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ARTICLE

# Green together? The effects of companies' innovation collaboration with different partner types on ecological process and product innovation

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**ABSTRACT**
This paper investigates the effect of companies' innovation collaboration with different partner types on the emergence of different typologies of ecological innovation (EI), specifically process- and product-EI. Econometric analyses, based on a sample of 546 German manufacturing companies collected as part of the Community Innovation Survey, indicate a differential effect of collaboration with individual partner types. Specifically, we find that collaboration with consumers is associated positively with both process- and product-EI, whereas collaboration with universities and suppliers is associated positively only with process-EI. Collaboration with enterprise customers and competitors is neither associated with process-EI nor product-EI. Our results shed light on the mechanisms within the recently established open eco-innovation mode and emphasise the importance for theory and practice of distinguishing among collaboration partners, contingent on the underlying typology of EI. We discuss important implications for theory and practice.

**KEYWORDS**
Ecological innovation; process ecological innovation; product ecological innovation; collaboration

**JEL**
M10 General Business; O30 Innovation - General

## 1. Introduction

Increasing regulatory pressure as well as customer demand for more ecologically sustainable products have garnered increasing importance of environmental aspects in products and processes for companies (Porter and Van der Linde 1995). Ecological innovations (EI), which refer to '*new or modified processes, techniques, practices, systems, and products to avoid or reduce environmental harms*' (Beise and Rennings 2005, 6), are regarded as a source of competitive advantage for companies across industries and sectors (Ambec et al. 2013; Ghisetti and Rennings 2014; Porter and Van der Linde 1995).

Recent findings from the open innovation and EI literature emphasise the importance of open innovation for the emergence of EI and show that innovation collaboration is even more important in the context of EI than in the context of regular, non-ecological innovation (De Marchi 2012; Horbach, Oltra, and Belin 2013). According to research

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from the open innovation literature, different types of collaboration partners, such as research organisations, suppliers, and customers, vary in their contribution to companies' innovation outcomes, both qualitatively and in the strength of their impact. These differential effects are contingent on the type of innovation (i.e., process innovation and product innovation) (Belderbos, Carree, and Lokshin 2004; Faems, Van Looy, and Debackere 2005; Tödtling, Lehner, and Kaufmann 2009). A direct transfer of these findings from the general open innovation literature is difficult, as EI is fundamentally different from regular innovation (Carrillo-Hermosilla, Del Río, and Könnölä 2010; De Marchi 2012; Horbach, Oltra, and Belin 2013). Compared to standard innovation, the context of EI is often characterised by relatively new technologies, a high complexity of environmental challenges, and a systemic nature (e.g., Del Río et al. 2016). Many EIs do not result from stand-alone innovations but from cumulative effects of changes and comprise various innovative components (e.g., Dougherty and Dunne 2011). EI often require additional innovation and changes in infrastructure and managerial decision and behaviour. For example, firms that strive to develop and implement EI in the transportation of products from their production facility to the customer via electric vehicles also have to change their infrastructure and processes, such as building charging stations at their sites and implementing new routes and schedules that account for the added weight of batteries and the limited range due to the lack of recharging infrastructure for longer routes (e.g., Pelletier, Jabali, and Laporte 2016). The expectance of a differential impact within the realm of EI is supported by findings of previous studies that some collaboration partners might be more important to EI than others (De Marchi 2012).

EI encompasses specific types of innovation, differing in both their goal and scope (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012). Specifically, EI refers to both the development and diffusion of products and services with a reduced environmental impact during their life-cycle (product-EI) as well as the adaption of processes and techniques aimed at reducing the environmental impact within the firm, e.g., during the manufacturing process (process-EI). These fundamentally different innovation typologies have been found to be significantly different in many aspects in general innovation studies (Pittaway et al. 2004; Roper, Du, and Love 2008) and with regard to the effect of collaboration activities (Tödtling, Lehner, and Kaufmann 2009). In summary, these considerations and previous findings warrant a nuanced investigation of the contribution of specific collaboration partner types to the emergence of different types of EI.

Several studies identified collaboration as an important determinant of EI (e.g., Cainelli, Mazzanti, and Montresor 2012; Horbach 2008; Horbach, Rammer, and Rennings 2012). While the existing literature contributed significantly to a better understanding of the role of collaboration in the context of EI, the majority of these studies are characterised by two important limitations. First, most prior studies focused on rather broad measures of collaboration, not distinguishing between different types of collaboration partners. The lack of such research is regrettable, as it restricts our theoretical understanding of the mechanisms through which collaboration is associated with EI. While we understand how firms' knowledge and collaboration networks influence the overall emergence of EI, it is still unclear what influence the nature of different collaboration partners within such a collaboration portfolio has on the emergence of different EI-typologies. The second limitation of prior research is that it primarily focused on more general measures to assess EI. Recent studies emphasise the necessity of acknowledging the multidimensionality of EI (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Ghisetti, Marzucchi, and Montresor

2015; Markard, Raven, and Truffer 2012). Distinguishing among different EI dimensions would expand our understanding of the open eco-innovation mode by directly linking individual types of collaboration activities to the multidimensionality of EI (Tödtling, Lehner, and Kaufmann 2009). A more nuanced understanding of the specific contributions that individual types of collaboration partners can provide to the emergence of specific types of EI '*would increase the accuracy of the policy and management implications (...) that interactions with different types of knowledge providers may have on the introduction of the different types of EI*' (Ghisetti, Marzucchi, and Montresor 2015, 1091).

The objective of the present study is to address the aforementioned research gaps by analysing the impact of firms' innovation collaboration with different partner types (i.e., science-based collaboration, supplier collaboration, enterprise customer collaboration, and consumer collaboration) on process-EI and product-EI. Conducting this analysis, we seek to contribute to the EI literature in three ways. First, building upon findings regarding the depth of knowledge interactions within collaboration (Ghisetti, Marzucchi, and Montresor 2015; Laursen and Salter 2006), we contribute to answering recent calls to take into account '*the intensity of the interactions*' and importance of different forms of collaboration (De Marchi 2012, 621). In particular, complementing already existing findings regarding the portfolio composition (Ghisetti, Marzucchi, and Montresor 2015), we contribute to a better understanding of the heterogeneity of collaboration partners and the resulting potential complementarities in innovation collaboration strategies in the pursuit of EI. Second, by understanding which collaboration partners are effective in promoting the emergence of certain dimensions of EI, we are able to identify collaboration relationships worthy of investigating in depth to learn why these types of collaborations are salient for the emergence of EI (cf. Belderbos, Carree, and Lokshin 2006; Faems, Van Looy, and Debackere 2005). Third, our results contribute to the important ongoing search for the drivers that foster the creation of EI. Because the creation of EI suffers from limited incentives due to a double market failure (Beise and Rennings 2005; Mazzanti and Zoboli 2005; Norberg-Bohm 2000), identifying non-market-based drivers of EI is crucial for the promotion of EI. A better understanding enables us to specify what type of collaboration is a driver of different EI dimensions, contributing to more theoretical clarity on the manner in which collaboration enhances EI. Based on such an improved theoretical understanding, we would be able to provide better guidance to practitioners concerned with innovation collaboration and EI. For example, based on the current body of knowledge, we cannot indicate with certainty which types of collaboration partners are well suited for the emergence of different EI types. An improved understanding of the differential effects of collaboration would allow us to give concrete recommendations, e.g., in which situations innovation managers should engage in collaboration with universities and research organisations instead of market-based partners in the pursuit of EI.

## 2. Literature review and hypotheses development

### 2.1. Literature review: characteristics of EI and the role of collaborations in developing EI

The characteristics of EI, especially where they represent a distinguishable difference from general non-ecological innovation, form the basis of our theoretical and conceptual considerations regarding the effects of collaboration with different partners on EI. The majority of definitions in the literature describe EI with regard to the specific type the innovation can take (e.g., product vs. process innovation) as well as with regard to their scope being focused at a reduction of environmental harm (for an overview of different EI definitions see Albort-Morant et al. 2017). Complementing this understanding, a strand of literature at the interface of ecological economics and innovation studies consentaneously established further peculiarities of EI that differentiate EI from other types of innovation (cf. De Marchi 2012; Ghisetti and Pontoni 2015; Horbach 2008). First, while externalities and a double market failure are relevant factors in the context of non-EI, EI *in particular* is subject to externalities and a double market failure (Beise and Rennings 2005; Mazzanti and Zoboli 2005; Norberg-Bohm 2000; Rennings 2000;). In addition to externalities induced by spillovers, as is the case for all innovation, the returns from investment in EI are to a large extent appropriated by general society, thus leading to market failure (Norberg-Bohm 2000; Rennings 2000) in the form of reduced incentives to invest in EI (Beise and Rennings 2005; Mazzanti and Zoboli 2005; Norberg-Bohm 2000). Market failure has a stronger effect in the context of EI compared to non-EI as the benefits of natural capital depletion are privatised, while the costs are often externalised. Furthermore, natural capital is still often undervalued by society as individuals are not fully aware of the real cost caused. As awareness of ecological aspects grows in society, these market failures are likely to diminish, e.g., society will increasingly realise the value of natural resources, which increases their economic value. However, currently firms still have not to internalise all costs. The consequences of this market failure are twofold. On the one hand, it leads to the superior role of 'regulatory-pull' as a crucial driver of EI (Kemp 2010; Norberg-Bohm 2000). On the other hand, the organisational and technological competencies required for EI often lie outside the trajectory and competencies of the firm (Horbach, Oltra, and Belin 2013; Rennings and Rammer 2009).

