs towards zero, it enables a more decentralized organizational structures which is better suited to the new flow of information (Bresnahan et al. 2002). Therefore, it is important to keep in mind that companies are fundamentally heterogeneous. They have different hierarchical structures, varying internal processes, diverging management styles and unique workplace practices, whereby some practices, structures or processes may be particularly synergistic with IT. Those are generally referred to as complementary organizational factors and defined as "non-IT resources within a firm that complement IT to affect organizational performance" (Wiengarten et al. 2013, p. 34). So in order to fully exploit the productivity-enhancing potential of IT, it is necessary for firms to adopt a set of complementary organizational factors (Brynjolfsson and Hitt 2000; Milgrom and Roberts 1990).

This raises the question, which organizational factors are complementary to IT. One mentioned in various studies is a decentralized organizational structure (e.g. Bresnahan et al. 2002; Tambe et al. 2012). As computer monitored processes, e-commerce or website traffic result in a tremendous amount of stored data, it becomes difficult for executives to process and analyze these nearly endless streams of information. This information overload can have negative effects on performance, as individuals tend to perform better when they have access to more information, but only up to a certain threshold (Eppler and Mengis 2004). When this threshold is reached, the performance of individuals drops rapidly, as any additional information cannot be included in the decision making process (O'Reilly III 1980). As a result, they get confused, have problems in prioritizing tasks and have difficulties in recalling prior information (Schick et al. 1990). In order to circumvent this phenomenon, firms can distribute information-processing tasks among various employees within the organization (Bresnahan et al. 2002). This can be achieved by an increase in lateral communication and a stronger reliance on decentralized decision-making (Brynjolfsson and Mendelson 1993). Francalanci and Galal (1998a, b) indicated based on their samples of 34 and 52 life insurance companies that an increase in IT expenses per se has a negative effect on labor productivity. According to Francalanci and Galal (1998b), an increase in IT expenses is, however, associated with productivity gains when accompanied by a decreasing proportion of clerical and professional workers. These results suggest that a decentralized decision structure is synergistic with IT, as such an organizational structure is generally accompanied by a higher proportion of managers and lower portion of clerical workers (Francalanci and Galal 1998b). Devaraj and Kohli (2000) discovered that IT investments in connection with restructuring measures increase the performance of hospitals. Bertschek and Kaiser (2004) indicated that a flattening of hierarchies and increased team-work do not increase the output elasticities of ICT investments. Commander et al. (2011) noted that Brazilian firms with flatter hierarchies deploy their ICT capital more productively. Enhanced monitoring of employees and strengthened management decision-making based on up-to-date information, however, had no influence on the impact of ICT capital on productivity. Tambe et al. (2012) considered a model consisting of IT, organizational structure and external focus (a company's ability to recognize and respond to changes in the external environment). They concluded that a decentralized decision structure and higher external focus are complementary to IT and, in combination, lead to higher productivity improvements than IT investment without these factors.

Besides structural changes, the skill and educational level of employees is another possible complementary factor to IT investments. IT is outperforming human resources particularly in cognitive and manual routine tasks. For this reason, computers and other machines are commonly applied for putting together pieces at an assembly line or double entry bookkeeping. As a result, the number of routine tasks performed by most employees has decreased. On the other hand, the number of complex and demanding tasks in the workplace has increased. Even though computers have a comparative advantage over human labor in performing routine tasks, they cannot identify creative or innovative solutions to unfamiliar problems (Autor et al. 2003). This is why especially highly qualified employees benefit from IT, as they are more capable of dealing with the altered focus towards more complex tasks. At the same time, qualified workers boost the productivity of IT. They are able to make adequate use of the capacity of computing systems and thus exploit the potential of the technology to a higher degree. Also, training costs can be minimized, since highly educated employees usually have more pronounced analytical as well as problem-solving skills and, thus, adapt to new technologies faster (Moshiri and Simpson 2011). For instance, Bresnahan et al. (2002) showed that a higher level of IT is associated with an increased delegation of decision power to individuals and teams as well as a higher education level of employees and that both factors increase the productivity-effects of IT. Becchetti et al. (2003) revealed that software investments enhance the demand for skilled labor. Gargallo-Castel and Galve-Górriz (2007) indicated a synergistic relationship between ICT investment, a high proportion of skilled workers and a proactive attitude by managers. Contrary, Giuri et al. (2008) found that combined investment in ICT, skilled workers and organizational change has a negative impact on the productivity levels of firms.

Other possible complementary factor to IT is certain management practices or the general commitment of managers towards IT. Especially nowadays, investments in IT often have very large volumes and firm-wide effects. Since managers have a good overview of the entire company, they are most capable of recognizing in which areas investments in IT appear to be sensible and how these can be adequately deployed to generate added value for the firm. Moreover, visible management support leads to a more positive attitude of employees towards the new technology, which in turn contributes to its smoother adaptation. Management should therefore not only decide on the purchase of IT, but also supervise the implementation of the IT investment and play a key role in planning the long-term direction of the investment (Thong et al. 1996). In addition, the alignment of IT investments with the strategic direction of the firm is crucial, as it creates a mutual direction of business and IT objectives and integrates the investment into a larger vision (Tallon et al. 2000). Weill (1992) showed that top management commitment to IT, prior IT experience, user satisfaction and political turbulences moderated the relationship between IT investment and firm performance. Bloom et al. (2012), who examined the productivity impact of

IT between European-based companies and US multinationals operating in Europe, concluded that US-lead companies deploy IT more productive than European ones. This is attributed to tougher human resources management. In US multinationals, above-average employees are promoted faster and receive bonuses more rapidly. In return, below-average employees are laid off quicker. These proactive human resources policies seem to be synergistic with IT investments.

