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# THE RELATIONSHIP OF TECHNOLOGICAL AND ORGANIZATIONAL INNOVATION WITH FIRM PERFORMANCE: OPENING THE BLACK BOX OF DYNAMIC COMPLEMENTARITIES

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# The Relationship of Technological and Organizational Innovation with Firm Performance: Opening the Black Box of Dynamic Complementarities

Priit Vahter and Maaja Vadi *

## Abstract

This paper explores the dynamic nature of complementarities between technological and organizational innovation at firms. Using Spanish firm level panel data (PITEC) over period 2008-2016, it investigates how the formation, keeping and ending of the joint adoption of these two core types of innovation is associated with firm performance. In the case of the general static test of complementarities we find no evidence of complementarities. However, once we focus on the analysis of within-firm changes in the complementarity bundle of innovation types, we observe clear evidence that some sequential as well as simultaneous strategy switches towards combining technological and organizational novelties are associated with significant performance premia at firms. Our findings point out the key role of technological innovation in these complementarities. We find evidence of sequential complementarity only when organizational innovation is added to the already existing technological innovation at the firm, not when organizational innovation is added as first component before technological innovation. In the case of dissolving the complementarity bundle of innovation types, the key disadvantage for the firm is related to dropping the technological innovation. Giving up only organizational innovation while keeping the technological innovation appears to have no negative effect, on average, on firm performance.

**Keywords**: technological innovation, organizational innovation, complementarities, sequential complementarity

**JEL classification**: D24, L23, L25, O31

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# 1. INTRODUCTION

This paper explores the dynamic nature of complementarities between technological and organizational innovation at firms. We add to the literature on complementarities-in-performance by analysis of the effects of dynamics of formation as well as ending of the joint adoption of these core types of innovation in the complementarity bundle of innovations. Our study underlines that without accounting for dynamics and sequence in adoption of innovations in the complementarity bundle, the existence and economic significance of complementarities may be underestimated.

The standard definition of complementarity, in the case of two binary activities, is that two activities A and B are (Edgeworth) complementary if adding one activity increases the returns from the other one (Milgrom and Roberts 1995, Brynjolffson and Milgrom 2013). Complementarity view in innovation follows the belief that combination of innovation types leads to better performance than their exploitation—one type at a time. The effects of introducing a combination of various types of innovations at a firm are traditionally expected to be greater than the benefits of adopting different innovations one-by-one (Milgrom and Roberts 1990, 1995; Ballot et al. 2015; Damanpour 2014, Ichniowski et al. 1997, Polder et al. 2010). The Resource-Based-View (RBV) provides here a theoretical foundation for the analysis of complementarities by focusing on the integrated assets, resources and capabilities (Teece 1986) and their recombination (Lockett et al. 2009).

The complementarity relationship poses the natural questions for an organization: about simultaneity and sequence in the adoption process (Jovanovic and Stolyarov 1997, 2000; Damanpour 2014; Battisti et al. 2015; Battisti and Stoneman 2010). Organizations can make a choice between three main options of adoption of technological and organizational innovations – modernize the technology and renew the organization at the same time; or start from the technological innovation and complement it with non-technological innovation; or do that vice versa. In reality, the optimal choice between these alternatives varies case-by-case. Innovations may have a different pattern with regard to uncertainty about their outcomes, costs of adoption and sunk costs (Ganter and Hecker 2013, Jovanovic and Stolyarov 2000, Smith 2005) as well as the learning process (Jovanovic and Stolyarov 1997), path dependence and life-cycles (Ganter and Hecker 2014), leading sometimes to sequential rather than simultaneous adoption patterns (Battisti et al. 2015).

RBV of the firm implies that resource base of the firm is continuously subject to the processes of resource creation and decay (Lockett et al. 2009). The analysis of the changes in the complementarity-bundle[1] of innovation types fits well under the RBV. The joint (simultaneous and sequential) adoption is similar to what Milgrom and Roberts (1995) in their seminal paper on complementarities between organizational practices refer to as the ‘upward movement’ in a system of complements. At the same time, they also point out the ‘downward movement’ or the decline and collapse of the system of complements. Understanding this ‘downward movement’ and how it is associated with firm performance is currently still a gap in the literature on the complementarities of innovation types.

In this paper, we aim to investigate how the changes within the complementarity bundles of innovation types at firms are associated with firm performance. We focus on three directions of dynamics here: adoption (i.e. upward dynamics), giving up (i.e. downward dynamics) and

[1] We apply in this paper the complementarity bundle term, which reflects the combined synergetic combination of innovation types.

retention of innovation types (i.e. persistence of components) within the complementarity bundle.

First, we study the forming of a complementary relationship between the innovation types that takes place through the addition of the one type of innovation to the existing other one, or by the simultaneous introduction of technological and non-technological (organizational) innovation. The standard analysis of complementarities-in-performance in prior empirical literature too often neglects the focus on the sequence of the within-firm changes in the complementarity bundle. The analysis based on representative large firm level datasets has often focused on supermodularity tests of complementarities based on a single cross-section of firm level innovation survey data, without in-depth investigation of within-firm changes in innovation strategies (e.g. Ballot et al. 2015, Guisado-González and Pérez 2015).[2]

Second, our analysis of giving up elements of the complementarity bundle (i.e. downward dynamics) addresses the situation when the complementarity bundle is dissolved by stopping introduction of one or both of the innovation types. This direction is about the situation when an organization that has previously adopted both technological and organizational innovation has decided or is forced to discontinue in next period's the introduction of either of them or both of them. The changing of the elements of the complementarity bundle one-by-one is costly and difficult, due to the complementarity forces in the existing system limiting the change of one element of the system only (Milgrom and Roberts 1995).

Third, we also study retention (persistence of components) of the complementary bundle at a firm over time; this means that no upward or downward movements take place. There is extensive literature on the persistence of innovation and how it is associated with a firms performance. This includes, for example, Le Bas and Scellato (2014), Guarascio and Tamagni (2019). However, understanding the relationships between a firm's performance and its retention of the components of the complementarity bundle has remained limited.

To investigate these issues, we used yearly innovation survey panel data of Spanish manufacturing firms covering the years 2008-2016, from the PITEC dataset from Spain. We focus here on the complementarities-in-performance. We use the log of sales per employee as the firm level performance measure. Based on standard 'static' investigation of complementarities using the widely used supermodularity tests (Milgrom and Roberts 1990, 1995, Brynjolffson and Milgrom 2013, Ballot et al. 2015, Polder et al. 2010) we do not find evidence of significant synergy effects between technological and organizational innovation. However, once we focus on the analysis of 'dynamic complementarities' — the effects of strategy switches between combinations of innovations over time within firms, we find clear evidence that some (sequential and simultaneous) strategy switches towards combining technological and organizational novelties are, in fact, associated with significantly higher firm performance premia achieved in subsequent periods. Our analysis challenges the common static approach for the empirical investigation of joint adoption of innovation in complementary bundles. We implement here a more 'dynamic' mode of analysis, that has value in the context of investigation of complementarity effects of the core types of innovation over time, previously

[2] Our study of the role of the sequence of the adoption of innovations based on representative firm level data of manufacturing firms extends and generalizes the prior analysis of sequential complementarities in Battisti et al. (2015). They investigated complementarity-in-use between technological and organizational innovation in design, where they found evidence of sequential adoption from use of CAD software to introduction of inter-firm collaboration teams in design, and not the other way around.

applied in another context of complementarities – the synergy effects of firm's own R&D and external knowledge sourcing (in Love et al. 2014).

The rest of the paper is organized as follows. The next section explains the theoretical background and foundations of analysis of complementarities and outlines also the typology of combinations of different types of innovation and the changes in the complementarity bundle that we investigate. The third section outlines data and descriptive statistics. Fourth section shows and discusses, for comparison, the empirical results based on standard supermodularity tests of complementarities. The fifth section investigates 'dynamic complementarities' between technological and organizational innovation. The last section summarizes and discusses the contribution and implications.