Second, EI is often characterised by great technological diversity and complexity, affecting products and processes on a systemic level (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Horbach 2008). As a result, firms often have to integrate technologies outside of their technological trajectory, technological regimes (Markard, Raven, and Truffer 2012), and spectrum of (core) competencies in the creation of impactful EI (Cainelli, Mazzanti, and Montresor 2012; De Marchi 2012; Horbach, Oltra, and Belin 2013). For example, car manufacturers that aim to replace combustion engines by electric engines require an entire set of new knowledge, resources, and competencies. Networks with prior collaboration partners may become obsolete as, e.g., universities and other researcher institutions with which a firm collaborated in the field of combustion engines may not be the best collaboration partners for electronic engines. These firms are likely to develop relations to new suppliers that complement existing suppliers as EI often entails multiple aspects from the technology, design, and user dimensions (Carrillo-Hermosilla, Del Río, and Könnölä 2010). Thus, EI is characterised as highly systemic, technologically advanced, and as penetrating multiple aspects of product development and innovation (Andersen and Foxon 2009; Ghisetti, Marzucchi, and Montresor 2015). The association with market failure and the large technological complexity of EI, substantiate the notion within the ecological economics and innovation studies literature that EI qualitatively differs from traditional innovation (Ghisetti, Marzucchi, and Montresor 2015; Horbach 2008; Horbach, Oltra, and Belin 2013; Rennings 2000). This differentiation pertains to *'externalities and drivers of their introduction'* (De Marchi 2012, 615) as well as to the management of knowledge drivers supportive of the notion that *'eco-innovators may follow different "eco-innovation modes", with respect to standard innovators'* (Marzucchi and Montresor 2017, p. 208), hence pointing towards a distinguished role of collaboration as a driver of innovation (and collaboration partners as knowledge drivers).

EI is described as being multidimensional (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Ghisetti, Marzucchi, and Montresor 2015; Markard, Raven, and Truffer 2012). This heterogeneity within the group of EI pertains especially to *'the different knowledge needs and combinations entailed by specific EIs with respect to generic ones'* and relatedly *'specific modes of eco-innovating within the same green realm'* (Marzucchi and Montresor 2017). Even when disregarding the aspects of EI relating to *'practices, techniques, and systems'* and focusing on its technological aspects, EI pertains to both product innovation and process innovation. As such, EI encompasses fundamentally different types of innovation, differing in their goal and scope. Specifically, EI refers on the one hand to the development and diffusion of products and services with a reduced environmental impact during their life cycle (product-EI), i.e., the improvement of existing products or the development of new products, which reduce the environmental impact of the product and its use. On the other hand, EI encompasses the adaption of measures aimed at the reduction of the environmental impact within the firm, e.g., during the manufacturing process (process-EI). Since product and process innovation have been found to differ considerably from each other in terms of goals, strategies, drivers, processes and organisational measures (Boer and During 2001; Polder et al. 2010) in the general innovation literature, it appears to be plausible that these differences will also apply to the various forms of EI. This third characteristic of EI has to be balanced with the conception that EI as a whole is qualitatively different from other types of innovation. Against the background of previous research, it is plausible to assume that while different typologies of EI share a differentiation from regular innovation, they differ from each other particularly with regard to the specific knowledge components and combinations embodied within them (cf. Marzucchi and Montresor 2017). While this multidimensionality also extends to further types of innovation, such as business model or management innovation, a focus on technological innovation implies the differentiation between process- and product-EI.

Against the background of these underlying considerations, the potential of innovation collaboration to support companies in addressing the difficulties associated with EI through several channels of innovation collaboration becomes apparent. The innovation literature generally distinguishes among several types of collaboration partners, which can be classified in the following groups (OECD & Eurostat, 2005): (1) universities and research organisations, (2) suppliers, (3) customers, and (4) competitors or other companies located in the same sector.[1] Based on three strands of theory (namely, the knowledge-based view, the organisational learning perspective, and the resource-based view), we develop arguments for the relationship between different collaboration partners. From the knowledge-based view (Grant 1996), collaboration with the aim of

[1]Please note that we do not consider the role of service providers in our study, as this group is highly heterogeneous and thus neither allows for the formulation of a consistent set of hypotheses against the background of the literature nor for drawing meaningful findings regarding this group.

innovation is associated with the generation of knowledge that is not available within the firm, e.g., specific technological knowledge (Belderbos, Carree, and Lokshin 2006). This line of thought is also supported by the literature on knowledge sharing and organisational learning that argues that in complex knowledge environments, the locus of innovation is likely to lie outside the companies' boundaries (Powell, Koput, and Smith-Doerr 1996). Collaboration with different partners widens the knowledge base that can be used in the recombination of knowledge, which is an important source of innovation. From an organisational learning perspective (e.g., Argote 2011), collaboration allows firms to develop the specific competences related to the technology and market aspects underlying an innovation. According to the resource-based view (Barney 1991; Wernerfelt 1984), innovation collaboration allows a firm to get access to a collaborating partner's resources (e.g., Wassmer and Dussauge 2012) and to diversify potential risks associated with an innovation and the innovation process (Belderbos et al., 2004). The lack of internally available resources and knowhow required for EI can be mitigated through the sourcing of knowledge and competencies from collaboration partners. The systemic nature of EI can be addressed through collaboration with horizontal, upstream, and downstream collaboration partners. Finally, it has been argued that collaboration could increase firms' embeddedness in green innovation systems (Ghisetti, Marzucchi, and Montresor 2015).

Given the specific nature of EI and the potential importance of collaboration partners, researchers have begun to explore the association between various types of collaboration and EI. Table 1 provides an overview of these studies.

We identified ten quantitative empirical studies and three qualitative empirical studies that explicitly or implicitly (i.e., included collaboration or cooperation as a control variable) examined the relation between collaboration and EI. The three qualitative studies indicate that collaboration is an important source of EI. The findings of the quantitative studies are more heterogeneous. While seven of the quantitative studies show a positive effect for at least one type of collaboration on EI, three studies show no significant effect of collaboration on EI. Five of the seven studies that show a significant effect are characterised by rather broad measures of collaboration, including different collaboration types or not explicitly specifying the collaboration type. Thus, these studies are not allowing for a comprehensive comparison of the specific effect of collaboration types on EI. Those studies that explicitly distinguished between different collaboration types utilised rather broad EI measures and, therefore, do not account for the multi-dimensional nature of EI. Three of the ten quantitative studies accounted for the multi-dimensional nature of EI. While the results by Triguero, Moreno-Mondéjar, and Davia (2013) show a positive association between science-based collaboration and both process-EI and product-EI, the results by Marzucchi and Montresor (2017) show a relation between collaboration and different EI dimensions (e.g., objectives, material, and energy) and no relation between collaboration and product-EI.

Our review also shows how researchers have assessed collaboration. Of the eleven quantitative studies, five studies assessed collaboration solely using a dummy variable that accounted for whether or not a firm collaborated with any partners, thus, not allowing to infer any insights on collaboration depth and breadth. Four studies examined the relation between the breadth of collaboration (i.e., the number of collaboration partners) and EI (Cainelli, De Marchi, and Grandinetti 2015; Christensen, Hain, and

**Table 1.** Overview of previous empirical studies examining the collaboration-eco innovation relationship.

| Study | Data collection and sample | Collaboration types | Innovation dimensions | Main findings |
|---|---|---|---|---|
| Cai and Zhou (2014) | Own survey, $N$ = 1266, China | - External network strength (including suppliers, competitors, consumers, universities and research institutions, local residents, administration) | - Eco-innovation performance | - External network strength is positively related to eco-innovation performance |
| Cainelli, De Marchi, and Grandinetti (2015) | Two waves of the Spanish Technological Innovation Panel (PITEC), $N$ = 4829, manufacturing firms, Spain | - Collaboration with external firms or institutions (supply chain partners, knowledge providers, universities and research centres, and competitors) (dummy)<br>- Cooperation breadth (count for number of collaborations) | - Environmental innovation (dummy)<br>- Technological product and process innovation (dummy) | - Collaboration is positively associated with both environmental innovation and technological innovation<br>- Cooperation breadth is positively associated with both environmental innovation and technological innovation |
| Carrillo-Hermosilla, Del Río, and Könnölä (2010) | Case study: Cross-case analysis including five firms (two Japanese, one US American, one Spanish, one Swedish) | - Public-private collaboration<br>- User-led eco-innovations | - Design eco-innovation<br>- Product and service eco-innovation | - Collaboration plays an important role in the development of eco-innovations |
| Christensen, Hain, and Nogueira (2017) | Combination of 2014 Community Innovation Survey (CIS) and Danish firm register database (FIDA), $N$ = 317, firms in the renewable energy sector, Denmark | - Whether a firm engaged in any collaboration<br>- Breadth of a firm's collaboration activities (various actors, such as suppliers, competitors, and universities) | - Innovation turnover (product) | - Breadth of collaboration has no effect on innovation turnover for firms active in renewable energy innovation |
| Cuerva, Triguero-Cano, and Córcoles (2014) | Own survey, $N$ = 205, cross-sectional, food and beverage industry, Spain | - Competitor collaboration (dummy)<br>- Supplier and customer collaboration (dummy)<br>- Public sector collaboration (dummy) | - Green innovation (dummy)<br>- Innovation (dummy) | - All three types of collaboration show no significant association neither with green innovation nor with non-green innovation |
| De Marchi (2012) | Spanish Technological Innovation Panel (PITEC), 2007, $N$ = 6047, Spain | - Cooperation on innovation with a) external partners (dummy), b) vendors (dummy), c) clients (dummy), d) competitors (dummy), e) science (dummy) | - Combined measure of process and product EI (dummy) | - Cooperation with vendors and science is positively associated with EI<br>- Cooperation with clients and competitors is not related to EI |
| Geffen and Rothenberg (2000) | Case study: Site visits and interviews, Automotive assembly plants, US | - Supplier collaboration | - Environmental performance | - Suppliers are important to achieve improvements in environmental performance |
| Ghisetti, Marzucchi, and Montresor (2015) | Community Innovation Survey (CIS) for the period 2006–2008, $N$ = 14,366, eleven countries | - Breadth and depth of R&D cooperation with cooperation partners<br>- Cooperation with cooperation partners (dummy) | - Probability of introducing an EI<br>- Extending the number of EI typologies adopted by the firm | - Cooperation as well as the breadth and depth of collaboration are positively associated with both dimensions of EI |

(*Continued*)