4.3.3 Environmental factors influencing IT

Besides, the complementary organizational factors which are controlled by firms, there are also environmental factors outside the firm that influence the productivity effects of IT investments (Schryen 2013). For instance, firms operate in different industries and markets. This in turn means that they are exposed to varying competition characteristics. In certain industries, such as oil and gas extraction, there are considerably higher entry barriers than in the field of software development. As a consequence, companies in areas with high competitive pressure caused by the constant emergence of new start-ups or other competitors have a higher incentive to make (early) returns on their investments. Therefore, it can be assumed that under such conditions IT investments yield on average higher returns, as the margin for error is smaller. Melville et al. (2007) found that firms operating in more competitive industries achieve particularly high returns on IT investments. Loukis et al. (2007) concluded that a higher bargaining power of suppliers leads to a higher contribution of ICT investment to output, as the enhanced pressure forces firms to use IT more efficiently.

Additionally, the countries in which firm operate bring varying challenges. In Germany employee protection laws are much more pronounced and trade unions more powerful than in the US, making it considerably more difficult to dismiss unproductive workers. This can be a potential disadvantage like already shown in the study of Bloom et al. (2012). Commander et al. (2011) explored the impact of the institutional and policy environment on the relationship between ICT capital and productivity in Indian and Brazilian firms. Their results indicated that poor infrastructure quality and stricter labor market regulation (pro worker) are related to lower ICT capital intensity, while poorer infrastructure is also linked to diminishing returns on ICT capital. The educational standards of a country must also be taken into account. Studies in developing countries such as Tanzania and Kenya even found negative effects of IT investments on productivity, as they may be a technology-skill mismatch (Chowdhury 2006).

4.3.4 Type of IT investments

Another important, but rarely discussed aspect is that not only firms and their environment is heterogeneous, but also the IT investments themselves (Dehning and Richardson 2002). Aral and Weill (2007) note that so far little is known about how different types of IT affect the performance of companies. Investments of similar magnitude in new computer keyboards or in a cyber-physical system (CPS) that allows the firm to improve the process management and increase the level of automation, are likely to have different impacts on a firm's productivity levels. Some IT investments may also be implemented with the objective to improve other areas like customer orientation (Nakata and Zhu 2006) or costumer service (Ray et al. 2005). In almost all studies we analyzed IT is regarded as a uniform asset with the aim to increase productivity. There are, however, a few exceptions. Rai et al. (1997) distinguished between expenditures for hardware, software, IS staff and telecommunications, whereby all components except software were positively associated with labor productivity. Weill (1992) differentiated between strategic, transactional (cost-reducing) and infrastructural investments and found that only transactional IT investments have a significant positive impact on firm performance.[5] IT investments with a strategic orientation even had a negative effect on the firm performance in the short-run and a neutral one in the long-run. Becchetti et al. (2003) revealed that ICT investments have a significant and positive influence on labor productivity. When ICT investments were decomposed into software, hardware and telecommunications, only software investments exhibited a significant effect. So, whereas some types of IT investment may lead to productivity increases, others may add value in different areas or no value at all.

4.3.5 A model of factors influencing the relationship between IT investments and productivity

Existing IT resources, complementary organizational factors, environmental factors or even the type of IT investment can all be causes of the varying productivity effects of IT investments (see Fig. 1).

The key question for most organizations is how to make the best possible use of IT investments in order to become a "positive outlier" in the data themselves. Thereby, it seems particularly important to understand the relation between organizational complements and IT investments. Although several studies have shown that highly skilled employees and a decentralized decision structure are complementary to IT and increase the return on IT investments, this cannot be viewed as a blueprint every firm should rely on. Given a firm's individual characteristics, a centralized decision structure with a low-skilled workforce in combination with IT may be the best option for some firms. For example, if they mainly invest in IT to implement automation initiatives. Determining a universally valid bundle of complementary factors to IT is therefore improbable. To identify a valid cluster of complementary activities or factors, IT investments have to be investigated at a disaggregated level, as IT investments that have a common objective or are of a similar type may require similar complements to be successful.

[5] Weil (2007) further disaggregated IT-Investments into infrastructural, informational, transactional and strategic ones.

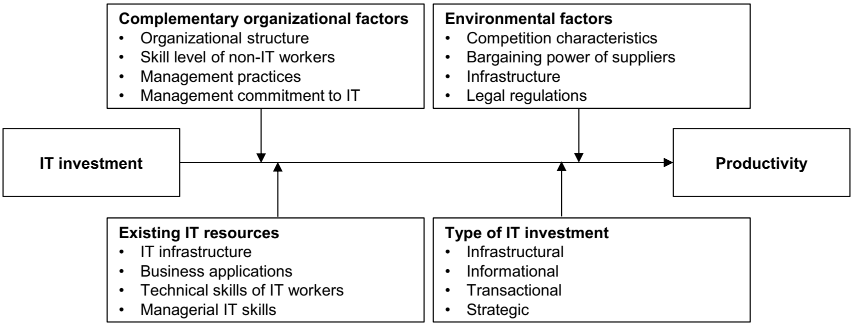

Fig. 1 A model of factors influencing the relationship between IT investments and productivity, based on Melville et al. (2004) and Aral and Weill (2007)