## 2. LITERATURE REVIEW

### 2.1. Complementarity view

There is general agreement that technological innovation may require further introduction of other complementary novelties, including organizational change, in order to have significant effects on productivity and performance of an enterprise (Brynjolffson et al. 2018, Teece 1986). Complementarities in the innovation process can create momentum for a virtuous cycle of change for a firm that is able to adopt the different types of complementary innovations together.[3] At the same time, the existence of complementarities between different types of innovation can create inertia in upgrading the technologies and organizational practice, even impede change in less capable firms (see also Milgrom and Roberts 1995, pp. 190-191). For example, Brynjolffson et al. (2018) argue that the large and widening productivity gap between top firms (superstar firms) in the world and the rest may be reflecting the fact that investments into organization of work and other complementary assets are needed for the benefits of the technological change to materialize.

This reasoning about the need for complementary assets to benefit from innovation builds on ideas by Teece (1986) in his profiting-from-innovation framework, observations by Rosenberg (1979, p. 26) that innovations "hardly ever function in isolation", as well as ideas by Schumpeter (1934) on complementarity between the product and process innovation. Because of complementarities, the adaptation of an identical technology in the same sector and at the same geographical area has been argued to result in very different outcomes (Barley 1986). The general distinction between technological and organizational innovation at firms relates also to the more general categories of technology and social structure: how these are related and how they impact upon each other (Evan 1966, Perez 2009).

Adopting a complementarity perspective (Milgrom and Roberts 1990, 1995), our study clarifies how technological and non-technological (organizational) innovation initiatives are combined in an intertwined way. The complementarity of innovation types represents a certain configuration of relationships between the forming elements. The central mechanisms and activities in the innovation process are linked together by complementarity and substitutability relationships. Complementarity means that the addition of an activity or mechanism to an existing bundle interacts with the effect of other activities and mechanisms in the bundle, and

[3] The complexity of copying the complementarity mechanisms between different types of innovations may act as a powerful source of competitive advantage of the more capable firms, and effectively act as factor limiting imitation by competitors (Rivkin 2000).

thus the overall effectiveness of the bundle changes and the changes result in effects on firm's performance (e.g. Milgrom and Roberts 1995, Bresnahan et al. 2002).[4]

There is large empirical as well as theoretical literature on complementarities in innovation (Teece 1986; Ballot et al. 2015; Damanpour 2014, Ichniowski et al. 1997, among many others). For example, Brynjolffson and Milgrom (2013) provide a literature review of various papers that study complementarities of the technological and the organizational change.[5] A standard distinction in the analysis of complementarities runs between the complementarities-in-use and the complementarities-in-performance (see Cassiman and Veugelers 2006, Ballot et al. 2015). The complementarities-in-use and the complementarities-in-performance are not the same. For example, firms may not know which complementarities are beneficial or they may simply copy other firms, leading to joint adoption (complementarities-in-use) without positive performance effects (complementarities-in-performance) (Ballot et al. 2015). As standard methods of analysis, Milgrom and Roberts (1990, 1995) develop the supermodularity framework used in empirical testing of complementarities-in-performance between various organizational practices as well as technology adoption.

## 2.2. Sequential complementarity

Damanpour (2014) provides a literature review and a discussion of the simultaneous vs the sequential introduction of the technological and the organizational innovations. Our contention is that the literature is possibly focused even too much on the complementarity effects of simultaneous (i.e. in the same period) adoption of different types of innovation (see Battisti et al. 2015 and Damanpour 2014 for discussions). Further, the prior analysis of complementarities between the technological and the organizational innovations has been often based on the cross-section of innovation survey data (e.g. Ballot et al. 2015). If there exist significant complementarities between the types of innovation, this should be reflected in a firm's behaviour over time and therefore should be estimated based on firm level panel data (e.g. see Brynjolffson and Milgrom 2013 and Love et al. 2014 for discussion). This is the approach that we adopt in this paper.

The analysis of complementarities is about situations when one innovation activity or output (or more) is either added to the other already existing one over time or, alternatively, the case when these activities are simultaneously adopted. This intrinsically requires a dynamic analysis of the determinants and the performance effects of changes in innovation strategy choices (here: combinations of different types of innovation) of the same firm over time. As shown in Love et al. (2014) in the context of analysis of open innovation, omitting such within-firm 'dynamic'

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[4] Complementarities can also hinder change at firm level. It is, for example, well known that organizational innovation at firms is fraught with difficulties and is costly. One reason for that can be the complementarities in innovation process, which can mean strong difficulties with changing only one component of the system (e.g. Brynjolfsson and Milgrom 2013), whereas materialization of the benefits from the organizational change can require further changes in other components of the system.

[5] This differentiation between two core categories of innovation is related to the broader distinction between the technology and the social system (Evan 1966). The division of innovation types into two broad categories is mentioned by Daft (1978) who has shown, on the example of schools, that the technology (or 'technical core' as he called it) and the organizational innovation (he used the term 'administrative core') affected each other. He concludes that "the process of innovation appears to be contingent upon both types of innovation" (1978: 206). Many scholars have adopted this distinction, including for example Kimberly and Evanisko (1981) Damanpour (1987).

complementarities can lead to misleading conclusions about complementarities between a firm's own R&D and external knowledge sourcing.

There are several reasons why sequential adoption of innovations may often be optimal, rather than the simultaneous adoption. As a basic conclusion, Rosenberg (1979) and Brynjolfsson et al. (2018, among many others, point out that a (technological) innovation may need other next innovations to emerge before it has strong impact. This can limit also the diffusion of innovation and may mean that certain combinations of innovations will be adopted sequentially by firms. Jovanovic and Stolyarov (2000) discuss the role non-convex adjustment costs of innovations. They show in their theoretical model that sunk costs of different size in the case of adoption of different innovations may result in an optimal sequential adoption pattern rather than the simultaneous one. Jovanovic and Stolyarov (1997) point to another reason for sequential adoption: that there may be a learning period for one innovation or input before that innovation or input is used efficiently. Further, Smith (2005) argue that there is a reason for sequential adoption if prices or costs of the two innovations are expected to fall at different rates. For example, there may sometimes be a reason to wait with adoption of some IT novelty if its price is likely to fall in the future. According to Smith (2005) another reason for sequential adoption is the uncertainty about the future benefits or costs of adopting the two innovations (combined with the existence of sunk costs in adoption of innovations).

Battisti et al. (2015) point out that the sequential adoption of innovations may simply reflect the resource constraints at the firm. In addition to lack of finance and tangible resources, the limitations may concern the managerial cognition in organizing the adoption of many novelties simultaneously (Battisti et al. 2015). This idea builds on the classical studies on 'attention-based theories of the firm' (Ocasio 1997). Adner and Helfat (2003) consider managerial cognition as one central aspect in building dynamic managerial capability. There may be significant limits in managerial cognition as managers may find it difficult to allocate enough attention to critical issues in the innovation process, especially if the process involves complexities and requires the adoption of several key novelties simultaneously.

## 2.3. Patterns of sequence

There are rather different suggestions in the literature concerning the optimal sequence of technological and organizational innovation: whether we can expect the optimal pattern in the case of sequential adoption to be from adoption of technology at first to organizational innovation as a next step or from organizational to technological innovation.

Technological development, in particular in the case of emergence of new general-purpose technologies, impacts not only economic development and performance directly but it also brings about institutional and social change (Perez 2009). An important conclusion in analysis of effects of new technologies in economics is that the emergence of effects of new technologies (esp. general purpose technologies) take time (e.g. Brynjolffson et al. 2018, Tambe et al. 2020, among others). It is not until necessary complementary processes and innovations have been invented and introduced in the society, that the effects of emerging new technologies become visible in (aggregate level) productivity data. This suggests the likely first emergence and adoption of technological innovation, followed then by introduction of the novel organizational changes and other new complementary investments. Such an order is often assumed, either implicitly or explicitly, in analysis of complementarities of technological innovations. For example, the highly influential paper by Bresnahan et al. (2002) outlines exogenous price falls in IT as a source for introduction of technology, followed then by other types of complementary innovation: *"Specifically, our theoretical framework can be summarized as follows: declines in the price of IT, which we take as largely exogenous to our model, lead to increased adoption and use of IT. In turn, this increases the economic attractiveness of complementary investments in certain specific types of work organization (WO) and product and service innovations (S)."*

Socio-technical Systems Theory (Trist 1978) has seen technology as central part in the socio-technical systems in manufacturing industry, and takes the view that technology adoption is the factor that leads then next to development of certain organizational structure and organizational setting (Woodward 1980[6]). Also Damanpour (2014) in his discussion of relevant management literature recognizes the tendency in much of the literature to assign priority to technological innovation, while nontechnological innovations are viewed as secondary and also secondary in the sequence of adoption.