**Table 1.** (Continued).

| Study | Data collection and sample | Collaboration types | Innovation dimensions | Main findings |
|---|---|---|---|---|
| Horbach (2008) | Employment panel of the Institute for Employment Research (2001 and 2004), *N* = 753, firms belonging to the environmental sector, Germany | - Collaboration (dummy) | - Environmental product innovation | - Collaboration is significantly related to environmental product innovation |
| Horbach, Oltra, and Belin (2013) | Community Innovation Survey (CIS) data for the period 2002–2004, Germany (*N* = 572) and France (*N* = 1782) | - R&D cooperation (dummy) | - Environmental innovation (dummy) | - Cooperation had neither a significant effect on environmental innovation for the German sample nor for the French sample |
| Klewitz, Zeyen, and Hansen (2012) | Manual categorisation and quantification of interview text, semi-structured interviews, seven case firms, metal- and mechanical engineering industry, Germany | - Collaboration with intermediaries from the public and private sector | - Process eco-innovation<br>- Product eco-innovation<br>- Organisational product innovation | - *"All of the studied companies deem the capacity to capitalise on external support mechanisms in the form of innovation intermediaries as relevant"* |
| Mothe, Nguyen-Thi, and Triguero (2017) | Community Innovation Survey (CIS), 2006–2008, *N* = , France | - R&D cooperation (dummy) | - Product-EI (dummy)<br>- Process-EI (dummy) | - R&D cooperation is positively associated with both product-EI and process-EI |
| Marzucchi and Montresor (2017) | Two waves of the Spanish Technological Innovation Panel (PITEC), around 7858 manufacturing firms, Spain | - Formal innovation cooperation (dummy) | - Environmental objectives<br>- Environmental material<br>- Environmental energy<br>- Environmental products<br>- Environmental other | - Cooperation is significantly and positively associated with environmental objectives, material, and energy<br>- Cooperation is not significantly related to environmental other and products |
| Muscio, Nardone, & Stasi (2017) | Own survey, *N* = 753, wine manufacturer, Italy | - Breadth and depth of cooperation with cooperation partners | - Number of EI | - Breadth is positively associated with the number of EI and depth is not significantly related to the number of EI |
| Triguero, Moreno-Mondéjar, and Davia (2013) | Eurobarometer survey, 27 European countries | - Collaboration with universities, research institutes and agencies (depth) | - Process eco-innovation<br>- Product eco-innovation<br>- Organisational innovation | - Collaboration is positively associated with all three types of eco-innovation |

Nogueira 2017; Ghisetti, Marzucchi, and Montresor 2015; Muscio, Nardone, & Stasi, 2017). Three of these studies found a positive relation between collaboration breadth and EI (Cainelli, De Marchi, and Grandinetti 2015; Ghisetti, Marzucchi, and Montresor 2015; Muscio et al, 2017). Three studies examined the association between the depth of collaboration and EI. Triguero, Moreno-Mondéjar, and Davia (2013) used a dummy variable to measure whether the collaboration was important or was not important for innovation, providing a rather broad measure of collaboration depth. Ghisetti, Marzucchi, and Montresor (2015) measured depth by the number of collaboration partners with a high importance for EI. Muscio et al. (2017) measured depth based on the average importance of the collaboration partner for EI. Two of the three studies show a significant positive association with EI (Ghisetti, Marzucchi, and Montresor 2015; Triguero, Moreno-Mondéjar, and Davia 2013). To the best of our knowledge, two studies have examined both breadth and depth of collaboration (Ghisetti, Marzucchi, and Montresor 2015; Muscio et al, 2017). One potential explanation for the mixed findings for collaboration depth could be that the depth of collaboration with specific partners is differently related specific EI dimensions. All three studies that included collaboration depth have not distinguished between different types of collaboration and two studies have not clearly distinguished between different EI dimensions (Ghisetti, Marzucchi, and Montresor 2015; Muscio et al, 2017).

In sum, the majority of previous studies focused on the question whether collaboration in general contributes to EI but we still lack a clearer understanding of the role of collaboration characteristics, in particular, the associations between the depth of collaboration for different collaboration types and different EI dimensions.

In sum, our brief review of the literature indicates that the majority of previous studies focused on the question whether collaboration in general contributes to EI but we still lack a clearer understanding of the role of collaboration characteristics, in particular, the associations between the depth of collaboration for different collaboration types and different EI dimensions.

### 2.2. Hypotheses development: differential effects of collaboration partners on EI

While EI is different from regular innovation, we argue that the general mechanisms of open innovation will still prevail, but that, due to the differences, their effects on EI cannot be inferred from existing studies. When it comes to the differential effects of collaboration with specific partner types on specific EI-dimensions, it is likely that not all partner types will be able to have an equally meaningful impact on different types of EI. This reasoning is based on two considerations: First, there is a consensus in the general innovation literature that the impact of collaboration on innovation is contingent on the combination of the collaboration partner and the focal innovation typology (Belderbos, Carree, and Lokshin 2006; Faems, Van Looy, and Debackere 2005) and that '*there are significant differences among the types of partners that can determine how the collaboration is managed and what kind of innovation can be achieved*' (Nieto and Santamaría 2007, p. 369). Second, EI is multidimensional, and the goals and mechanisms behind different forms of EI vary (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012). It is thus highly plausible that while collaboration in general is associated positively with EI, not all collaboration partners will have an equally positive impact on all types of EI.

The general innovation literature has found differential effects of individual collaboration partners on different types of innovation (e.g., Aschhoff and Schmidt (2008) and Belderbos, Carree, and Lokshin (2004) for product vs. process innovation). However, based on empirical findings and conceptual considerations, we argue that these findings cannot be transferred directly to analogous types of EI. Prior empirical research has shown that the effects of open innovation and innovation collaboration differ between regular innovation and EI. Specifically, openness is generally more important in the realm of EI (De Marchi 2012; Horbach 2008; Horbach, Oltra, and Belin 2013) and the relative importance of partners differs between regular and green innovators (De Marchi 2012). Similarly, the relationships between open innovation portfolio properties and innovation arguably differ from those relationships found for regular innovation (cf. Ghisetti, Marzucchi, and Montresor 2015; Laursen and Salter 2006; van Beers and Zand 2014). Conceptual considerations support our assumption because recent studies propose that '*eco-innovators may distinguish from standard innovators also in the management of their portfolio of knowledge drivers*' (Marzucchi and Montresor 2017, p. 208). In the general innovation literature, it is well established that with regard to external innovation sources, different types of innovation rely on different knowledge interactions (Tödtling, Lehner, and Kaufmann 2009), and different collaboration partners and innovation modes provide varying benefits to specific types of innovation (Aschhoff and Schmidt 2008; Evangelista and Vezzani 2010; Fitjar and Rodríguez-Pose 2013; Köhler, Sofka, and Grimpe 2012). Innovation collaboration has been argued to be effective through mechanisms from the knowledge- and resource-based view of the firm as well as from organisational learning. Because the resources, knowledge, and skills associated with EI differ from those for regular innovation, distinct effects between regular innovation and EI are highly likely. Against the background of our knowledge regarding the characteristics of collaboration partners as well as of EI, we developed the conceptual model shown in Figure 1 and made three conjectures in developing our hypotheses.

First, given a lack of extant literature on specific collaboration partners' contribution to EI, hypotheses have to be derived that are centred on the specificities of EI as developed by the EI literature and are matched with the potential contributions to these specific requirements from individual types of collaboration partners. Regarding the latter, supporting qualitative implications regarding the knowledge-, skill-, and resource-based contributions of partner types and the underlying transaction mechanisms can be drawn selectively from outside the realm of EI, cautiously considering the specificities that distinguish EI from general innovation. Second, the more valuable the potential contribution of the partner type is to the emergence of EI, the greater the association between collaboration with this partner type and EI performance will be. Specifically, the more beneficial the knowledge, resources, and skills a specific partner type can contribute within the collaboration for the emergence of a specific type of EI, the greater his contribution to increased respective EI performance will be. Third, the deeper the interaction with a specific partner type, the more the potential of the partner to further EI will permeate into the emergence of EI within the focal firm. Successful EI often depends on implicit knowledge (Preuss 2007). The knowledge base of a firm consists of codified explicit knowledge

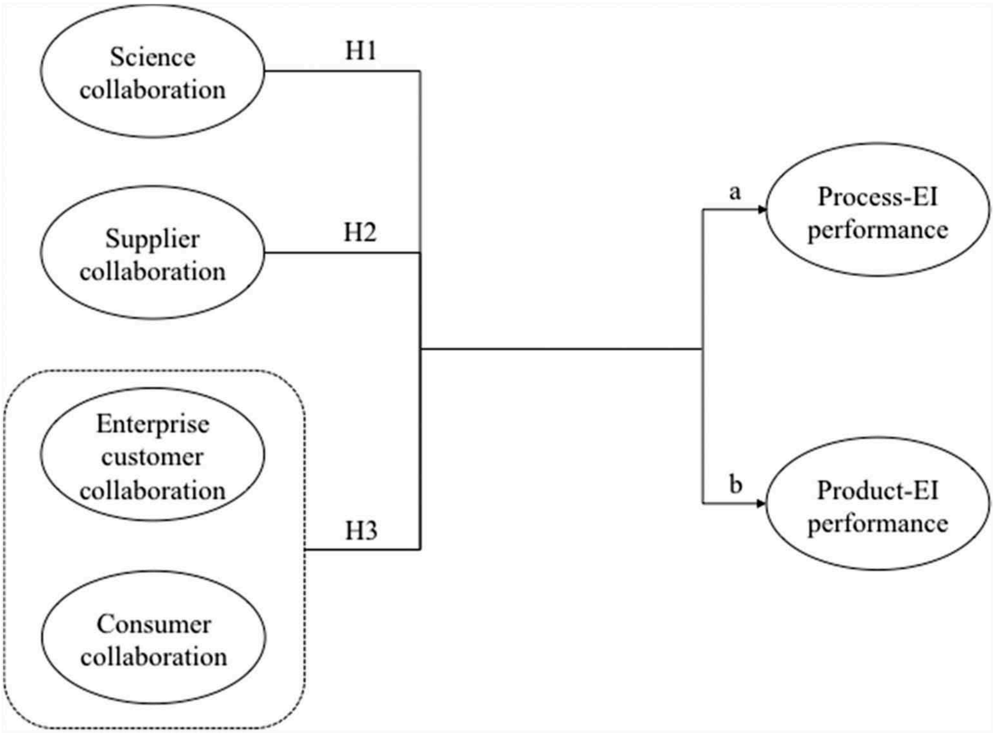


**Figure 1.** Conceptual model.

assets and tacit knowledge residing in the social relations between the employees. An intensive collaboration with a partner allows firms to get access to and learn from the collaboration partners more tacit knowledge, which is more difficult to share and requires interaction for being transferred. Important specificities of EI are its large degree of technological complexity and its systemic nature (Carrillo-Hermosilla, Del Río, and Könnölä 2010), as well as its reliance on new technology and knowledge (Cainelli, Mazzanti, and Montresor 2012). Moreover, EI is often based on technologies that lie outside the competencies and technological trajectory of firms (Cainelli, Mazzanti, and Montresor 2012; De Marchi 2012; Ghisetti, Marzucchi, and Montresor 2015; Markard, Raven, and Truffer 2012). We argue that this combination of new, complex technologies, paired with little capacity or interest in these technologies within firms, is unique to EI, and EI is highly susceptible to the inflow of external knowledge.