4.4 Lag effects of IT investments

Even though, early studies in particular may have been affected by longer time periods between the IT investment and its payoff, there is always a certain delay until a technology is fully adopted by a firm. It is difficult to predict how long it exactly takes to realize the desired productivity effects from IT investments (Brynjolfsson 1993; Kauffman and Weill 1989; Weill and Olson 1989). Yorukoglu (1998) showed that an one-year increase in the average age of IT capital led to an 2% increase in output, indicating substantial learning-by-doing effects. Hitt et al. (2002) indicated a slowdown in business performance and labor productivity shortly after the implementation of ERP systems. However, the financial markets rewarded users of ERP systems with a higher market valuation. The market probably anticipates that investments in ERP systems will generate added value in the future and includes this future increase in the current market value. Brynjolfsson and Hitt (2003) found that computer investments contribute approximately their factor share after one year. This means that computers add to production growth in the short term, but not to productivity growth. Over a longer time horizon (between 3 and 7 years) computer capital is associated with an output contribution that is two to five times greater than the short-term effect, resulting in a substantial contribution to long-term productivity growth. This suggests that studies that do not take into account time lags tend to underestimate the actual impact of IT investments. As a result, cross-sectional studies seem inadequate to measure the impact of IT investments, as time lag cannot be taken into account (see Mahmood and Mann 2005). Also, Menon et al. (2009, p. 299) pointed out that "the maturation rate—that is, the pattern of business value of IS over time—of different types of IS will differ." Besides, Tambe and Hitt (2012) noted that IT investments pay off quicker in mid-sized firms than in large firms. It seems therefore unlikely to determine a specific time delay for IT investments as a whole. Rather, studies have to divide IT into different systems or types and group firms into different categories (e.g. small/large or low/high degree of vertical integration) to gain a more profound understanding of the lag effects.

4.5 Measurement issues

Especially during the inception of the Solow Paradox, measurement errors were a topic various researchers referenced as the cause of the low measured productivity of IT (Baily et al. 1988; Brynjolfsson 1993; Denison 1989; Triplett 1999). Thereby, pointing at either the difficulties in accurately assessing the input, the output or both.

4.5.1 Measurement problems of the independent variable

The most obvious problem is to define and specify the independent variable. The first step is to clarify what IT investment or IT capital is and how it can be measured. In their work, Hitt and Brynjolfsson (1996, p. 127) describe how IT investments should be measured: “Ideally, we wanted to incorporate all components that are considered IT into our measure. A broad definition could have included hardware expenses (computers, telecommunications, peripherals), software expenses (in-house or purchased), support costs, and also complementary organizational investments such as training or the costs of designing and implementing IT-enabled business processes.”

At the same time, however, they state that such a measurement of IT investments was not attainable due to the lack of adequate data. This problem applies to all studies listed in the literature review. There is not a single study that measures IT investment at its full extent. There is most likely a correlation between the commonly used expenditure on hardware and overall cost of the IT investment. Nevertheless, there is a systematic measurement error in the literature, which can lead to phenomena like the excess returns on IT investments. This is particularly problematic, as 30 years ago hardware expenditures may have been an acceptable equivalent of IT investment, but nowadays hardware expenses are often only a fraction of total IT investment. These days, not the number of computers, nor the total computing power are the most critical factors to the success of IT projects, but the embedded software and the way it is utilized. The intangible nature of these two components makes the empirical measurement even more difficult. The key problem of studies on the Solow Paradox therefore seems to be the collection of accurate data on the independent variable. This also fosters inaccuracies when specifying the independent variable. Even if studies refer to the same construct like IT intensity or IT capital it can contain completely different components and consequently result in different findings. The recent study by Acemoglu et al. (2014, p. 397) makes exactly this point: “different measures of IT intensity thus appear to give different results.”

4.5.2 Measurement problems of the dependent variable

A largely neglected aspect is that the widely used Cobb–Douglas production function assumes that inputs cause output. In practice, however, the output level can also have an impact on the input level, e.g. when the IT budget is tied to prior firm performance. Hu and Plant (2001) and Baker et al. (2017) confirm this assertion by showing that firms with higher productivity levels increased their IT investments, whereas the level of IT investments had no direct effect on productivity.

But also the output cannot always be unambiguously quantified. The accurate measurement of productivity presupposes that both the output quantity and quality can be adequately measured. Otherwise, the resulting bias can cause an over- or underestimation of the output elasticities. As far as the output measurement is concerned, deflation of prices to account for inflation and quality changes is particularly important in order to be able to compare real values (Jorgenson et al. 2000). More difficult than the necessary deflation is the estimation the value completely new goods and services create, as they have no predecessors to compare them to (Brynjolfsson 1993). But the industry also plays an important role. Due to the intangible nature of services, improvements cannot always be traced back to the increasing use of IT and, thus, accurate output measurement is particularly difficult in the service sector (Triplett 1999). Furthermore, the kind of benefits often attributed to IT, such as an improvement in customer service or higher product variety, are not directly reflected in the productivity statistics or accounting figures (Brynjolfsson and Hitt 1995).