Some empirical data confirm that the adoption of the technological innovation at firms leads to the changes in organizational practices. For example, the study of Desouza et al. (2007) shows that at first the technology was adopted and only afterwards the work practices were adopted. These work practices modified the initially adopted technology by personalization, customization, as well as new inventions. Quite similarly, Brusoni and Prencipe (2006) demonstrate that robotized production leads to fundamental changes in organizations. Another example is by Battisti et al. (2015) who conclude that investment in IT at firms was a driver of organizational innovation, not the other way around. One likely reason for the sequence of adoption in their study were the declining prices of IT. In a further study, Arvantis and Hollenstein (2001) show that starting a complementarity bundle from the technological innovation has advantages because it leads to the cumulative learning.[7]

However, there is also evidence pointing to the converse type of the optimal sequence: the adoption of organizational innovation before technological innovation may be optimal. Evan (1984) finds, based on the sample of 85 public libraries, that organizational innovation triggers technological innovation more readily than the reverse. Also, the results of Colombo and Mosconi (1995) imply that organizational change at the firm will facilitate the installment of new state-of-the-art technology.

Many studies in the innovation diffusion literature and management literature argue that organizational innovation leverages the effect of other innovation practices (Anzola-Román et al. 2018, Mothe and Thi, 2010). The influences can take place through organizational culture and climate (O'Reilly and Tushman 2016, Hogan and Coote 2014, Brynjolfsson and Milgrom 2013), organization structure (Karim and Kaul 2015, O'Connor 2008, Teece 1996), management practices (Bloom and Van Reenen 2010, Gumusluoglu and Ilsev 2009, Birkinshaw et al. 2008), organizational members' creativity (Doehne and Rost 2021, Chaubey et al. 2021. Non-technological innovation facilitates attitudes, values, and behavioural patterns that may create preconditions for successful technological innovation.

[6] Woodward's (1980/1965) seminal findings show that firms with similar production systems appeared to have similar organizational structures. According to her study, technological change drives the various elements of organizational structure.

[7] Also, Lynch (2007) shows that organizational innovations at the firm are positively associated with past technological innovation (IT investments). Cumulative learning in technology adoption is empirically investigated in depth by Bourke and Roper (2016).

## 2.4. Dissolution of the complementarity bundle

Our analysis of dissolution of the complementarity bundle is about the situation when an organization has decided or is forced to discontinue joint implementation of technological and non-technological innovation. Such change is costly and difficult: namely due to the complementarity forces in the existing system. Building on the standard Edgeworth complementarity notion, we would expect there to be a large negative effect on performance in the case of both dropping both types of innovation or only one type (one element in the system) from the complementarity bundle. Dropping only one element would not only have its own direct negative effect but added large negative effect because dropping an element in a complementarity system would lower the returns from the other remaining element(s) (Milgrom and Roberts 1995).

Milgrom and Roberts (1995) further discuss complementarities linked to a firm's strategy. They point to the high importance of co-ordination of decision making in the case of complementarities and that centrally directed change can be vital for changing a complementarity-based system. Another important general aspect that they point to, is that the complementarity can mean that downward movement in the complementarity system, once started, would tend to continue. For instance, removing an element from the system may lead to the collapse of the system of complements. While there is much empirical literature on complementarities in general or simultaneous and sequential adoption of innovations, there is little attention on the issue of effects of dissolving the complementary system at firms. The analysis of effects of dissolution of a complementarity bundle (system of complements) of technological and organizational innovation is also related to the literature on effects of abandoned innovation (Leoncini 2016, Madsen and Desai 2010, Tsinopoulos et al. 2019, Love e tal. 2020). These, however, are not focused on specifically the consequences of abandonment of components of the complementary bundle of innovations. Such effect of dissolution of system of complements may be rather different from the positive effect of experimentation with different innovation inputs and projects, which has been shown in the past to be highly positively associated with firm's innovation performance (e.g. Leoncini 2016, Love et al. 2021).

## 2.5. Retention (persistence of components) of the complementarity bundle

A final key aspect in the dynamics of the system of complements between the technological and the organizational innovations is the retention (persistence) of implementation of these two types of innovation together over time. There is literature on the persistence of innovation and how it is associated with firm performance (see for example, Le Bas and Scellato 2014, Guarascio and Tamagni 2019, Cefis 2003, among others). However, there is less attention specifically to the retention of the components of the complementarity bundle. For example, Cefis and Marsili (2005) find that firms with both product and process innovation have higher likelihood of survival. Le Bas and Poussing (2014) find that complex innovators (product and process innovators) tend to be more persistent than innovators that introduce only the product or the process innovation. More recently, the study by Bartoloni and Baussola (2018) is one exception that links the discussion of the complementarities and the persistence and the firm performance effects. They test for complementarity between technological and non-technological innovation, in the case of the persistent and the occasional mode of innovation. They find, based on firm level data from Italy, that the capacities to develop market-oriented behaviour and introduce new organizational innovations complement the technological innovation and that their complementarity-in-performance is stronger if there is persistence in organizational and technological innovation.

In general, we would expect that the persistence in both technological and organizational innovation over longer time periods would be associated with high performance of the firm. We expect this effect to be higher than persistence in technological innovation alone or organizational innovation alone.

## 2.6. Research Propositions

For our analysis of complementarities-in-performance between technological and organizational innovation we outline four key mutually exclusive combinations of innovation at a firm:

1. No technological and No organizational innovation (*None*)
2. Has technological innovation and No organizational innovation (*onlyTech*)
3. No technological and Has organizational innovation (*onlyOrg*)
4. Has both technological organizational innovation (*Both*)

Technological innovation encompasses here both the product and the process innovations (as defined in Oslo manual 2005). Indicators of movement of a firm between these four key categories function as key basis categories for analysis of dynamic complementarities: including upward dynamics towards joint adoption of both types of innovation, as well as retention of the existing complementarity bundle and downward dynamics in terms of giving up one or both components of the complementarity bundle. The movements in terms of forming and dissolving of the complementarity bundle are summarized in Table 1 below.

**Table 1.** Directions in the forming and dissolving of the complementarity bundle between technological and organizational innovation

| To / From | None (1) | onlyTech (2) | onlyOrg (3) | Both (4) |
|---|---|---|---|---|
| None (1) | 1→1 | 1→2 | 1→3 | ⬆ 1→4 |
| onlyTech (2) | 2→1 | 2→2 | 2→3 | ⬆ 2→4 |
| onlyOrg (3) | 3→1 | 3→2 | 3→3 | ⬆ 3→4 |
| Both (4) | 4→1 ⬇ | 4→2 ⬇ | 4→3 ⬇ | = 4→4 |

Note: (1) Directions in the forming of complementarity bundle: upward⬆, downward⬇, retention =

(2) There are 4 mutually exclusive strategies or categories in each period:

1: None (No TechInn and no OrgInn); 2: onlyTech (Has TechInn and no OrgInn); 3: OnlyOrg (No TechInn and has OrgInn); 4: BOTH (Has TechInn and has OrgInn). Analysis of dynamic complementarities focuses on strategy switches over time. E.g. 2→4 denotes a switch from OnlyTech in current period to BOTH in the next period.

Drawing upon the discussion in the literature review above, we outline the key research propositions that we investigate in our empirical analysis.