#### *2.2.1. The association between science-based collaboration and EI*

Science-based collaboration partners, in principle, have the potential to provide the knowledge, skills, and resources to facilitate the employment of technologies. Given the great interest of public (funding) bodies (Kemp 2010; Markard, Raven, and Truffer 2012), we argue that there is a large body of science-based research and development of EI-related technologies. Hence, it is highly plausible that science-based collaboration partners can be effective in furthering the emergence of EI within collaborating firms by providing access and co-developing technologies embodied in EI (cf. Carrillo-Hermosilla, Del Río, and Könnölä 2010; Norberg-Bohm 2000). Furthermore, because collaborations with universities are often publicly funded, are conducted with partners outside the immediate market environment, and are in comparatively early stages of innovation (Belderbos et al. 2004), one could argue that they also have the potential to mitigate the negative aspects of EI resulting from concerns regarding appropriability and absent incentives, thus serving as a 'sandbox' for experimentation technologies related to EI. Further findings support this notion: Collaboration with universities and research organisations has been found to aid companies in gaining access to basic research at the technological frontier and technologies new to the firm (Estrada et al. 2016; Hall, Link, and Scott 2003; Tether and Tajar 2008; Tödtling, Lehner, and Kaufmann 2009) and has been associated with mitigating the risks associated with the introduction of new technologies (Aschhoff and Schmidt 2008; Monjon and Waelbroeck 2003). Against this background, we argue that an intensive collaboration with universities and public research institutions will be beneficial for the emergence of EI. Therefore, we propose the following hypothesis:

*Hypothesis 1a. The depth of firms' collaboration with universities and public research institutions is positively associated with their performance in process-EI.*

While product- and process-EI are two different types of the multidimensional construct of EI (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012), both require the application of new and complex technologies. Given that universities and public research institutes are usually considered providers of the knowledge and technology required for the implementation of such technologies and given that research in such institutions extends to production technologies, we argue that collaborating with such partners will have a positive effect on product-EI performance. Furthermore, we argue that collaboration with universities and public research institutes provides firms access to scientific knowledge and complementary assets for its ecological product innovation and that it can also offer opportunities to enter into indirect collaborations and alliances with other firms, thereby gaining access to their innovation system. Furthermore, collaborations with universities and research institutes can help a firm to reduce R&D expenditure. Collaborations with universities and public research institutes can give firms access to the equipment they need for new product development and the knowledge and expertise of the university's or research institution's personnel, reducing the costs of running a research facility. As a result, the firm may be able to support more new product development projects or more strongly focus on the ecological component of new product development. Collaboration with universities and public research institutes can also benefit a firm by providing greater legitimacy to the firm itself as well as to its products (e.g., if the firm collaborates with a prestigious university with a reputation for ecological and green matters) and may provide access to alumni as well as other firms, which might open up possibilities for further collaboration. Against this background, we formulate the following hypothesis:

*Hypothesis 1b. The depth of firms' collaboration with universities and public research institutions is positively associated with their performance in product-EI.*

#### *2.2.2. The association between supplier collaboration and EI*

Collaboration with suppliers has been associated with process adaptions leading to cost reductions and productivity gains (Belderbos, Carree, and Lokshin 2004; Hagedoorn 1993; Tödtling, Lehner, and Kaufmann 2009). However, given the specificities of EI, especially its technological complexity, it is questionable whether collaboration with suppliers can be beneficial to the creation of meaningful process-EI. Supplier collaboration is often regarded as incremental in nature, aiming at productivity gains, and only complementing the firm's existing technology base (Belderbos et al. 2004; Belderbos, Carree, and Lokshin 2004), which counters the previously established characteristics of EI. At the same time, however, collaboration with suppliers '*is often related to the tendency to focus on core business through outsourcing, while closely collaborating with suppliers to guarantee input quality improvements aimed at further cost reductions*' (Belderbos, Carree, and Lokshin 2004, 1479). In principle, this relation is in line with the notion of firms in pursuit of EI outside their technological trajectory sourcing in EI-relevant knowledge, skills, and resources from suppliers. Indeed, initial evidence from the EI literature supports the assumption of a positive effect of supplier collaboration on process-EI. It has been shown that eco-innovators collaborate with suppliers more frequently than regular innovators (De Marchi 2012) and that bilateral learning with material suppliers is important to achieve environmental goals (Theyel 2006). We argue that meaningful changes in manufacturing processes aimed at ecological sustainability require new or modified equipment and input materials. Hence, it is highly plausible that collaboration with suppliers can have an impact on process innovation aimed at the reduction of the environmental impact of manufacturing through the sourcing or co-development of input materials or production equipment that requires less energy or produces less emissions in the manufacturing process. Thus, an important role of suppliers of equipment and input materials for the emergence of process-EI is highly plausible. Against this background, we propose the following hypothesis:

*Hypothesis 2a. The depth of firms' collaboration with suppliers is positively associated with their performance in process-EI.*

With regard to the role of supplier collaboration for the emergence of product-EI, one has to consider the primary role of suppliers as contributors to incremental improvements (Cincera et al. 2003; Freel 2003; Fritsch and Lukas 2001; Hagedoorn 1993; Handfield et al. 1999; Monjon and Waelbroeck 2003). Again, considering that meaningful EI is characterised as technologically systemic and complex (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012), it is questionable to what degree supplier collaboration could contribute to the emergence of product-EI. However, the specificities of EI allow one to argue for a positive association between supplier collaboration and product-EI. The components that are purchased from suppliers influence the quality, competitiveness, design, costs, and market availability of a firm's products and their ecological performance, which is largely determined by their 'upstream' environmental impact (Pujari 2006). The early involvement of suppliers in the development of ecological product innovations can increase the quality of the development process and reduce research and development time. The sustainability literature concerned with new product development suggests that companies striving for sustainability improvements of their products have to take into account a greater extent of the supply chain than when innovating for pure economic or technological reasons, as is the case for regular innovation. This notion is especially relevant when closed product life cycles are focal (Seuring and Müller 2008). Furthermore, it is argued that in developing eco-friendly products, input materials outside of the company's existing scope have to be sourced (Seuring 2004), and the eco-viability of the input materials has to be ensured (Albino, Balice, and Dangelico 2009). We argue that collaboration with suppliers will facilitate the eco-related management of the entire value chain beyond what would be enabled by the mere solicitation of eco-focused changes for input materials outside of a collaborative relationship. Collaborative relationships with suppliers have the potential to improve the ability of firms to ensure the eco-viability of input materials and especially to consider and employ technologies that have been previously outside the scope of the firm. Consequently, we argue that due to the specificities of EI, the contribution of supplier collaboration will not be limited to process-EI but will have a positive impact on product-EI performance. We thus propose the following hypothesis:

*Hypothesis 2b. The depth of firms' collaboration with suppliers is positively associated with their performance in product-EI.*

### 2.2.3. The association between customer collaboration and EI

Customers' role in the context of collaborative innovation has been described as primarily aiming at market acceptance, diffusion, and usability. As such, customer collaboration can complement companies' existing technological competences and the technological inputs from other collaboration partners (Belderbos, Carree, and Lokshin 2006; Tether and Tajar 2008). In the context of process innovations, customers play a more passive role and, in particular, function as an information provider for their specific product needs and may also provide input on product solutions. Therefore, customers do not closely interact with firm employees on matters related to the production processes. Traditionally, the limited influence of customers on process innovation has been linked to an indirect effect through aspects of product design (Papinniemi 1999) or through customer-driven demands for greater flexibility in manufacturing processes (Ettlie and Reza 1992). However, it is questionable to what extent customer collaboration can influence process-EI for two primary reasons: First, process-EI requires substantially changed technologies. Customers, however, can only complement the technological input from firm-internal R&D or other collaboration partners, and their direct influence on the technological aspects of innovation is limited (Tödtling, Lehner, and Kaufmann 2009). Hence, given the technological requirements of EI and the missing link between usage patterns and process-EI, it is questionable whether enterprise customers and consumers can provide meaningful input to process-EI. Second, sustainability aspects are still widely regarded as '*credence features*' (De Marchi 2012; Rex and Baumann 2007). The credence feature designation implies that customers do not immediately recognise and (economically) evaluate the benefit of environmentally advantageous products in comparison to alternative offerings, and hence, they have a limited understanding and incentive to provide the respective inputs. This limitation is especially evident regarding process-EI, which only determines the environmental impact of the manufacturing firm and not the impact through the use of the product on the customer side (Adner and Levinthal 2001; Iles 2008). Increasing customer demand for sustainability aspects, including in the form of (voluntary) certification processes or value chains spanning environmental management systems, may mitigate concerns about the credence nature of EI. However, such increasing demand is captured by market effects, independent of collaborative relationships, and it does not mitigate the underlying notion of customers' inability to contribute the knowledge, resources, or skills required to promote process-EI within the innovating firm. Hence, we argue that due to their limited ability to contribute technological input and due to the lower value attributed to process-EI as a credence feature, collaboration with customers will have no impact on process-EI.