5 Discussion of the modern productivity paradox

While it became apparent that in the beginning of the computer age most studies did not find IT-induced productivity improvements, studies covering an observation period from the late 1980s through 2006 have overwhelmingly indicated a positive relationship between IT investments and productivity. At least on the basis of the conducted studies at firm level, we would argue that the Solow Paradox might have temporarily disappeared during this time interval. This does not imply that the Solow Paradox would have re-emerged at the firm level afterwards, but merely that there are not enough studies with an observation period after 2006 to assess the impact of IT investments on productivity during this period. While firm level studies with an observation period after 2006 are scarce, industry or country level studies are actually indicating that the Solow Paradox might have recently returned, as despite the growing investments in modern technologies, there is no measurable acceleration in productivity growth (Agrawal et al. 2019a; Brynjolfsson et al. 2018, 2019b). Thus, the often proclaimed fourth industrial revolution and subsequent adoption of modern technologies like IOT, AI or blockchain seem to have failed to live up to the high expectations placed upon them so far. This early lack of productivity effects from the adaptation of new technologies displays parallels to the beginning of the computer age, when no increases in productivity could be measured either. Naturally, this raises the question whether the insights gained from the literature on IT productivity research can be extended to the modern productivity paradox and contribute towards uncovering some causes for the current productivity slowdown. During the course of this work, we identified a variety of potential causes for the absence of IT-induced productivity effects, which are grouped into four overarching categories: adjustment delays, measurement issues, exaggerated expectations and mismanagement (see

Table 3 Possible causes for the emergence of the Solow Paradox

Classification	Causes of the Solow Paradox	Selected references
Adjustment delays	Small IT capital stock	Brynjolfsson and Hitt (1998)
	Compensatory effects	Dewan and Min (1997)
	No spillover-effects due to the limited diffusion of IT	Chang and Gurbaxani (2012), Tambe and Hitt (2014b)
	Learning-curve effects	Brynjolfsson (1993), Yorukoglu (1998)
	Pronounced phase of organizational restructuring	Brynjolfsson and Hitt (1998), David (1990)
	Emergence of new and complex tasks	Autor et al. (2003), Spitz-Oener (2006)
Measurement issues	Over-or underestimation of inputs and output	Brynjolfsson (1993), Diewert and Fox (1999), Triplett (1999)
	Reallocation and dissipation of profits	Brynjolfsson (1993)
Exaggerated expectations	IT is simply less productive enhancing than expected	Carr (2003), Gordon (2000)
Mismanagement	Shortcomings in the deployment, use and evaluation of IT	Brynjolfsson (1993), Dos Santos and Sussman (2000), Willcocks and Lester (1996)
	Lack of organizational complements to IT	Brynjolfsson and Hitt (2000), Clemons and Row (1991), Melville et al. (2004), Wade and Hulland (2004)

Table 3).[6] Therefore, we discuss the current productivity slowdown in light of the identified causes for the emergence of the Solow Paradox.

5.1 Adjustment delays

The first line of reasoning is that although there is no acceleration in productivity growth due to modern technologies yet, the slowdown in productivity growth is not necessarily permanent (Brynjolfsson et al. 2019b; Crafts 2018). Like at the beginning of the computer age, companies have just started to invest in modern technologies such as AI, Blockchain or VR. Thus, the nature of investments must be kept in mind. From an economic point of view, an investment is the purchase of resources that are not consumed today, but will be utilized in the future to create additional value. This is also applicable to investments in modern technologies. Therefore, it may still be too early to expect substantial productivity improvements in the near future. For example, global blockchain spending is expected to reach \$2.9 billion in 2019, which pales in comparison to the estimated global IT spending of \$3.76 trillion in 2019 (Gartner 2019; IDC 2019). Consequently, the investments in modern technologies may so far simply be too modest and the accumulated capital stock too small to have a significant influence at the corporate, industry or national level. Also, due to this limited diffusion of modern technologies, firms probably are not able to benefit from spill-over effects yet.

[6] These categories are quite similar to the ones proposed by Brynjolfsson (1993), but contain different sub-categories.

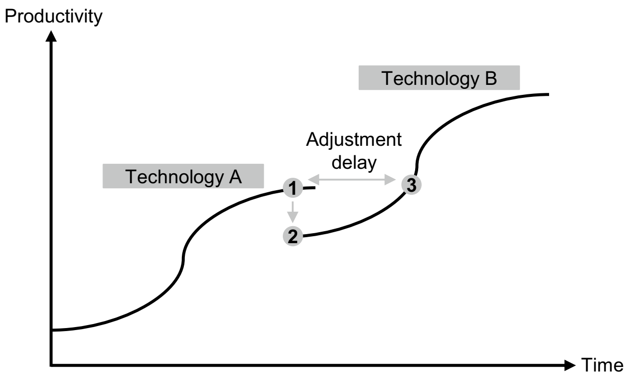

Fig. 2 Adoption of a new technology by a firm can lead to a temporary decline in productivity (1–2) as internal process need to be adjusted and employees need to be trained in the use of a new technology (2–3)

Furthermore, many firms are in a learning phase regarding the opportunities to make productive use of modern technologies. On the one hand, if companies want to offer new products based on modern technologies, they must initially invest in research and development in order to develop those products. These investments will, however, lead to no revenue boost in the near future, since it takes time before these products are ready to be launched. Thus, they are increasing the input, without affecting the output, leading to a possible short-term decline in productivity (Brynjolfsson et al. 2019b). Due to learning-by-doing effects it takes also some time until new products can be produced with the same degree of efficiency as existing products. On the other hand, firms may not only utilize modern technologies to develop new products, but also implement them to improve internal processes, which can be a lengthy process (Brynjolfsson and Hitt 2000). While a technological change may result in a higher productivity in the long-term, the associated adaptation phase on the product as well as process level can cause a temporary decline in productivity (see Fig. 2).