Proposition 1. Simultaneous adoption of technological and organizational innovation is associated with improved firm performance, compared to firms that do not adopt innovations or do not adopt innovations in tandem (This corresponds to the movement in categories 1→4 in Table 1, compared to 1→1 and 1→2, 1→3).

Proposition 2. Sequential adoption of technological and organizational innovation is associated with higher firm performance, similar in magnitude to the relationship of simultaneous adoption of technological and organizational innovation with firm performance. (This corresponds to movement over time in categories 2→4 and 3→4 compared to 1→4 in Table 1).

Proposition 2a. Sequential adoption of technological innovation and organizational innovation. Adopting organizational innovation if the firm previously already had technological innovation is associated with higher firm performance, compared to adopting organizational innovation on its own without prior technological innovation at the firm. This corresponds to the comparison of the movements 2→4 with 1→3 in Table 1.

Proposition 2b. Sequential adoption of technological and organizational innovation. Adopting technological innovation if the firm previously already had organizational innovation is associated with higher firm performance, compared to adopting technological innovation on its own without prior organizational innovation at the firm. This corresponds to comparison of effects of movement 3→4 with 1→2 in Table 1.

Proposition 3. The retention (persistence) of complementary bundle of joint adoption of technological and organizational innovation over time (movement 4→4 in Table 1) has stronger relationship with firm performance than persistence in only the technological innovation or only the organizational innovation.

Proposition 4. Giving up a component of the existing complementary bundle of innovations (i.e. giving up either technological and organizational innovation from the existing bundle) has negative relationship with performance of the firm, whereas giving up the technological innovation (4→3 movement) has a stronger negative relationship with firm performance than giving up the organizational innovation (4→2 movement).

# 3. DATA AND DESCRIPTIVE STATISTICS

Our econometric analysis is based on yearly innovation survey data of Spanish manufacturing firms. We use yearly information of 2008-2016 from a balanced panel dataset PITEC. PITEC covers balanced panel data of more than 12,000 firms.[8] Of these, we focus on manufacturing firms. PITEC is a yearly panel version of the Community Innovation Survey in Spain. It has been developed by the Spanish Statistical Office – Instituto Nacional de Estadística (INE) – and Fundación Española para la Ciencia y la Tecnología.

[8] We acknowledge that due to the balanced nature of the dataset our analysis of complementarities is representative for surviving firms in Spain, but not for the new entrants and exiting firms. However, the balanced nature of the panel means also that the treatment and comparison group of incumbents are in fact more comparable compared to the case if the control group could cover also new entrants and exiters.

PITEC covers data on a wide set of innovation inputs and outputs, a s well as barriers and objectives of innovation and firm level characteristics such as sales and the number of employees, export market orientation, ownership of the firm. PITEC shares advantages and limitations with other datasets based on the CIS survey. See, for example, Mairesse and Mohnen (2010) for a discussion of advantages and limitations of the CIS). The PITEC dataset has, however, a key positive advantage over most of other countries' CIS datasets as it covers the same firms over a reasonably long period. This means that unlike much of the other analyses of complementarities, we can focus here on the within-firm changes in innovation. Overall, the years covered in the PITEC were 2003-2016. However, as some relevant variables are not available in the first years of the panel, we focus in our empirical analysis on yearly information of the same set of firms during 2008-2016.

PITEC is especially suitable for the purposes for our study, as it enables to cover the upward movements, retention and downward movements within the complementarity bundle of innovations, within the same firm. We focus in our investigation on manufacturing firms to ensure the comparability of the results across firms. The information in PITEC is collected yearly. However, in each survey wave at year *t* the questions on innovation inputs and outputs are about the last 3-year period, i.e. years t, t-1 and t-2. Other firm level controls such as employment and sales are available at yearly frequency. The dataset enables to calculate as key performance indicator the log of sales per employee, which we use in the analysis of complementarities-in-performance as a dependent variable (measured here in lead periods, after within-firm change in the complementarity bundle). PITEC also covers a number of firm level other characteristics that are used as controls in our regression-based analysis of complementarities.

## 3.1. Key explanatory variables

The key explanatory variables that are used in building the indicators of innovation strategy switches (as defined in the previous sections) in our analysis are the standard measures of the innovation outputs. We focus on dummies of technological innovation (either product or process innovation) and organizational innovation. The definitions of these variables are based on the OECD Oslo Manual (2005). A process innovation is defined here as the "application of new or significantly improved methods for the production or delivery/distribution of a good or service." Product innovation is the "provision of the new or significantly improved goods or services." Organizational innovation covers "new or significantly changed business practices in the organization of work, business structure and decision-making or in ways to manage external relations." Innovation can be either new to the market or new to the firm. We note that our analysis focuses on novelties that are at least new to the firm.

Construction of innovation strategy indicators and strategy switches at firm level builds on the two central innovation output indicators: A) technological innovation dummy (equal to 1 if the firm engaged in technological innovation in last 3 years) and B) organizational innovation dummy (equal to 1 if the firm engaged in organizational innovation in last 3 years). There are 4 mutually exclusive strategies or categories of firms in each period: 1: None (No TechInn and no OrgInn); 2: onlyTech (Has TechInn and no OrgInn); 3: OnlyOrg (No TechInn and has OrgInn); 4: BOTH (Has TechInn and has OrgInn).

Based on these 4 categories we construct indicators of strategy switches (transitions between the 4 categories) over time. As there are 4 combinations of the core innovation types by the firms, there are correspondingly 16 strategy switches (transitions) leading to upward or downward movements within the complementary bundle or retention of the components in the complementary bundle. For example, 2→4 movement in Table 3 below denotes a switch from OnlyTech in current period to BOTH in the next period, that is addition of organizational innovation to the already existing technological innovation.

## 3.2. Other controls

We include in our regression analysis in next sections also a set of additional control variables, to account for other observable factors of firm performance and to not confound the complementarity effects with these other factors. These include variables used as controls in other studies of complementarities (e.g. Ballot et al. 2015, Love et al. 2014, among others). We include firm size (log of employment) to account for the fact that large firms may be performing better than smaller ones. We further include as a control variable a dummy variable indicating whether the firm is a part of a larger group of firms and a dummy for foreign ownership, as both of them are known to be likely factors of firm performance (e.g. Arnold and Javorcik 2009). An important standard factor of performance to control for is R&D, therefore we include a dummy to indicate investment in R&D. Human capital and training can significantly impact the productivity of firms. Therefore we include a dummy variable to indicate firms that invest in training their employees for the purposes of innovation. Finally, we add year dummies and sector level dummies (the classification in PITEC is broadly similar to NACE 2-digit classification) to account for the period specific and the sector specific fixed differences.[9]

**Table 2.** Proportion of sample in each category of combination of technological and organizational innovation at the firm, period 2008-2016

| | **2008-2016 proportion (No)** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
|---|---|---|---|---|---|---|---|---|---|---|
| NONE | 0.26 (11,069) | 0.19 | 0.18 | 0.18 | 0.31 | 0.34 | 0.35 | 0.24 | 0.25 | 0.34 |
| ONLYTECH | 0.26 (11,109) | 0.29 | 0.32 | 0.35 | 0.23 | 0.20 | 0.20 | 0.26 | 0.25 | 0.20 |
| ONLYORG | 0.07 (2,877) | 0.05 | 0.04 | 0.04 | 0.06 | 0.09 | 0.10 | 0.08 | 0.09 | 0.09 |
| BOTH | 0.41 (17,689) | 0.48 | 0.46 | 0.43 | 0.40 | 0.37 | 0.35 | 0.42 | 0.41 | 0.37 |

Note: manufacturing firms. Total sample of 42,744 firm-year observations. There are 4 mutually exclusive categories of firms in each period: 1: None (No TechInn and no OrgInn); 2: onlyTech (Has TechInn and no OrgInn); 3: OnlyOrg (No TechInn and has OrgInn); 4: BOTH (Has TechInn and has OrgInn).

[9] In robustness tests we extend the set of controls to further account for collaboration in innovation, as well as barriers to innovation such as financial constraints. These do not change the results on complementarities reported in Results section.