*Hypothesis 3a. The depth of firms' collaboration with customers is not associated with their performance in process-EI.*

Turning to the role of customer collaboration and product-EI, we argue against the background of the EI literature that the diffusion of ecological innovation requires sustainability transitions at the customer side, alongside considerable required adjustments by customers and users of products in their usage behaviour (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012). Radical examples of such transitions are considerably changing usage patterns and personal infrastructure adaptions when transitioning from traditional to electric mobility. These adaptions likely span the entire product life cycle for the user and are hence to be considered far-reaching. Given the resulting importance of including the customer perspective for the facilitation and success of such transitions, it is highly plausible to assume that demand information and tacit customer knowledge are important for the emergence of product-EI. Customers can provide tacit customer knowledge about usage patterns that allow for innovation that reduces the environmental impact of products over their life cycle or information that allows companies to ease the adaption process of customers to fundamentally changed products. The transfer of precisely such knowledge and information is facilitated by customer collaboration (Tether 2002; Urban and Von Hippel 1988; Von Hippel 1994). Against this background, we assume that customer collaboration will be positively associated with product-EI, and we propose the following hypothesis:

*Hypothesis 3b. The depth of firms' collaboration with customers is positively associated with their performance in product-EI.*

Other potential collaboration partners are competitors or other companies in the same sector. Horizontal collaboration with competitors and other companies is associated with a contribution in the field of new technologies that are far from market introduction through the sharing of risk, equipment, and expertise (Belderbos et al. 2015; Hagedoorn 2002). Another function of horizontal collaboration is the establishment of industry standards (Gnyawali and Park 2011). As such, collaboration with competitors could contribute to EI through shared investments in far-from-market technologies and through the creation of shared environmental standards. Moreover, direct competitors and companies from the same sector are especially likely to face similar technological EI challenges and experience comparable regulatory pressure, a central driver of EI, and changes in customer demand. This aspect could speak in favour of a positive effect of competitors' collaboration on EI. At the same time, however, these direct competitors and companies from the same sector would likely follow very comparable technological trajectories, thus hindering a valuable sharing of new knowledge, resources, or skills. As far as regulatory pressure is concerned, it is furthermore likely that companies facing identical pressures could have a higher incremental interest in collaborating towards easing or circumventing such regulatory pressure (i.e., lobbying) and would thus inhibit EI. However, from a more general standpoint, competitor collaboration suffers from issues of appropriability and secretiveness (Gnyawali and Park 2011) and is associated primarily with cost and risk sharing as well as imitation and is thus more defensive in nature (Monjon and Waelbroeck 2003; Roper, Du, and Love 2008). This defensive nature of competitor collaboration contradicts, in principle, the more groundbreaking nature of EI. From a knowledge and resource-based perspective, firms should collaborate with organisations that differ in their knowledge and resources to increase the benefits of the collaboration as more heterogeneous companies are more likely to bring more diverse pools of information and expertise into a collaboration, potentially allowing to identify and integrate new environmental approaches. On the other side, it may be more difficult to collaborate with companies that are more different than with direct competitors, which are more similar, as more similar companies share comparable knowledge bases and understandings (e.g., Melander and Lopez-Vega 2013).

Empirical evidence on the effect of competitor collaboration on general product and process innovation performance is mixed (Belderbos, Carree, and Lokshin 2004; Monjon and Waelbroeck 2003). In the realm of EI, competitor collaboration has not received extended theoretical scrutiny. The few existing empirical studies have not found that eco-innovators are significantly more likely to engage in competitor collaboration than non-eco-innovators (Cuerva, Triguero-Cano, and Córcoles 2014; De Marchi 2012). Consequently, the literature provides no clear guidance in developing hypotheses regarding the influence of competitor collaboration on either product-EI or process-EI. We thus refrain from developing hypotheses for this relationship.

## 3. Data and methodology

### 3.1. Dataset

Data for our study were available from the German contribution to the *Community Innovation Survey* (CIS). CIS data are gathered through an EU-wide harmonised survey that is widely used in the innovation literature. According to Laursen and Salter (2006), more than 60 peer-reviewed papers use one of the several national editions of these data in their analysis. For our study, we created a time-lagged dataset based on the 2008 and 2009 waves of the MIP. We chose these two waves in particular, since the 2009 wave is the most recent wave containing the variables that are of interest in our study, and the 2008 wave contained information regarding innovation collaboration activities of firms. Using these two waves to create a time-lagged dataset allowed us to consider the time lag between collaborative innovation activities and the adoption or diffusion of the EI (Belderbos et al. 2015). For the 2009 CIS, a total of 35,197 companies were contacted

(2008: 21,060). The scientific use files contain 6,404 observations for the 2009 wave (2008: 5,274). Given that we had to construct a time-lagged dataset, observations for firms where data were available for only one period had to be excluded prior to analyses, leading to a total of 2,512 observations. We excluded observations for which not all variables under investigation were available, leading to a further reduction to 848 observations. Additionally, we limited our analysis to companies in manufacturing sectors to provide a clear sectoral focus and to limit effects resulting from varying sectoral business structures and regulatory frameworks. These exclusions led to our final sample of $N$ = 546 companies. Table 2 provides details of the sample composition.

Given that the CIS relies on self-reported data, a potential sample selection problem could arise as firms that are successful (or that are not successful) might not participate in the following year. Using a t-test on mean differences, we compared the information reported by the 546 firms included in the dataset for 2009 with the information reported by the usable firms in the overall sample in 2008 (i.e., firms that reported information for the variables under investigation) (e.g., Ghisetti 2017). Given that we found no significant differences for the dependent and independent variables, we feel confident that our results are robust in this regard.

## 3.2. Variables

### 3.2.1. Dependent variables

To operationalise our two dependent variables, process-EI and product-EI, we used the nine sub-items pertaining to process-EI and the three items referring to product-EI from the MIP questionnaire. Adopting and modifying the operationalisation employed by Ghisetti, Marzucchi, and Montresor (2015), we computed the variables measuring process-EI and product-EI based on these indications. Specifically, respondents to the survey were asked to indicate whether they had introduced a specific subtype of product-

**Table 2.** Sample description.

| Sector | Number of firms | % of total firms | 2-digit classification (WZ93) | Sector description |
|---|---|---|---|---|
| Food, tobacco | 26 | 4.76 | 15, 16 | Manufacture of food products, tobacco |
| Textiles | 34 | 6.23 | 17–19 | Textiles, clothing and leather products |
| Wood, paper | 68 | 12.45 | 20–22 | Wood, paper, printing |
| Chemicals | 38 | 6.96 | 23, 24 | Refining petroleum, coke manufacture, chemical industry |
| Plastics | 33 | 6.04 | 25 | Manufacture of rubber and plastic products |
| Glass, ceramics | 21 | 3.85 | 26 | Glass, ceramics, other non-metallic mineral products |
| Metals | 97 | 17.77 | 27, 28 | Manufacture of basic metals and fabricated metal products; steel, metal structures. |
| Machinery | 66 | 12.09 | 29.00 | Manufacturing of machinery, weapons and ammunition, domestic appliances n.e.c. |
| Electrical equipment | 53 | 9.71 | 30–32 | Manufacturing of office machinery and computers, electrical machinery and apparatus; radio, television and communication equipment and apparatus |
| Medical and other instruments | 54 | 9.89 | 33.00 | Manufacture of medical, precision and optical instruments |
| Transport equipment | 31 | 5.68 | 34, 35 | Manufacturing of motor vehicles and parts, other transport equipment, aircraft and spacecraft |
| Furniture | 25 | 4.58 | 36.00 | Manufacturing of furniture, jewellery, musical instruments, sports equipment, games and toys |

and process-EI and to rate the impact of this innovation subtype as being 'low', 'medium', or 'high'. The specific sub-types of EI used to operationalise process-EI and product-EI are listed in Table 3. We used this assessment to operationalise process-EI and product-EI, which hence include the number of introduced sub-types and the impact of each introduced subtype of EI (1 = low impact, 2 = medium impact, 3 = high impact). For example, a firm indicating having introduced a product-EI that reduces the energy usage of their products with a high impact (3), a product-EI reducing the emissions of products with a medium impact (2), and a further product-EI that improves the ability to recycle the product with a low impact (1) would score the value of six in this operationalisation of product-EI. Because product-EI is operationalised based on three sub-types and process-EI on nine sub-types), the performance variables have a theoretical maximum range of 0 to 9 for product-EI and 0 to 27 for process-EI. The use of this operationalisation represents a direct output measure of EI as defined by Kemp (2010). Conceptually, this operationalisation means that we identify EI performance as higher when a company introduces more individual measures pertaining to process-EI or product-EI and when the ecological impact of the introduced innovations is higher. Examination of the data for process-EI and product-EI shows that firms at the time of the data collection had realised more process-EI than product-EI. Of the 546 firms included in our dataset, a total of 243 firms (45%) reported at least one product-related EI and 363 firms (67%) reported at least one process-related EI. A total of 221 firms (41%) reported to have at least one process-EI and product-EI, 152 firms (28%) reported to have either product or process EI, and 167 firms (31%) reported to have neither process-EI nor product-EI.