Moreover, certain modern technologies like AI possess the potential to emerge as GPTs (Aghion et al. 2019; Agrawal et al. 2019a; Brynjolfsson et al. 2018, 2019b; Cockburn et al. 2019; Trajtenberg 2019), which can entail an even more pronounced restructuring phase. Since it has taken other GPTs (e.g. steam engine or electricity) decades until they led to significant productivity gains, the same could be true for modern technologies. This can be attributed to the circumstance that GPTs are heavily reliant on complementary innovations and fundamental restructuring of processes to realize their full potential (Bresnahan and Trajtenberg 1995).

Though, not only firms need to adapt to technological change, but also labor markets and the education system. Acemoglu and Restrepo (2018, 2019) assume that an increase in automation through modern technologies will be accompanied by the emergence of new, labor-intensive tasks in which workers have a comparative advantage over modern technologies. As a result, workers who have been displaced by automation are reintegrated into new fields of activity, partially offsetting the displacement effect of automation. However, the imperfections of the labor market and weaknesses in the education system can slow down this process and mitigate the productivity gains from automation. Since jobs with completely new qualification requirements are created, there is a discrepancy between the requirements of the new occupations and the actual qualifications or skills of workers. The labor market is therefore not able to adequately occupy the newly created jobs with qualified workers at the beginning of a technological change. Considering that Frey and Osborne (2017) indicated that 47% of the 2010 US employment is at a high risk of being (at least) partially computerized within the next one or two decades, the far-reaching and comprehensive change in tasks performed by workers due to modern technologies could be a major contributor to a contemporary productivity slowdown.

5.2 Measurement issues

The second line of reasoning is that although there is productivity growth, it might be not measured accurately (Feldstein 2015; Mokyr 2014; Brynjolfsson et al. 2018). Syverson (2017) argues that there are two potential measurement issues, which could explain the current productivity slowdown. First, only a small portion of the utility, new technologies like smartphones provide to consumers, is included in their prices. This argument is based on the premise that the actual selling price of new technologies like smartphones is relatively low in relation to the time consumers spend utilizing them. Building on this observation it could be argued that new technologies generate substantial benefits for consumers, leading to a growing consumer surplus, while only a small part of the customer benefits is reflected in the sales figures of firms. Second, the stagnation in productivity could be due to the use of incorrect price deflators for new technologies. Syverson (2017) concludes, however, that even though there are most likely some unmeasured benefits of new technologies (see Brynjolfsson et al. 2019a; Diewert et al. 2018), the measurement error is too small to explain the current productivity slowdown. In a similar vein, Byrne et al. (2016, p. 109) stated that they “find little evidence that this slowdown arises from growing mismeasurement of the gains from innovation in information technology” and Acemoglu and Restrepo (2019, p. 210) noted that “the productivity mismeasurement hypothesis [is] unlikely to account for all of the slowdown.”

Although, there seems to be consensus that problems in assessing output quality, price deflators and consumer surplus are not the sole origin of the modern productivity paradox, Brynjolfsson et al. (2018) brought forward another type of mismeasurement, which could explain the modern productivity paradox. They suggested that when firms are adopting a new GPT (e.g. AI), they are temporally forgoing output to build up stock of unmeasured capital assets, i.e. firms are undertaking measurable investments in labor or capital to generate intangible, non-measurable capital inputs (e.g. knowledge), which have at first no impact on output levels. Consequently, as companies invest to accumulate non-measurable capital inputs, productivity growth is initially underestimated. As soon as these intangible capital assets begin to have an effect on output productivity growth is overestimated because the employed input is underestimated. Assume a firm wants to implement a new AI-based solution to

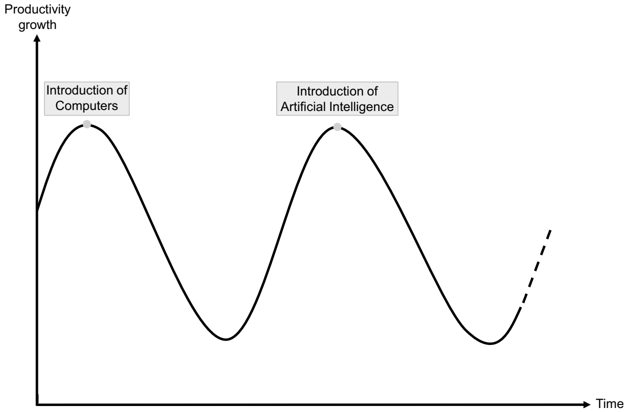

Fig. 3 Potential pattern of productivity growth due to the properties of GPTs

predict purchases of customers based on their online behavior, as prediction is one of the most promising applications of machine learning (Agrawal et al. 2019b). In a first step, they need to hire new personnel and train current employees. Also, they have to restructure established business processes to collected, store and analyze the data. The firm is not creating any measurable output, but gains knowledge about how to restructure the business processes, how to implement such software and what the best ways are to predict purchasing behavior. They compile knowledge, which is not measured on the balance sheet and has at the beginning no effect on the revenue of the firm. Thus, it remains hidden from the productivity statistics in the respective periods. But once the AI-based solution starts to increase the revenue and the accumulated knowledge yields a return, the inputs are underestimated and productivity growth is overstated (Brynjolfsson et al. 2018). Thus, there is potentially a underestimation of productivity during the inception of a GPT and a overestimation of productivity as it diffuses, leading to a potentially decline in measured productivity growth after its introduction and an surge in measured productivity growth later on (see Fig. 3).