**Table 3.** Transitions between the four core categories over time, share (%) of observations in each category

| **From / To** | **None (1)** | **onlyTech (2)** | **onlyOrg (3)** | **Both (4)** | **Sum, %** |
|---|---|---|---|---|---|
| None (1) | 84.64 | 6.84 | 5.42 | 3.09 | 100 |
| onlyTech (2) | 15.45 | 68.10 | 0.76 | 15.69 | 100 |
| onlyOrg (3) | 21.05 | 4.07 | 58.23 | 16.65 | 100 |
| Both (4) | 2.01 | 12.85 | 4.39 | 80.75 | 100 |

Note: Transition between two consecutive CIS 3-year time periods, over 2008-2016. There are 4 mutually exclusive strategies or categories of firms in each period: 1: None (No TechInn and no OrgInn); 2: onlyTech (Has TechInn and no OrgInn); 3: OnlyOrg (No TechInn and has OrgInn); 4: BOTH (Has TechInn and has OrgInn).

Table 2 and 3 show descriptive statistics of frequency of the 4 core categories of combinations of technological and organizational innovation (Table 2) and transitions of firms over two consecutive 3-year periods between these core categories of innovators (in Table 3, the category change is between the period covering years *t, t-1* and *t*-2 compared to the period covering years *t+1, t+2* and *t+3*). The largest share of firms is in the group BOTH, where firms introduce both types of innovation. On average, 41 per cent of all firm-year observations belong to this group of more ‘complex’ innovators. This could suggest likely complementarity-in-use of these two core types of innovations. However, joint use does not necessarily always imply stronger performance effects (complementarity-in-performance). Joint adoption could sometimes also simply reflect the fashions and management fads leading to adoption of certain types of novelties (e.g. Damanpour 2013). The next two groups by share of observations are the firms that introduce only technological innovation (26 per cent) and the firms that introduce neither type of innovation (26 per cent). The smallest group is the firms that introduce only organizational innovation at the firm (7 per cent). The lesser adoption of organizational innovation on its own compared to joint adoption together with technological novelties suggests that organizational innovation may be strongly linked to and driven by the technological change at firms.

Among the firms in PITEC, we do not observe any systematic increase (see Table 2) in adoption of both types of innovation during the studied time period. This suggests persistent barriers and (sunk) costs of adopting this more complex innovation strategy, despite its potential benefits in terms of effects on future performance. As we observe from Table 3, there is strong persistence of firms in both the BOTH category and NONE category. In the case of those that have in one period both types of innovation (BOTH in Table 2 and 3), even 80.8 per cent of those stay in that ‘complex’ innovator category in the subsequent period.

In the case of the upward shifts towards joint adoption, there is much evidence that the adoption of innovations is rather sequential than simultaneous. Only 3.1 per cent of firms with no innovation adopt simultaneously both types of innovation. This is likely to reflect the limited (complementary) resources and capabilities, including access to finance, for covering the sunk costs of the more complex innovation activities at these firms. There is much more movement upwards towards the more complex complementarity bundle among firms that have already introduced innovation in the past periods. As much as 15.7 per cent of those that start with only technological innovation end up with both types of innovation by the next period. We also observe that changing focus of innovation from only technological to only organizational is almost non-existent, less than 1 per cent of firms that start with technological innovation show such change over time.

Concerning the downward dynamics in a potentially complementary bundle: if firms give up an element in the bundle of innovations, then it is normally the organizational innovation. Only 4.4 per cent of firms that start from doing both types of innovation end up doing only organizational innovation in the next period (movement 4→3). However, even 12.9 per cent end up doing only technological innovation. Thus, giving up technological innovation is a much less preferred option and thus likely to be a costlier choice for the firm. Notably, only 2 per cent of firms that start in one period with both types of innovation end up with neither in next period (see Table 3). Such movement is much less frequent than other types of downward movements (see the last row in Table 3).

We further show descriptive statistics on firm performance (see Table 4), by the four mutually exclusive key combinations of technological and organizational innovation at the firm (NONE, ONLYTECH, ONLYORG, BOTH; as defined above). Clearly, the highest level of firm performance is among firms that have introduced both technological and organizational innovation. This can, of course, reflect selection of the best firms into introducing potentially complementary bundles of innovations, as this means a need to cover high sunk costs, as well as the separate and joint complementarity effect of the combination of these innovations on firm performance. The second-ranking group is the firms that engage only in technological innovation. Their gap with the performance level of BOTH category varies by year, with a 0.03 – 0.14 log points difference with the more 'complex' innovators that introduced both types of innovation. The third-ranking group consists of firms that do only organizational innovation. As expected, the lowest group is firms that do neither types of innovation.

**Table 4.** Firm performance (log sales per employee) by combination of technological and organizational innovation at the firm, 2008-2016

| | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
|---|---|---|---|---|---|---|---|---|---|
| NONE | 11.73 | 11.58 | 11.63 | 11.71 | 11.70 | 11.70 | 11.98 | 11.96 | 11.81 |
| ONLYTECH | 12.01 | 11.85 | 11.92 | 12.02 | 12.05 | 12.09 | 12.11 | 12.20 | 12.22 |
| ONLYORG | 11.94 | 11.76 | 11.83 | 11.84 | 11.89 | 11.94 | 12.09 | 12.17 | 12.02 |
| BOTH | 12.10 | 11.99 | 12.06 | 12.15 | 12.16 | 12.20 | 12.24 | 12.28 | 12.26 |

Note: manufacturing firms. There are 4 mutually exclusive categories of firms in each period: 1: None (No TechInn and no OrgInn); 2: onlyTech (Has TechInn and no OrgInn); 3: OnlyOrg (No TechInn and has OrgInn); 4: BOTH (Has TechInn and has OrgInn).

# 4. RESULTS

## 4.1. Standard analysis of complementarities based on supermodularity tests

Our empirical investigation of complementarities starts, as an introduction, from the standard supermodularity tests in regression model framework, building on the approach as developed and discussed in Milgrom and Roberts (1990, 1995)[10] and Mohnen and Röller (2005) or Athey and Stern (1998). This is the approach that is used in the closely related studies. One example is the paper by Ballot et al. (2015) based on CIS 2004 data from UK and France, among others (e.g. Polder et al. 2010). Also, supermodularity tests have been applied before based on data from Spain and the PITEC dataset that we use here as well: in Guisado-González and Pérez (2015) to investigate the complementarity between product, process and organizational innovation, where they find no complementarity in the case of 5 out of 6 pairwise relationships investigated. The approach based on the supermodularity test has advantages over the analysis of complementarities-in-use. Unlike the latter, the supermodularity test based investigation of complementarities-in-performance does not investigate only conditional correlations between two or more practices but focuses on the joint effects on performance indicators.

We start here from formal supermodularity definition of complementarity of two activities. Formal definition from Milgrom and Roberts (1990), Athey and Stern (1998) or Brynjolffson and Milgrom (2013) is as follows. Suppose there are 2 activities $A_1$ and $A_2$. Both activities $j$ can be performed by the firm ($A_j = 1$) or not ($A_j = 0$), $j \in \{1, 2\}$. The performance/payoff function $\Pi(A_1, A_2)$ is supermodular (Milgrom and Roberts 1990) and $A_1$ and $A_2$ are complements only if the following condition holds:

$$\Pi(1, 1) + \Pi(0, 0) \geq \Pi(1, 0) + \Pi(0, 1), \qquad (1)$$

i.e., complementarity or supermodularity of the performance function means here that adopting both activities $A_1$ and $A_2$together produces more positive effects on performance than the sum of the results produced by each strategy/activity choice individually.

The Condition (1) can be rewritten also as:

$$\Pi(1, 1) - \Pi(0, 1) \geq \Pi(1, 0) - \Pi(0, 0), \qquad (2)$$

i.e., adding an activity if the other activity is already being performed has a higher incremental effect on performance (Π) than adding the activity in isolation. This reflects the (Edgeworth) complementarity definition. In our context $A_1$ and $A_2$ would be technological and organizational innovation. There would be Edgeworth complementarity if adding organizational innovation increases the returns from doing technological innovation, or if adding technological innovation increases the returns from the firm's organizational innovation.