**Table 3.** Description, operationalisation, and descriptive statistics for variables.

| Variable | Description | *M* | *SD* | *MIN* | *MAX* | *Range* |
|---|---|---|---|---|---|---|
| PROCESSEI | Process-EI Performance[a] | 4.51 | 5.26 | 0.00 | 25.00 | 25 |
| PRODUCTEI | Product-EI Performance[b] | 1.56 | 2.23 | 0.00 | 9.00 | 9 |
| SCIENCECOLLAB | Depth of collaboration with universities and research institutes[c] | 0.79 | 0.89 | 0.00 | 2.00 | 2 |
| SUPPLIERCOLLAB | Depth of collaboration with material suppliers[c] | 1.17 | 0.90 | 0.00 | 2.00 | 2 |
| B2BCOLLAB | Depth of collaboration with customers: enterprises[c] | 1.35 | 0.91 | 0.00 | 2.00 | 2 |
| B2CCOLLAB | Depth of collaboration with customers: consumers[c] | 0.64 | 0.89 | 0.00 | 2.00 | 2 |
| COMPCOLLAB | Depth of collaboration with competitors/enterprises in the same sector[c] | 0.67 | 0.80 | 0.00 | 2.00 | 2 |
| ACI | Average R&D Intensity, R&D spending as percentage of total sales | 0.02 | 0.03 | 0.00 | 0.15 | 0.15 |
| ACII | Average R&D continuity, 0 no internal R&D, 1 ad-hoc internal R&D, 2 continuous internal R&D | 0.87 | 0.87 | 0.00 | 2.00 | 2 |
| ACIII | Average proportion of all employees with university degree; in intervals | 2.92 | 1.94 | 0.00 | 8.00 | 8 |
| EXPORT | Average Export Intensity, share of revenue from exports | 0.26 | 0.27 | 0.00 | 0.85 | 0.85 |
| FUNDING | Public funding received for EI activities (DUMMY) | 0.05 | 0.22 | 0.00 | 1.00 | 1 |
| REGULATION | EI introduced in response to regulation, expected regulation, or voluntary agreements (DUMMY) | 0.32 | 0.46 | 0.00 | 1.00 | 1 |
| MARKET | EI introduced in response to current or expected market demand (DUMMY) | 0.18 | 0.39 | 0.00 | 1.00 | 1 |

[a]EI-Typologies summarised under process-EI are (1) Reduced material use per unit of output, (2) reduced energy use per unit of output, (3) reduced CO2 footprint by your enterprise, (4) reduced air pollution, (5) reduced water pollution, (6) reduced soil pollution, (7) reduced noise pollution, (8) replaced dangerous materials, (9) recycled waste, water, or materials. For each introduced innovation, a value was attributed to the indicated impact (1 = low, 2 = medium, or 3 = high). Variable computed as sum of impact ratings across subtypes introduced in this category.
[b]EI-Typologies summarised under product-EI are (1) Reduced energy use of products, (2) reduced air, water, soil or noise pollution of products, (3) improved recycling of product after use. For each introduced innovation, a value was attributed to the indicated impact (1 = low, 2 = medium, or 3 = high). Variable computed as sum of impact ratings across subtypes introduced in this category.
[c]Items on scale 0 not relevant, 1 unimportant, 2 important

### 3.2.2. Independent variables

We computed a total of five variables indicating the importance of collaboration partners for the innovation activities of the firms. By relying on items referring to innovation partners, we adopt a perspective of open innovation that embodies an active, bilateral partnership. As such, this view of open innovation and innovation collaboration goes beyond considering collaboration partners as actual partners and as mere innovation sources (OECD & Eurostat, 2005). Our independent variables took the value 0 if respondents indicated the particular partner type to be 'not relevant', 1 if they indicated it to be 'unimportant' and the value 2 if they indicated it to be 'important'. In using this operationalisation, following suggestions by previous research (De Marchi 2012), we expect to better account for the intensity of interactions and the importance of the interactions with the respective partner types. This strategy resulted in the five independent variables indicating the importance of partnerships: (1) *SCIENCECOLLAB* for partnerships with universities and research institutes, (2) *SUPPLIERCOLLAB* for partnerships with material suppliers, (3) *B2BCOLLAB* for partnerships with 'enterprise' customers, (4) *B2CCOLLAB* for partnerships with consumers, and (5) *COMPCOLLAB* for partnerships with competitors and firms in the same sector (as we do not formulate a hypothesis for this collaboration type we included this collaboration type as a control variable). The data for collaboration were taken from the 2008 wave of the survey, i.e., from the wave preceding the wave contributing the data for the dependent variable. Taking the data from the 2008 wave of the survey, we are able to implement a time lag between collaborative innovation activities and the emergence of EI, thereby addressing a recent call by Ghisetti, Marzucchi, and Montresor (2015).

### 3.2.3. Control variables

Based on our literature review, we included a set of control variables in our analyses. First, we control for three aspects of *absorptive capacity*, as absorptive capacity has been shown to play a role in the context of both open innovation and EI (Ghisetti, Marzucchi, and Montresor 2015; Rennings 2000). The variables we use to control for absorptive capacity capture the R&D intensity (*ACI*), the continuity of internal R&D (*ACII*) and the share of employees with a higher education degree (*ACIII*). Second, we control for the export intensity of the firms using the variable *EXPORT*. Third, to specifically control for the other drivers of EI emphasised by previous studies (Ghisetti, Marzucchi, and Montresor 2015; Horbach, Oltra, and Belin 2013), we introduce the following three dummy variables: (1) a dummy variable controlling for whether the company indicated having introduced EI due to regulatory requirements or industry self-regulation (*REGULATION*) or (2) due to specific market demands (*MARKET*); (3) and we control for whether a company received public funding for its EI activities (*FUNDING*). Furthermore, we use 11 industry dummies to control for belonging to one of the 12 manufacturing sectors included in our sample following the NACE classification. Finally, to control for a potential influence of firm size, we introduce two size dummies to control for the size of the firm measured by the number of employees in three categories as having fewer than 50, between 50 and 250, and more than 250 employees. Table 3 provides an overview of the variables used, their definition and operationalisation, and descriptive statistics.

## 4. Results

### 4.1. Hypotheses tests

Correlations between variables in our analysis are reported in Table 4. All forms of collaboration are positively associated with process-EI and product-EI. The different collaboration types are moderately correlated with each other. Only supplier collaboration and enterprise customer collaboration are more strongly correlated. The dependent variables process-EI and product-EI are pure count variables (i.e., variables with non-negative integer values), which exhibit distributions that approximate Poisson distributions. Poisson regression models are the preferred estimation strategy for count data (Hausman, Hall, and Griliches 1984). However, standard Poisson regression models misspecify the effect of zero counts whereas zero-inflated Poisson regression models take zero counts into consideration (Greene 1994). We conducted Vuong's (1989) test for each of our models. Given that results were consistently greater than 1.96 across all models, a zero-inflated Poisson model was preferable.

Tables 5 and 6 depict the results of our econometric analyses. We included the four collaboration forms we utilise to test our hypotheses separately in models one to four and included all four collaboration forms in the fifth model. Hypothesis 1a predicts a positive association between science-based collaboration (*SCIENCECOLLAB*) and process-EI. Considering the individual coefficients (Model 1 in Table 5), we found a positive effect of science-based collaboration on process-EI, thus confirming Hypotheses 1a. Hypothesis 2a predicts that supplier collaboration (*SUPPLIERCOLLAB*) is positively associated with process-EI. We found a positive association between supplier collaboration (Model 2) and process-EI, thus confirming Hypotheses 2a. Hypothesis 3a predicts a positive association between customer collaboration, i.e., enterprise customer collaboration (*B2BCOLLAB*) and consumer collaboration (*B2CCOLLAB*), and process-EI. We found no significant association between enterprise customer collaboration and process-EI (Model 3). Moreover, we found a positive relationship between consumer collaboration and process-EI (Model 4), thus partially confirming Hypothesis 3a. Thus, science-based collaboration, supplier collaboration, and consumer collaboration are associated with process-EI when not controlling for the other collaboration forms. When we control for the collaboration forms and the other collaboration forms are kept constant, the results for science-based collaboration,

**Table 4.** Correlations for variables.

| | Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PROCESSEI | 1.00 | | | | | | | | | | | | | |
| 2 | PRODUCTEI | 0.66 | 1.00 | | | | | | | | | | | | |
| 3 | SCIENCECOLLAB | 0.24 | 0.23 | 1.00 | | | | | | | | | | | |
| 4 | SUPPLIERCOLLAB | 0.24 | 0.17 | 0.32 | 1.00 | | | | | | | | | | |
| 6 | B2BCOLLAB | 0.19 | 0.17 | 0.39 | 0.61 | 1.00 | | | | | | | | | |
| 7 | B2CCOLLAB | 0.16 | 0.12 | 0.14 | 0.36 | 0.35 | 1.00 | | | | | | | | |
| 8 | COMPCOLLAB | 0.11 | 0.13 | 0.28 | 0.40 | 0.41 | 0.34 | 1.00 | | | | | | | |
| 9 | ACI | 0.01 | 0.09 | 0.48 | 0.08 | 0.21 | 0.02 | 0.09 | 1.00 | | | | | | |
| 10 | ACII | 0.26 | 0.28 | 0.67 | 0.31 | 0.38 | 0.14 | 0.20 | 0.60 | 1.00 | | | | | |
| 11 | ACIII | −0.01 | 0.05 | 0.36 | 0.05 | 0.16 | 0.04 | 0.09 | 0.52 | 0.42 | 1.00 | | | | |
| 12 | EXPORT | 0.12 | 0.09 | 0.33 | 0.15 | 0.19 | 0.00 | 0.03 | 0.19 | 0.40 | 0.22 | 1.00 | | | |
| 13 | FUNDING | 0.24 | 0.13 | 0.07 | 0.03 | 0.04 | 0.06 | −0.03 | 0.05 | 0.10 | 0.02 | −0.02 | 1.00 | | |
| 14 | REGUATION | 0.44 | 0.42 | 0.20 | 0.15 | 0.14 | 0.06 | 0.12 | 0.17 | 0.26 | 0.13 | 0.10 | 0.19 | 1.00 | |
| 15 | MARKET | 0.33 | 0.39 | 0.18 | 0.17 | 0.13 | 0.06 | −0.01 | 0.10 | 0.21 | 0.07 | 0.09 | 0.25 | 0.40 | 1.00 |

*N* = 546, Correlations above .09 and below −.09 are significant at $p < 0.05$.