Another measurement problem, which is primarily of concern for studies at the industry or country level, is the reallocation of revenue or profits between different firms (Brynjolfsson 1993). What is quite remarkable about the current productivity slowdown is that there is a continuing increase in labor productivity growth at frontier firms (firms with the highest productivity levels) while laggard firms (all other firms) seem to stagnate. This causes an increasing divergence in labor productivity between firms at frontier as well as laggard firms and a stagnation of productivity growth on average (Andrews et al. 2016; Gal et al. 2019). At the same time, a small number of superstar firms are gaining more and more market share, while in turn smaller firms are losing out (Autor et al. 2017). This may be due to the emergence of new platform- and data-driven business models and the increasing relevance of network effects. The more users participate in a platform, the lower the marginal costs per user and the more attractive the platform gets, which in turn attracts additional users (van Alstyne et al. 2016). Ultimately, "positive feedback makes the strong get stronger and the weak get weaker, leading to extreme outcomes" (Shapiro et al. 1999, p. 175). The same applies to data-driven business models. The more data is collected (e.g. by having more users), the more "training data" is available to improve the underlying machine learning algorithms. If more people use Google because it provides the best search results, more data is generated, which improves the machine learning algorithms and in turn leads to smarter search results. So it is of little surprise that Google dominates the global search engine market with a market share of approximately 92% as of December 2018 (Statcounter 2018). This powerful positive feedback loop helps firms to establish a quasi-monopoly by acquiring as well as controlling critical and large data sets and can cumulate in a race between firms for users and data (Cockburn et al. 2019). Ultimately, this "the winner takes it all" logic, will cause a very small number of highly productive and profitable firms with high market shares to remain in the market, while other market participants are being slowly displaced. Due to the market power of the remaining firms, it becomes almost impossible for competitors to re-enter the market. The current use cases for many new technologies may therefore make only a few firms disproportionately more productive without increasing the productivity of an industry or the economy as a whole. Gordon (2016) accordingly states that companies IT expenditure for marketing-purposes (e.g. big data analytics) has grown three times as fast in recent years as other corporate IT expenditures, as the battle for market share becomes increasingly important. Likewise, AI is currently used primarily to optimize targeted advertising and pricing in e-commerce (Bauer and Jannach 2018; Brynjolfsson et al. 2018). Although these applications may increase the customer base and sales of individual companies, it does not generate added value for the industry as a whole, since the gain in market shares is at the expense (loss of customers) of competitors. Naturally, this can force competitors to increase their budgets for marketing expenses in order to regain market share, which leads to intense competition and can ultimately end in a race for survival which makes no company more productive.

5.3 Exaggerated expectations

The third line of reasoning is that the expectations about modern technologies are exaggerated, as they will not induce the anticipated productivity improvements (Gordon 2016; Nordhaus 2015). Gordon (2016) argues that earlier innovations such as steam power, internal combustion engines or electricity have had far more far-reaching effects than modern technologies and that the primary increase in productivity due to digitization was captured in the late 1990s and early 2000s in the form of increasing automatization. Following this reasoning, modern technologies may simply be not as revolutionary as generally assumed and have only marginal effects on certain sectors or in specific applications. When taking, for instance, a closer look at smart products, the added utility they provide could indeed be questioned, particularly on a consumer level. Smart running shoes do not make anyone run faster than traditional ones would or smart watches fulfill their primary function of displaying time not any better than an analog watch. Similar arguments could be made for smart TVs, smart washing machines, smart door locks, smart refrigerators, smart coffee makers and so on. None of these products has an impact like the introduction of automatic washing machines, dishwashers or refrigerators had, which led to enormous time savings and a substantial increase in consumer welfare (Gordon 2004). When examining the smart products offered to end-costumers, most of them do not improve the core function of the device but add additional options like smart watches enabling someone to monitor its puls rate or smart running shoes recording the distance run. Though, these functions seem to only add marginal benefits to customers. One can just wear a puls watch or calculate the distance run via a (virtual) map. Thus, a lot of smart devices seem to primarily add some convenience but not necessarily groundbreaking new functions to the devices, making these innovations rather incremental than revolutionary. For instance, it can be argued that the invention of the washing machine and the refrigerator had opened the way for women (at the time mainly women were responsible for household chores) into gainful employment, revolutionizing society. The effect the introduction of smart washing machines or smart refrigerators had, seems in comparison to be marginal at best (Gordon 2016). This could make it difficult for firms to charge high prices for their smart products, as the added utility provided to end-costumers seems to be rather small. Although consumers may not be willing to spend that much more on a smart product compared to a traditional version, firms may have already incurred substantial product development costs, leading to an increase in input without a corresponding rise in output. Of course there are some innovations like autonomous driving vehicles or smart factories, which could have substantial effects on productivity, but they are either not available or deployed at a large enough scale yet. At least for now, a case for over-optimism and exaggerated expectations regarding modern technologies could be made. If it does hold true, the paradox will endure, as productivity growth will not accelerate.