A standard approach has been to test the complementarities between innovation types by testing the Condition (2) using regression framework with labour productivity or firm performance as dependent variable. In our analysis we use panel data for that. Usually in the majority of other related papers firm level cross-section data from the CIS surveys is used. For example, Ballot et al. (2015) test pairwise complementarity of the product, the process and the organizational

[10] Milgrom and Roberts (1990, 1995) build on lattice theory from mathematics (Topkis 1976).

innovation, using data from one wave (CIS2004) of CIS from UK and France. The complementarities-in-performance testing operates by regressing firm performance (measured here in lead year *t+3*) on a mutually exclusive set of combinations of indicators (dummy variables) of technological and organizational innovation at the firm, as well as other key control variables that may affect performance. These four mutually exclusive combinations are defined as in previous sections, from (0, 0) for lack of technological and organizational innovation ($i.e., A_1 = 0$ and $A_2 = 0$ ) to (1, 1) for presence of both types of innovation ($i.e., A_1 = 1$ and $A_2 = 1$ ). There are 4 mutually exclusive categories of firms in each period. Correspondingly we have four dummy variables in our regression model: None (No TechInn and no OrgInn); onlyTech (Has TechInn and no OrgInn); OnlyOrg (No TechInn and has OrgInn); BOTH (Has TechInn and has OrgInn).

The corresponding regression model is the following:

$$Performance_{it+3} = \alpha_1 NONE_{it} + \alpha_2 onlyTECH_{it} + \alpha_3 onlyORG_{it} + \alpha_4 BOTH_{it} + \alpha_4 Z_{it} + \lambda_j + \tau_t + \nu_{it} \quad (3)$$

Here, *i* denotes a firm, *j* denotes a sector (at 2-digit NACE level), and *t* stands for the year. Vector Z stands for other controls, as defined in the data section. The model includes also sector specific effects and time period specific effects. $\nu_{it}$ denotes the error term. The model is estimated with simple OLS, with robust standard errors.[11] The coefficients of these mutually exclusive category dummies (4 dummies) will be then used for supermodularity test of complementarity between the two types of innovation, exactly as defined in Condition (2).

The results of the complementarities' analysis and the complementarities test as in Condition (2) are shown in Table 5. The highest productivity is, after accounting for other covariates, in the categories of firms that have either both types of innovation (coefficient with value 11.837) or firms that have only technological innovation (coefficient 11.830). These coefficients of BOTH and ONLYTECH variables are not statistically significantly different in the regression model in Table 5. We further observe that the productivity level of firms that have only organizational innovation is markedly lower, with the coefficient of this category dummy equal to 11.696, which is close to the level of productivity of firms that have neither types of innovation. Thus, we see as key distinction between firms the fact whether they engage in technological innovation. The benefits of organizational innovation are much lower compared to technological innovation. We note that these results are also confirmed if we use firm performance from year *t* instead of *t+3*.[12]

[11] As the analysis is based on OLS estimation, we note that the estimated performance premia can also reflect to an extent the selection of the best-performing firms into adopting both types of innovation, not only the causal effect of the complementary bundle of innovations on performance. The model is estimated without the constant.

[12] However, the same survey year's performance effect may reflect, to a large extent, the performance based selection into different innovation combinations. Therefore we prefer the specification with the dependent variable from *t+3*. We acknowledge that this specification may still suffer from endogeneity issues due to reverse causality and omitted variable biases, especially as it does not look specifically at the within-firm changes.

**Table 5.** Mutually exclusive innovation combinations and a firm's performance: standard supermodularity test of complementarities of technological and organizational innovation

| **Dependent variable:** | **Log of sales per employee, at t+3** |
|---|---|
| BOTH (1, 1) | 11.837*** |
| | (0.032) |
| ONLYTECH (1, 0) | 11.830*** |
| | (0.031) |
| ONLYORG (0, 1) | 11.696*** |
| | (0.038) |
| NEITHER (0, 0) | 11.673*** |
| | (0.034) |
| lnSize | 0.0944*** |
| | (0.006) |
| Member of a group of firms | 0.330*** |
| | (0.014) |
| Foreign ownership | 0.164*** |
| | (0.016) |
| R&D dummy | 0.058*** |
| | (0.013) |
| Training (dummy) | -0.0264* |
| | (0.0148) |
| Sector and period dummies | Yes |
| Complementarity test (p-value of F-test of differences in coefficients):<br>H0: BOTH-ONLYTECH< ONLYORG-NONE | p=0.596 (F-test value: 0.28) |
| N | 25,692 |

Notes: coefficients from OLS regression model with robust standard errors in parentheses * p<0.1, ** p<0.05, *** p<0.01.

The high level of productivity of joint adoption of the two types of innovation, as evidenced from the regression table, by itself, does not indicate complementarity. For that we perform the formal complementarity test based on differences of coefficients of the four category variables. This test as shown in Table 5 leads to the following result. We cannot reject the H0 of lack of complementarities between technological and organizational innovation. This is clear if we look at differences between coefficients between key coefficients of the 4 category dummies in Table 5. Adding organizational innovation or technological innovation if the other type of innovation is already introduced (correspondingly increase in log points of productivity by 0.007 and 0.141) does not increase performance more than adding the organizational or technological innovation in isolation, without prior other type of innovation (correspondingly the increase in log points of productivity by 0.023 and 0.157). That is, the static complementarity test tells us that the added payoff of BOTH category compared to ONLYTECH or ONLYORG is not larger than that that adoption of only technological or only organizational innovation compared to the NONE category.

## 4.2. Dynamic complementarities

The analysis of complementarities is about situations when one innovation activity or output (or more) is either added to the other already existing one over time or, alternatively, the case when these activities are simultaneously adopted. This suggests a dynamic analysis of the determinants and performance effects of changes in innovation strategy choices (here: combinations of types of innovation) of the same firm over time. Love et al. (2014) have previously shown that omitting such within-firm 'dynamic' complementarities can lead to misleading conclusions about complementarities between firm's own R&D and external knowledge sourcing.

Testing for dynamic aspects of complementarities in terms of combining the technological and the organizational innovations over time involves the analysis of performance premia associated with movement of firms between the four categories as defined in the previous section of this paper. This involves upward dynamics in terms of moving to joint adoption of the two types of innovations, i.e. movement from ONLYTECH or ONLYORG category to BOTH category (where both types of innovations are implemented). As there are 4 base categories of innovators in each period, our analysis of the category/innovation strategy switches involves all the 16 category switch possibilities over time. These include 12 upward or downward movements in terms of adding or dropping innovation types and 4 "switches" when the category of the firm stays the same as the original one.

We re-estimate the firm performance Equation in (3) by replacing in next Equation (4) the previous 4 category dummies with the dummies indicating category movements of the same firm over time (between two consecutive 3-year periods in PITEC):

$$Performance_{it+3} = \beta_k SwitchingCategoryDummies_{it} + \gamma Z_{it} + \kappa_j + \tau_t + \varepsilon_{it} \qquad (4)$$

The notations and other controls stay the same as in Equation 3. There are altogether 16 'switching categories'. For example, here in Table 6 the switching category dummy SW44 indicates the firms that continue in both the starting period and the following period as complex innovators doing both technological and organizational innovation (i.e. continue with BOTH innovation strategy/category). SW24 indicates the firms switching from doing only technological innovation (ONLYTECH) to introducing both types of innovation (BOTH). SW34 indicates the firms switching from doing only organizational innovation (ONLYORG) to introducing both types of innovation (BOTH). SW12 and SW13 indicate switching from having neither type of innovation to doing technological innovation only (SW12) or organizational innovation only (SW13).