**Table 5.** Results of zero-inflated Poisson regression for process-EI.

| | Product-EI | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model 1 | | Model 2 | | Model 3 | | Model 4 | | Model 5 | | Model 6 | |
| Variables | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. |
| SCIENCECOLLAB | 0.078* | 0.03 | | | | | | | 0.068* | 0.03 | 0.054* | 0.03 |
| SUPPLIERCOLLAB | | | 0.127*** | 0.03 | | | | | 0.115*** | 0.03 | 0.133*** | 0.03 |
| B2BCOLLAB | | | | | 0.037 | 0.03 | | | −0.065* | 0.03 | −0.079* | 0.03 |
| B2CCOLLAB | | | | | | | 0.138*** | 0.25 | 0.133*** | 0.03 | 0.137*** | 0.03 |
| COMPCOLLAB | −0.005 | 0.03 | −0.036 | 0.03 | −0.004 | 0.03 | −0.033 | 0.03 | −0.061* | 0.03 | −0.069* | 0.03 |
| ACI | −0.386 | 1.02 | −0.044 | 0.99 | 0.034 | 0.99 | −0.400 | 1.00 | 0.028 | 1.03 | 0.930 | 1.00 |
| ACII | 0.035 | 0.04 | 0.032 | 0.04 | 0.054 | 0.04 | 0.039 | 0.04 | 0.004 | 0.04 | 0.016 | 0.04 |
| ACIII | −0.048*** | 0.01 | −0.040** | 0.01 | −0.044** | 0.01 | −0.047** | 0.01 | −0.048** | 0.01 | −0.042*** | 0.01 |
| EXPORT | 0.077 | 0.09 | 0.062 | 0.09 | 0.086 | 0.09 | 0.101 | 0.09 | 0.072 | 0.09 | 0.038 | 0.09 |
| FUNDING | 0.296*** | 0.05 | 0.306*** | 0.07 | 0.299*** | 0.07 | 0.289*** | 0.07 | 0.294*** | 0.07 | | |
| REGULATION | 0.350*** | 0.05 | 0.345*** | 0.05 | 0.347*** | 0.05 | 0.343*** | 0.05 | 0.347*** | 0.05 | | |
| MARKET | 0.162** | 0.05 | 0.140** | 0.05 | 0.161** | 0.05 | 0.163** | 0.05 | 0.142** | 0.05 | | |
| INDUSTRY DUMMIES | Included | | included | | included | | included | | included | | included | |
| SIZE DUMMIES | Included | | included | | included | | included | | included | | included | |
| CONSTANT | 1.683*** | 0.11 | 1.596*** | 0.11 | 1.661*** | 0.11 | 1.540*** | 0.11 | 1.497*** | 0.11 | 1.653*** | 0.11 |
| Logit Inflation: PRESSURE | −1.702*** | 0.25 | −1.711*** | 0.26 | −1.700*** | 0.25 | 1.706*** | 0.26 | −1.729*** | 0.27 | −1.822*** | 0.28 |
| $R^2$ | 0.11 | | 0.12 | | 0.11 | | 0.12 | | 0.13 | | 0.11 | |
| Wald Chi Square (df) | 249.29 (22) | | 262.55 (22) | | 244.64 (22) | | 274.30 (22) | | 293.38 (25) | | 165.99 (22) | |
| Prob > Chi Square | *** | | *** | | *** | | *** | | *** | | *** | |
| Log likelihood | −1460.317 | | −1.453.69 | | −1462.64 | | −1447.816 | | −1438.28 | | −1501.97 | |
| Observations | 546 | | 546 | | 546 | | 546 | | 546 | | 546 | |

$N = 546$, ***$p < .01$; ** $p < .05$; *$p < 0.1$.

**Table 6.** Results of zero-inflated Poisson regression for product-EI.

| | Product-EI | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model 1 | | Model 2 | | Model 3 | | Model 4 | | Model 5 | | Model 6 | |
| Variables | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. | Coef. | S.E. |
| SCIENCECOLLAB | 0.078* | 0.03 | | | | | | | 0.068* | 0.03 | 0.054* | 0.03 |
| SUPPLIERCOLLAB | | | 0.127*** | 0.03 | | | | | 0.115*** | 0.03 | 0.133*** | 0.03 |
| B2BCOLLAB | | | | | 0.037 | 0.03 | | | −0.065* | 0.03 | −0.079* | 0.03 |
| B2CCOLLAB | | | | | | | 0.138*** | 0.25 | 0.133*** | 0.03 | 0.137*** | 0.03 |
| COMPCOLLAB | −0.005 | 0.03 | −0.036 | 0.03 | −0.004 | 0.03 | −0.033 | 0.03 | −0.061* | 0.03 | −0.069* | 0.03 |
| ACI | −0.386 | 1.02 | −0.044 | 0.99 | 0.034 | 0.99 | −0.400 | 1.00 | 0.028 | 1.03 | 0.930 | 1.00 |
| ACII | 0.035 | 0.04 | 0.032 | 0.04 | 0.054 | 0.04 | 0.039 | 0.04 | 0.004 | 0.04 | 0.016 | 0.04 |
| ACIII | −0.048*** | 0.01 | −0.040** | 0.01 | −0.044** | 0.01 | −0.047** | 0.01 | −0.048** | 0.01 | −0.042*** | 0.01 |
| EXPORT | 0.077 | 0.09 | 0.062 | 0.09 | 0.086 | 0.09 | 0.101 | 0.09 | 0.072 | 0.09 | 0.038 | 0.09 |
| FUNDING | 0.296*** | 0.05 | 0.306*** | 0.07 | 0.299*** | 0.07 | 0.289*** | 0.07 | 0.294*** | 0.07 | | |
| REGULATION | 0.350*** | 0.05 | 0.345*** | 0.05 | 0.347*** | 0.05 | 0.343*** | 0.05 | 0.347*** | 0.05 | | |
| MARKET | 0.162** | 0.05 | 0.140** | 0.05 | 0.161** | 0.05 | 0.163** | 0.05 | 0.142** | 0.05 | | |
| INDUSTRY DUMMIES | Included | | included | | included | | included | | included | | included | |
| SIZE DUMMIES | Included | | included | | included | | included | | included | | included | |
| CONSTANT | 1.683*** | 0.11 | 1.596*** | 0.11 | 1.661*** | 0.11 | 1.540*** | 0.11 | 1.497*** | 0.11 | 1.653*** | 0.11 |
| Logit Inflation: PRESSURE | −1.702*** | 0.25 | −1.711*** | 0.26 | −1.700*** | 0.25 | 1.706*** | 0.26 | −1.729*** | 0.27 | −1.822*** | 0.28 |
| $R^2$ | 0.11 | | 0.12 | | 0.11 | | 0.12 | | 0.13 | | 0.11 | |
| Wald Chi Square (df) | 249.29 (22) | | 262.55 (22) | | 244.64 (22) | | 274.30 (22) | | 293.38 (25) | | 165.99 (22) | |
| Prob > Chi Square | *** | | *** | | *** | | *** | | *** | | *** | |
| Log likelihood | −1460.317 | | −1.453.69 | | −1462.64 | | −1447.816 | | −1438.28 | | −1501.97 | |
| Observations | 546 | | 546 | | 546 | | 546 | | 546 | | 546 | |

$N$ = 546, ***$p$ < .01; ** p < .05; *$p$ < 0.1.

supplier collaboration, and consumer collaboration remain stable but a significant negative association between enterprise customer collaboration and process-EI emerges, which is contrary to Hypothesis 3a. This difference in the coefficient between Model 3 and Model 5 and the positive correlation coefficient between enterprise customer collaboration and process-EI indicate that the interrelations of the collaboration forms cause this result. By solely interpreting the regression coefficients, however, we do not know which interrelations of collaboration forms account for this result. Therefore, we conducted a commonality analysis in the supplementary analyses.

In the next step of the analysis, we examined the association between the different collaboration types and product-EI. Hypothesis 1b predicts that science-based collaboration is positively associated with product EI. Considering the individual coefficients of each collaboration form for product-EI (Table 6, Model 1), we found no significant association between science-based collaboration (*SCIENCECOLLAB*) and product-EI, so Hypothesis 1b is not confirmed. Hypothesis 2b predicts a positive association between supplier collaboration and product-EI. We found no significant association between supplier collaboration (*SUPPLIERCOLLAB*) and product-EI (Model 2), so Hypothesis 2b was not confirmed. Hypothesis 3b predicts positive associations between customer collaboration and product-EI. We found a positive association between consumer collaboration (*B2CCOLLAB*) and product-EI, whereas the relationship between enterprise customer collaboration (*B2BCOLLAB*) and product-EI was insignificant, thus partially confirming Hypothesis 3b.

Regarding the effects of the control variables employed, we found the following results. First, we found no significant effect for competitor collaboration for both EI performance outcomes. Second, we found no significant effect for two operationalisations of absorptive capacity (R&D intensity and the continuity of internal R&D). Third, we found a negative effect of absorptive capacity operationalised by the share of employees with a higher education degree on process-EI. As expected, we found regulatory demand and market demand to have a positive relationship with process-EI and product-EI. Additionally, we found a positive relationship between public funding for EI activities and process-EI, but not product-EI. Given that the measures for regulatory demand, market demand, and funding are based on self-reported data and not on exogenous variables, we assess the robustness of our findings to evaluate a potential confounding effect. Accordingly, in Model 6 we excluded the three variables. The main results for the collaboration variables remain robust. We calculated the Variance Inflation Factor (VIF) as well as the Condition Number in the post-estimation of our models. Depending on the respective model, the highest mean VIF calculated is 1.61 and the highest mean Condition Number is 8.96.[2]

While we were primarily interested in analysing the presence and direction of effects between collaboration and the emergence of EI, our analyses also allow for a more nuanced interpretation regarding the magnitude of the impact of collaboration through the relative factor change in expected counts *exp(β)*. Regarding process-EI, we found that for a one-unit increase in collaboration depth with universities and research

[2]Please note that given the high correlation between the dependent variables, we investigated potential dependencies of estimations for process-EI vs. product-EI. Simultaneous Poisson estimation indicated that our results are robust to the independent estimations, i.e., the inter-relationship between process-EI and product-EI does not influence the reported results, and reporting two different models appears justified.

organisations (*SCIENCECOLLAB*), the expected count of process-EI increased by 10 percent (*SUPPLIERCOLLAB*: 10.7%; *B2CCOLLAB*: 10.6%). Regarding product-EI, we found that for a one-unit increase in consumer collaboration (*B2CCOLLAB*), the expected count of product-EI increased by 12 percent. These results indicate that the positive effects of collaboration with individual partner types on the emergence of EI are not only statistically significant but also considerable in magnitude. While the magnitude of effects appears to be slightly greater for product-EI, the effects of the individual partners do not vary to a large extent.