5.4 Mismanagement

A fourth line of argumentation is that modern technologies have the potential to enhance productivity growth, but managers are unable to properly implement and utilize them. In a digital economy in which shareholders are demanding investment in disruptive technologies (Lim et al. 2013) and managers are accelerating technological changes due to the fear of missing out on the latest technology revolution, a decline in business performance due to excessive and precipitous investments by managers appears to be a noteworthy risk. On the one hand, there is currently an immense amount of hype or buzz around the potential applications of modern technologies. On the other hand, there is only little known about best practices and only a few reliable clues regarding their true benefits, leading to a high uncertainty around the expected returns of modern technologies. There may even be managers who do not really understand how most of the modern technologies function (Davenport and Ronanki 2018). Under uncertain conditions like these, it can occur that managers begin to follow trends that are raised by "trendsetting" institutions such as consulting firms or mass media, even though the adoption of these "fashions" may be a suboptimal strategy (Abrahamson 1991, 1996). Hence, there is the inherent danger that managers may just buy into the hype around modern technologies and follow the narrative of ever more digitization, while disregarding traditional methods of fundamental analysis, leading to overshooting (Ho et al. 2011). For instance, Wang (2010) showed that companies associated with IT fashions in the media exhibit no improved short-term firm performance, but enjoy a better reputation and higher executive compensation. Based on these findings, it would be even rational for managers to pursue narratives of more digitization to increase their compensation, even though the company cannot expect performance benefits from these investments. In other words, a principal-agent conflict arises because the incentives of the managers (agents) are not in line with the interests of the shareholders (principal), which can lead to sub-optimal investment decisions and an improper effort allocation (Jensen and Meckling 1976; Ross 1973). In many cases, it is also not the technology, but the individual who represents the bottleneck in the production process (Triplett 1999). If management introduces a new technology without employees having exhausted the potential of the current technology or are not yet able to utilize the new technology, the question arises of how much additional value is created by such pre-emptive investment. An increase in investments without eliminating existing bottlenecks in the firm will not lead to an increase in productivity, but end in stagnation.

But even if managers invest in a modern technology at a reasonable scale, there is still the possibility that they deploy the technology incorrectly. Especially for firms, which are currently primarily users of modern technologies, one of the important challenges is the additional development of smart and connected products as well as services (Porter and Heppelmann 2014, 2015). Process improvements only help for a while to stay afloat in the face of declining value-added shares of physical products. This is why managers cannot simply try to become more efficient, i.e. to achieve more output with the same inputs, but must simultaneously use the existing inputs to generate higher-valued output. Otherwise, they end up in a competition marked by shrinking margins due to lower production costs in correspondence with decreasing sales, as a reduction in selling prices is the only way to remain competitive against providers of digital products. Abernathy (1978) already suspected that the excessive focus of firms on increasing efficiency limited their flexibility and innovative power. In his opinion, a company's competitiveness was not based on mere efficiency gains, but on the ability to be efficient without neglecting innovation. The focal point of a successful digital transformation lies therefore in equipping products with digital capabilities and being able to offer customers tailored services and solutions to meet their individual needs. Modern technologies should not be misunderstood as a medium to purely improve process innovation or automatization, but as a tool to equip products with digital capabilities to enable new services and business models to achieve long-term growth. Thus, firms must try to transform themselves from pure users of modern technologies to providers of digital products and services. Based on their global survey of 3076 business executives and 36 in-depth interviews Ransbotham et al. (2018) indicate that the focus of leading AI adopters has switched from utilizing AI to achieve cost savings towards revenue-generating applications, hinting at the fact that manager are slowly starting to realize the potential of modern technologies.

Moreover, Acemoglu and Restrepo (2019) argue that too large of an emphasis is being placed on utilizing AI to automate tasks and processes. On the one hand, this excessive automatization[7] fosters inefficiencies, directly reducing productivity and, on the other hand, is shifting focus away from other productivity-enhancing activities or technologies, slowing down productivity indirectly. There are currently a plethora of modern technologies like blockchain, AI, IOT, VR, AR or robots which firms could adopt. But the corporate (and research) emphasis is heavily skewed towards AI, as the presumably most promising technology. Thus, managers may focus too much on AI, without considering other technologies that could be better suited to meet their specific needs.

There is also a possible lack of complementary organizational factors like management skills to implement digitization strategies and to develop new business models (Amit and Zott 2010; Berman 2012; Chesbrough 2010). This subject is particularly important, as "a mediocre technology pursued within a great business model may be more valuable tha[n] a great technology exploited via a mediocre business model" (Chesbrough 2010, p. 354). Firms are currently facing the challenge of monetizing digital products and services. According to a study by Kart et al. (2013), which surveyed 720 IT and business executives, the monetization of collected data presents businesses with a greater challenge than the technical feasibility of data analysis. As digital transformation progresses, interconnected systems, sensors and e-commerce create more and more data for industrial and service companies, which need to be processed, stored and analyzed (Hartmann et al. 2016). However, if managers or executives are not in a position to eventually monetize the data, then there is an increase in investments without an equivalent upswing in output. The lack of productivity improvements could therefore be attributed to the fact that managers have so far failed to adopt new business models for modern technologies. Ignoring the importance of other complementary factors like the organizational structure or skill level of human capital can be equally detrimental, because what use does the best technology have, if workers cannot utilize it. Thus, an over-focus on the technology itself and a disregard for complementary organizational factors is a pitfall managers need to avoid.

Lastly, there is the difficulty for managers to evaluate investments in modern technologies, as the added value is oftentimes intangible and not fully depicted in accounting figures. Due to the novelty of modern technologies there also are no real benchmarks or best practices firms can use to compare the outcomes of their investment to. This can ultimately result in managers basing their investment decisions on their perceived value of the investment instead rigorous cost–benefit analysis. Oz (2005, p. 797) even assumes that executives may have completely abandoned the task of measuring the returns of IT: "Corporate boards of directors have long given up expecting a detailed return on investment calculation for investment in IT. They understand that it is infeasible. They approve investments because they believe in the intangible benefits." Such a behavior can be hazardous, particularly when managers develop a preconceived opinion about certain technologies, making over-optimism

[7] Meaning a "faster automation than socially desirable" (Acemoglu and Restrepo 2019, p. 210).