The results of estimation of the conditional performance premia associated with the different movements by the firms between the four categories over time are shown in Table 6 of the regression results. A visually more compact summary of the statistically significant results from Table 6 is given in Table 7. Table 7 shows the upward and downward movements of firms between the key categories, including the simultaneous and sequential adoption of innovation types. The coefficients in individual cells show how these movements between categories are associated with performance. Table 7 uses a simpler format than Table 6, omitting here the coefficients of other controls.

The comparison category (base category) is here in both Table 6 and 7 'SW11', i.e. firms that stay in NONE category (that do neither type of innovation in both periods). So, all the 15 coefficients of switching categories in Table 6 show the performance premium in the following period (performance measured here at year t+3; innovation indicators pertaining to the period covering years t, t-1 and t-2) compared to the base category of doing neither type of innovation in both periods.

As a key result, we see that both the sequential and the simultaneous forming of the complementarity bundle of innovation types are associated with a significant positive performance premium. Proposition 1 in previous sections is supported by the data. Simultaneous adoption of technological and organizational innovation is associated with higher firm performance, compared to firms that do not adopt innovations in either period or adopt only one type of innovation. This corresponds to comparison of the performance premium 'effect' of movements in terms of categories 1→4 (sw14) in Table 1 with movement 1→1 (sw11) and 1→2 (sw12) and 1→3(sw13). We see that firms that move from doing neither type of innovation to doing both simultaneously earn a firm performance premium of 0.21 log-points. This is about 23.4 per cent higher performance, calculated as exp(0.21)-1= 0.2337, compared to firms that stay in NONE category and do not introduce either type of innovation. This is also higher than the performance premium associated with the movement 1→3 (sw13 in table 6) from doing neither type of innovation in one period to doing organizational innovation only in the next, and also higher than the 'effect' of movement 1→2, from doing neither innovation to introducing technological innovation.

In fact, it turns out that adding only organizational innovation if the firm had neither type of innovation before does not lead to any performance premium compared to the base category (sw11). Movement over time by the same firm from NONE to ONLYTECH category (sw12) is, however, associated with 0.14 log-points higher sales per employee. This is a sizeable performance premium, but falls still short of the premium associated with moving to the simultaneous adoption of both types of innovation (sw14). Note however, that the move from no innovation to complex innovation with both types of innovation is rare in our dataset (see the Table 3 in prior sections).

A key finding is that the benefits are not restricted only to simultaneous adoption. Our estimation results in Table 6 confirm that neglecting sequential adoption patterns from analysis would lead to underestimation of the importance of complementarities in innovation process. Similar performance premium compared to simultaneous adoption is also associated with sequential adoption if the firm had previously (in *t, t-1 and t-2*) technological innovation and in the next period adds organizational innovation to the bundle (sw24 in Table 6, movement from ONLYTECH to BOTH). The premium is again 0.21 log points compared to the performance level of the base category (sw11).

So, the Proposition 2 is supported. Sequential adoption of the technological and the organizational innovations is associated with higher firm performance, similar in magnitude to the effect of simultaneous adoption of technological and organizational innovation. (This corresponds to movement in categories 2→4 and 3→4 compared to 1→4 as outlined previously in Table 1).

We also see that this estimated effect suggests complementarity. We compare the estimated 'effect' of adding the organizational to the already existing technological innovation (see the coefficient of sw24 in Table 6) with the 'effect' of movement from having no innovation to having only organizational innovation (sw13). We see that the coefficient of sw24 is greater than that of sw13 in performance equation (see also the p-value of test of the difference of the corresponding coefficients in Table 6). This is essentially the test of sequential complementarity: adding organizational innovation once the firm already had technological innovation has a larger 'effect' compared to the case of adding organizational innovation if a firm has no prior technological innovation.

However, the sequence order of adoption matters. We see the sequential complementarity only if technological innovation is introduced first and organizational innovation comes as second. If the order of adoption is vice versa—the organizational innovation first and the technological after that ~~in~~ the subsequent period, then we do not observe complementarity between the two types of innovations. This is reflected in the test of difference of the coefficients of the dummy variables 'sw34' and 'sw12.[13]

So, we have found support for our Proposition 2a: that sequential adoption of the technological and the organizational innovations, with the sequence order of adding the organizational innovation to the already existing technological innovation is associated with higher firm performance, compared to adding the organizational innovation on its own without the prior technological innovation at the firm. However, there is no support for Proposition 2b. Sequential adoption of the technological and the organizational innovations, with the sequence order of adding the technological innovation to the already existing organizational innovation is not associated with the higher firm performance compared to adding the technological innovation on its own without the prior organizational innovation at the firm.

These results are in accordance with the prior evidence from the study on adoption of design related innovations in Battisti et al. (2015). Their study showed sequential complementarities-in-use between adoption of the CAD software at first and introduction of inter-firm design teams with customers and suppliers of the firm (organizational innovation) as the next step: but not in the case of sequential adoption the other way round .

We outlined in previous sections also research propositions concerning the persistence/retention of the complementarity bundle and the firm performance. We observe that Proposition 3 on the 'effect' of retention of the components of the complementarity bundle is not supported. The retention (persistence) of the complementary bundle of adoption of both the technological and the organizational innovations (movement 4→4 in Table 1) has stronger effect on the firm performance than the persistence in only organizational innovation. However, the retention of the complementary bundle of the two types of innovation is associated with a similar premium as the persistence in the technological innovation alone (without the organizational innovation). This points again to the limits and costs of engaging in only the organizational innovation.

In analysis of the downward dynamics by dropping some type(s) of innovation, we observe again the importance of keeping the technological innovation. Here we compare the coefficients of movements 4→1, 4→2, 4→3 in Table 6. Dissolution of the complementarity bundle between the innovation types is found to maintain the reasonable positive previous level of performance compared to the retention of the complementary bundle (movement 4→4 and variable 'sw44' in Table 6), when it involves dropping of non-technological innovation (movement 4→2 and variable 'sw42'). But dissolving the complementarity bundle by dropping the technological innovation has a clear negative effect for performance (compared to movement 4→4).

[13] Based on the estimation results in Table 6, there is clearly no evidence that adding the technological innovation to the already existing organizational innovation type would have larger effect than adding the technological innovation on its own. In fact the coefficients of both switching category variables are the same, both are associated with 0.14 log points higher firm performance.

**Table 6.** Testing 'dynamic complementarities' between adoption of the technological and the organizational innovation

| **Dependent variable:** | **Log of sales per employee (in year t+3)** | |
|---|---|---|
| **Switching category dummies:** | **Coefficient** | **St. error** |
| sw22 | 0.153*** | (0.04) |
| sw33 | -0.118 | (0.129) |
| sw44 | 0.163*** | (0.037) |
| sw12 | 0.144*** | (0.059) |
| sw13 | 0.053 | (0.083) |
| sw14 | 0.211*** | (0.072) |
| sw21 | 0.172*** | (0.042) |
| sw23 | 0.064 | (0.069) |
| sw24 | 0.214*** | (0.043) |
| sw31 | -0.138 | (0.107) |
| sw32 | 0.029 | (0.083) |
| sw34 | 0.136** | (0.068) |
| sw41 | 0.040 | (0.054) |
| sw42 | 0.167*** | (0.043) |
| sw43 | 0.095* | (0.049) |
| R&D dummy | 0.097*** | (0.012) |
| LnSize | 0.098*** | (0.006) |
| Training | -0.015 | (0.015) |
| Member of a group of firms | 0.331*** | (0.014) |
| Foreign ownership | 0.165*** | (0.016) |
| Constant | 11.762*** | (0.037) |
| Sector and year dummies | Yes | |
| Observations | 25,692 | |
| Tests of inequality of coefficients (p-values of the F-test): | | |
| H0: lack of sequential complementarity, tech --> org, sw24≤sw13 | p=0.045 (can reject H0), results suggest sequential complementarity from Tech-->Org | |
| H0: lack of sequential complementarity, Org --> Tech, sw34≤sw12 | p=0.561 (cannot reject H0), no sequential complementarity from Org --> Tech | |

Notes: coefficients from OLS regression model with robust standard errors in parentheses * p<0.1, ** p<0.05, *** p<0.01. Sample of manufacturing firms, PITEC dataset, 2008-2016. SWxx: dummies denoting changes (strategy switches) in the complementarity bundle, the first number denotes the starting category in the first 3-year period of years t, t-1 and t-2; the second number denotes the next observed category in the next 3-year period (t+1, t+2, t+3). Categories: None (1), onlyTech (2), onlyOrg (3), Both (4).