(potential over-investment) as detrimental as too much skepticism (potential under-investment). Essentially, managers should treat investments in modern technologies like any other investment and diligently calculate costs and benefits.

6 Future research and limitations

During the course of this work, we have identified a number of themes that warrant further research. For one, there seems to be still a lack of knowledge about the emergence und continued persistence of excess returns on IT investments at the firm level. While the research on spillover effects at the firm level has increased significantly in recent years, the relationship between IT investment, risk and productivity remains largely neglected. In addition, there is a lack of studies reflecting the full scope of IT investments, as there is at least to our knowledge no study including expenses for employee training and consulting services into their IT measure. Without truly depicting the entire cost of IT investments, the returns will always be overstated.

A better understanding of the timing of the amortization of investments in IT is needed as well. As companies invest in a variety of different IT projects, it is difficult to determine an average time lag between investment and pay-off. Investments in a digital manufacturing technology, for example, will yield returns much faster than investments in the development of digital product innovations, which may probably never come to market. Depending on the focus of the respective investment, the time intervals until the actual payout are highly variable. A first step towards answering this question would be to divide the IT investment into different types. A mere subdivision of IT investments into those with process and product orientation might already provide a better idea of the time lags.

In addition, it is still unclear under what conditions IT investments yield particularly high (or low) productivity gains. Thereby, it is important to consider which internal as well as external factors are critical to the successful deployment of IT. Within this paper, some aspects such as a high educational level of human capital or a decentralized decision structure were discussed as complements to IT. Due to the differences between firms it is, however, difficult to determine a specific set of factors that are synergistic with IT. In order to at least partially avoid this problem and to accommodate the heterogeneity of firms, case studies might provide a valuable method to gain deeper insights into the interplay of complementary factors and IT.

A striking characteristic of the current literature on the modern productivity paradox is the predominance of studies relying on conceptual or theoretical models as well as aggregated data at the industry or national level (e.g. Agrawal et al. 2019a; Brynjolfsson et al. 2018, 2019b). Consequently, there is a lack of empirical studies at the firm level, which can be attributed to the absence of data, particularly for non-physical technologies. Thus, there are various areas for future research, such as:

- Determining the effects of investment and use of modern technologies on the productivity, profitability, market value or intangible outcomes.

- Investigating which type of firms are primarily adopting modern technologies and what kind of strategies they are pursuing.
- Examination how modern technologies impact the decision making process of executives and employees (e.g. decision enhancement via AI).

Our systematic literature review is not without limitations. First, only articles published in academic, peer-reviewed journals were considered due to the preliminary nature of working papers or conference proceedings. Second, we solely included articles written in English, leading to the potential omission of relevant studies in other languages. Third, as part of our search process we have made some restrictions to ensure the relevance of the collected studies. This marks a trade-off between the relevance of the collected papers and the completeness of the review, but is a natural limitation when conduction a systematic literature review (Webster and Watson 2002). Lastly, although we performed an extensive search process, we cannot rule out the possibility of unintentionally omitting an article from our review.

7 Conclusion

In light of the persistent doubts about the productivity effects of IT investments and the current productivity slowdown, we tried to synthesize the existing knowledge on the Solow Paradox. Thereby, it became evident that the research on the Solow Paradox can be divided into two groups. While studies with an observation period after the late 1980s mainly found insignificant effects of IT investments, studies with a subsequent observation period indicated predominantly a positive impact of IT investments on the productivity levels of firms, partly suggesting even excess returns. The only exceptions seem to be studies conducted in the healthcare sector and in some developing countries. Thus, the proposed resolution of the Solow Paradox by Brynjolfsson and Hitt (1996) does not seem premature, at least according to the studies we analyzed. Based on the insights from our review, we discussed four overarching explanations namely adjustment delays, measurement issues, exaggerated expectations and mismanagement as reasons for the modern productivity paradox. While the current discussion focuses primarily on adjustment delays and measurement issues, the topic of mismanagement has so far been hardly considered, although it played a central role in the debate of the Solow Paradox. This can most likely be attributed to the macroeconomic focus of the current debate.

We provide five different arguments as a basis for potential mismanagement: First, excessive or precipitous investments in modern technologies as managers follow a narrative of ever more digitization. Second, a disproportionate focus on process improvements instead of simultaneously promoting product innovations. Third, exaggerated emphasis on AI as the key technology of the future. Fourth, lack of complementary organizational factors to modern technologies such as management skills to develop new business models and fifth, difficulties in evaluating the benefits of investments in modern technologies. These arguments do not necessarily imply that a deterioration in management quality has happened in recent years, but more likely that the demands placed on managers have risen due to the complexity of the digital transformation.

The current productivity slowdown can of course not be solely linked to the adoption of modern technologies. There are also other possible explanations like lingering effects of the financial crisis or the fact that productive ideas are progressively harder to find (Bloom et al. 2017). But to not at least consider the ongoing technological change as an important determinant of the deceleration in productivity growth seems ill-advised. Ultimately, time will tell if tech-pessimists like Gordon or tech-optimists like Brynjolfsson are proven right, even though the arguments brought forward by researchers currently point towards a future resolution of the modern productivity paradox.

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