**Table 7.** Directions in the forming and dissolution of the complementarity bundle over time, relationship with the firm performance (based on Table 6)

| To / From | None (1) | onlyTech (2) | onlyOrg (3) | Both (4) |
|---|---|---|---|---|
| None (1) | | 0.14*** | | ⬆ 0.21*** |
| onlyTech (2) | 0.17*** | 0.15*** | | ⬆ 0.21*** |
| onlyOrg (3) | | | | ⬆ 0.14*** |
| Both (4) | ⬇ | 0.16*** ⬇ | 0.09* ⬇ | = 0.16*** |

Note: (1) Directions in the forming of complementarity bundle: upward⬆, downward ⬇retention =

(2) Summary table of results based on Table 6. Grey cells denote that the firm performance in that category of movement is not statistically significantly different from the base category 1→1 (i.e. firms with neither types of innovation in both periods). Sample of manufacturing firms, PITEC dataset, 2008-2016.

# 5. DISCUSSION AND CONCLUSIONS

As we outline in the title of the paper, the black-box of complementarities deserves to be opened further. The focus of our analysis on within-firm changes in adoption and dropping of components of the complementary bundle of innovations gave us the possibility to shed light on some lesser investigated aspects of the dynamics within the complementarity bundle of innovation types. In the following paragraphs we discuss more in depth these 'dynamic complementarities'.

First, as a general result, we observe that both the sequential and the simultaneous forming of the complementarity bundle of innovation types have a significant positive role in shaping organizational performance. The benefits are not restricted only to the simultaneous adoption. Thus, we confirm that excluding the sequential adoption patterns from the analysis would result in underestimating the importance of the complementarities and the complementarities-in-performance in the innovation process.

As an important limitation of the standard approach to the analysis of complementarities, we observed significant differences between the static test of complementarities and the more 'dynamic' analysis of the within-firm changes in terms of adoption of the innovations. The static test of complementarities did not indicate the complementarity-in-performance between the technological and the organization innovations, confirming the broad results in Ballot et al. (2015) from UK and France. However, once we focused on the analysis of within-firm changes in the complementarity bundle, we found that the switches towards the simultaneous or the sequential adoption of the two types of innovation are, in fact, associated with significantly higher firm performance in the subsequent periods. We thus observe evidence suggesting complementarity between technological and organizational innovation.

Second, the order of adoption of the organizational and the technological innovations matters. We observe sequential complementarities between the two types of innovations only when the technological innovation is adopted first, never when the organizational innovation is adopted first. This finding is at odds with some of the prior management literature suggesting that the optimal sequence can be from the adoption of the organizational change to precede the technological innovation: as the organizational change can be expected to create the organizational culture and capabilities conducive to reaping the benefits of adoption of new technology.

A potential explanation of our findings of the different effects depending on the sequence of adoption could be that the organizational innovation needs a good and specific fit with the internal processes at the firm, whereas the adoption of the new-to-firm technological innovation (e.g. process innovation) involves usually the pretested elements (pre-tested often by other firms in other contexts and thus better predicted). Organizational innovation can be partially implemented (Sakowski et al. 2019) or organizational innovations do not age as fast as the product innovations do (Armbruster et al. 2008).

Third, this study further demonstrates that technological innovation is the vital driver of performance in the complementarity bundle, at least in the case of the firms in the PITEC dataset. We do not observe positive performance effects from adoption of the organizational innovation on its own or from the persistence in the organizational innovation only. We acknowledge that despite the lack of such average effects the adoption of organizational innovation could potentially have significant benefits in longer term or in the case of a more selected set of top-performers (see also Brynjolffson et al. 2020 for the discussion of the role of intangibles in the case of superstar firms). In these firms with the additional strong capabilities , inimitable knowledge resources, and human capital, the prior existence of organizational innovation could be likely to help the organization to reap the benefits of adoptions of technological innovations in the next periods. Organizational innovation could support flexibility, learning, and other processes needed for and in conjunction with the successful adoption of technological innovation. However, our findings highlight that it is not a general feature that firms on average are successful in implementing such organizational innovation(s) and in benefiting from this change.

Fourth, this study shows how the dissolution of a complementarity bundle is correlated with the next period's performance of the firm. Full dissolution of the prior complementarity bundle of innovation types has a strong negative effect: the performance premium in $t+3$ in this case falls to the level of firms that had neither type of innovation already in the previous periods. Dissolution of the prior complementarity bundle of the innovation types one-by-one is found to have no substantial negative consequences on a firm's performance premium if the elimination concerns only the non-technological innovation. Dissolving the complementarity bundle in the direction of keeping only the non-technological innovation and dropping the technological innovation is detrimental to the performance. This again underlines the central role of the technological innovation in the complementary bundle.

Fifth result is about retention. This means that the same complementarity bundle of innovation types continues to exist over different periods. We observe in this case no additional significant performance premium compared to persistence in doing only technological innovation. Compared to persistence in doing only the organizational innovation, however, both the persistence in the technological innovation and the persistence in adoption of both innovations were associated with superior performance.

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# KOKKUVÕTE

## Tehnoloogilise ja organisatsioonilise innovatsiooni seosed ettevõtte sooritusega: vaade dünaamilise komplementaarsuse „musta kasti"

Uurimuses keskendutakse kahe üldise innovatsioonitüübi komplementaarsuse ehk täiendatavuse võimalustele. Innovatsioonitüüpide komplementaarne seos on dünaamiline, hõlmates endas ülenevat (üheaegne ja järjestikune täiendatavus) ja alanevat (komplementaarsest kombinatsioonist loobumist) suunda ning ka innovatsioonitüüpide täiendatavuse pikaajalist püsivust. PITEC (Hispaania iga-aastane regulaarne innovatsiooniuuring) andmete alusel selgub, millise tulemuslikkusega tootmisettevõtetes üheksa aasta jooksul innovatsioonitüüpide täiendatavusest tulu teeniti. Vaatluse all on tehnoloogiline ja organisatsiooniline innovatsioon ning see, kas ja kuidas nende koostoime soorituse tõstmisse panustab. Analüüsiti 12 000 ettevõtte valikuid pikal perioodil (2008–2016) ja neid seoti ettevõtte majandussooritusega, mida mõõdeti kui logaritm näitajast „käive töötaja kohta" olukorras, kus kolme aasta jooksul alustati või loobuti kombinatsioonist. Selgub, et innovatsioonitüüpide komplementaarne rakendamine ettevõtete on seotud kõrgema sooritusega ja seda eriti neis ettevõtetes, kus innovatsioonita ettevõttes algatati üheaegselt tehnoloogiline ja organisatsikooniline uuendus või kui tehnoloogilisele lisati organisatsiooniline uuendus. Kui ettevõte loobub ühe innovatsiooni tüübi rakendamisest ning jätkab vaid teisega, siis positiivne seos sooritusega säilib võrrelduna nendega, kes innovatsiooniga tegelemise täielikult olid lõpetanud. Alaneva komplementaarsuse dünaamika korral on tehnoloogilise innovatsiooni säilitamine tulusam kui vaid organisatsioonilise innovatsiooniga jätkamine. Need tulemused panustavad innovatsioonitüüpide komplementaarsust käsitlevasse kirjandusse, näidates, kas ja kuidas innovatsioonitüüpide täiendatavuse dünaamilised seosed suhestuvad ettevõtete majandustulemustega. Lisaks täiendab see uuring ka komplementaarsuse analüüsi meetodeid, sest traditsioonilise supermodulaarsuse testi kõrval rakendatakse dünaamilist innovatsioonitüüpide kombinatsioonide kõrvutamist.