### 4.2. Supplementary analyses

To complement the regression analysis, we conducted a commonality analysis to assess the extent to which the common effects among the collaboration forms versus the unique effects of each collaboration form explain the two dimensions of EI performance (Nimon and Oswald 2013). Zero-inflated Poisson regression analyses with all combinations of the four collaboration forms were conducted, and the unique and common components of explained variance were calculated based on the $R^2$ values from the regression analyses and the formulas provided by Nimon et al. (2008). Figure 2 depicts the decomposition of the variance explained by the four collaboration types into unique and common effects.

Unique effects identify the amount of variance unique to each of the four collaboration forms. Common effects identify the amount of variance decomposed into all possible combinations that contribute to variance explained jointly with other collaboration forms. The main advantage of commonality analysis is that it is able to identify the sources of negative effects in regression analyses (i.e., it identifies which combinations of

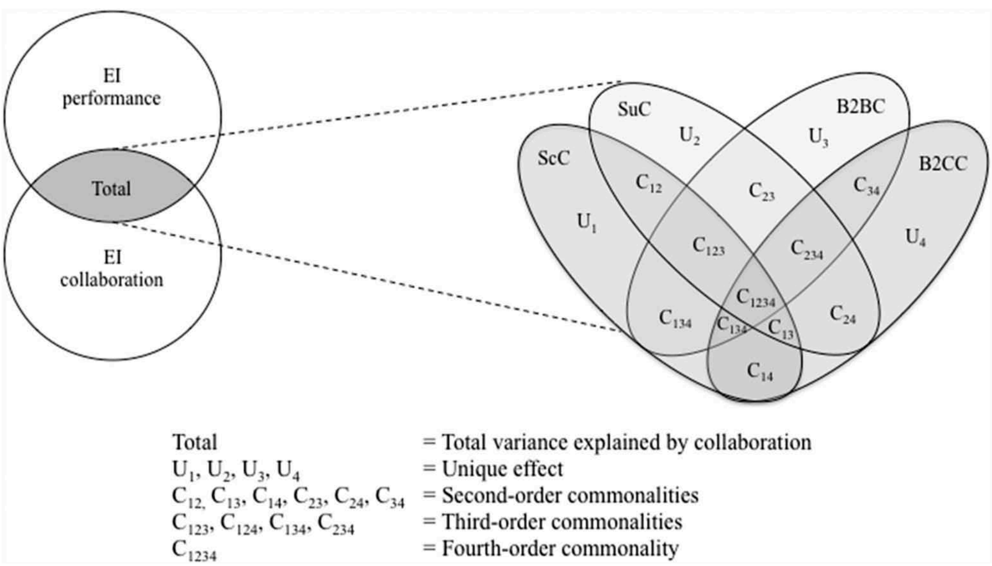


**Figure 2.** Decomposition of variance explained by different types of collaboration.

Note: ScC = science collaboration, SuC = supplier collaboration, B2BC = enterprise customer collaboration, B2CC = consumer collaboration variables result in a negative effect). Results of the commonality analysis for the two EI performance outcomes are reported in Table 7.

Process-EI was mainly explained by variance unique to consumer collaboration (47%) and supplier collaboration (13%). The common effect of enterprise customer collaboration and consumer collaboration (27%) accounted for the major joint effect of collaboration types, followed by the shared effect of all four collaboration types (13%). For process-EI, 69 percent of the variance is explained by unique effects and 31 percent is explained by common effects. The common effects can only be realised if *all* respective collaboration types are present. For example, the 27 percent of the common variance that are explained by enterprise customer collaboration and consumer collaboration together can only be realised if a firm utilises *both* collaboration types. If a firm is only using one of the two collaboration partners, this shared effect will not be present. A notable result was that both enterprise customer collaboration and consumer collaboration had a negative joint contribution to process-EI in their shared effect with science-based collaboration and supplier collaboration, indicating a suppression effect (Nimon and Oswald 2013). This result indicates that collaboration with universities and other research institutions, suppliers, and customers (enterprise customers and consumers) should be aligned. A consistent result across the two EI performance outcomes was that consumer collaboration showed the strongest unique contribution to the explained variance. In summary, the results of the commonality analysis a) explain the negative effect of customer enterprise collaboration on process-EI, b) show that consumer collaboration contributes

**Table 7.** Results of supplementary commonality analysis.

| Variance component | Process-EI ($R^2$ = .126/.016) | Product-EI ($R^2$ = .093/.004) |
|---|---|---|
| *Unique effects* | | |
| $U_1$ SCIENCECOLLAB (ScC) | .001 (6%) | .000 (0%) |
| $U_2$ SUPPLIERCOLLAB (SUC) | .002 (13%) | .001 (25%) |
| $U_3$ B2BCOLLAB (B2BC) | .001 (6%) | .000 (0%) |
| $U_4$ B2CCOLLAB (B2CC) | .007 (47%) | .002 (50%) |
| *Common effects* | | |
| *Second-order commonalities* | | |
| $C_{12}$ (ScC/SuC) | .001 (7%) | .000 (0%) |
| $C_{13}$ (ScC/B2BC) | .000 (0%) | .000 (0%) |
| $C_{14}$ (ScC/B2CC) | .000 (0%) | .000 (0%) |
| $C_{23}$ (SuC/B2BC) | .000 (0%) | −.001 (−25%) |
| $C_{24}$ (SuC/B2CC) | .000 (0%) | .000 (0%) |
| $C_{34}$ (B2BC/B2BC) | .004 (27%) | .000 (0%) |
| *Third-order commonalities* | | |
| $C_{123}$ (ScC/SuC/B2BC) | −.001 (−6%) | .000 (0%) |
| $C_{124}$ (ScC/SuC/B2CC) | −.001 (−6%) | .000 (0%) |
| $C_{134}$ (ScC/B2BC/B2BC) | .000 (0%) | .000 (0%) |
| $C_{234}$ (SuC/B2BC/B2B) | .000 (0%) | .001 (25%) |
| *Fourth-order commonality* | | |
| $C_{1234}$ (ScC/SuC/B2BC/B2BC) | .002 (13%) | .001 (25%) |
| *Summary* | | |
| *Unique effects* | .011 (69%) | .003 (75%) |
| *Common effects* | .005 (31%) | .001 (25%) |
| *Total effect* | .016 (100%) | .004 (100%) |

The table presents the result of commonality analysis of the effect of the four collaboration forms on process-EI and product-EI while controlling for all control variables included in the regression analyses presented in Tables 5 and 6. Cells report the commonality coefficients and the explained variance relative to variance explained by all four collaboration forms. The total effect may, due to rounding, not sum up to 100 percent. U = unique effect, unique = total of unique effects, c = common effect, common = total of common effect.

to both process-EI and product-EI in particular individually, c) and that firms need to align their collaborations to realise their full potential.

We used necessary condition analysis (NCA; Dul 2016) to explore whether the different collaboration types represent a necessary condition for EI. The underlying logic of NCA is different from regression analysis, which seeks to assess whether an increase in the predictor variable is associated with an increase in the outcome variable. The objective of NCA is to identify if there is a necessary relationship in *degree*, i.e., a specific level of X is necessary for a specific level of Y. Given our interest in the level of depth in different collaboration types as a condition for the number of process- and product-EI, NCA is an adequate statistical approach to go beyond the findings of our regression analyses. We used R and the NCA package (Dul 2018) to conduct the analysis. Table 8 shows the results of the NCA.

The results for process-EI show that all types of collaboration are necessary conditions for process-EI. All NCA effect sizes are above the threshold of $d = 0.1$ (Dul 2016). Four of the collaboration types show a medium effect size ($d = 0.1$ to 0.3) and enterprise customer collaboration (*B2BCOLLAB*) shows a large effect size ($d = 0.3$ to 0.5). The results for product-EI show that only two collaboration types represent necessary conditions for product-related EI. Supplier collaboration (*SUPPLIERCOLLAB*) and enterprise customer collaboration (*B2BCOLLAB*) show medium effect sizes. In summary, the results of the NCA shed new light on the role of different collaboration types by showing that a specific degree of depth in collaboration is a necessary but not sufficient condition for a specific degree of process-EI and that a specific degree of depth in supplier collaboration and enterprise customer collaboration is a necessary but not sufficient condition for a specific degree of product-EI.

To further substantiate the results of the regression analyses and to provide a more in-depth analysis of the underlying collaboration relationships, we rerun our analyses with a modified set of independent variables operationalising the depth of collaboration. Specifically, we modelled the collaboration depth of all relationships using dummy variables. Each dummy variable represents a collaboration that was either evaluated as 'not relevant', 'unimportant', or 'important' by firms. As such, this operationalisation represents a categorical operationalisation of the previously employed, linear operationalisation. The results of this analysis are depicted in Table 9.

The results generally confirm the relationships observed in the primary analyses. Positive and negative effects found in the primary analyses are confirmed by the supplementary analyses. However, with the exception of consumer collaboration, these effects are only observed for deeper collaboration relationships (evaluated as 'important') by firms. With regard to supplier collaboration, we find a positive relationship for deep ('important') collaborations in line with previous results, but a negative relationship for less-deep, 'unimportant' collaboration.

## 5. Discussion and conclusion

This study set out to investigate the differential effect of innovation collaboration with different types of partners on the extent of implemented process- and product-EI. Our results partially confirm hypotheses regarding a differential impact of collaboration on product- and process-EI. First, our results underline the importance of science-based collaboration for process-EI. These results are supportive of the notion that meaningful EI is highly reliant on new technologies (De Marchi 2012) and that collaboration with

**Table 8.** Results of supplementary necessary condition analysis.

| | Process-EI | | | | | Product-EI | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | SCIENCE COLLAB | SUPPLIERCOLLAB | B2B COLLAB | B2C COLLAB | COMP COLLAB | SCIENCE COLLAB | SUPPLIERCOLLAB | B2B COLLAB | B2C COLLAB | COMP COLLAB |
| Effect size (*d*) | .200 | .300 | .320 | .220 | .200 | .056 | .220 | .220 | .000 | .056 |
| *p*-value | .026 | .007 | .018 | .008 | .008 | .100 | .002 | .026 | 1 | .081 |
| *p*-value 95% CI | .016/.036 | .002/.012 | .010/.026 | .002/.014 | .002/.014 | .081/.119 | .000/.005 | .016/.036 | 1/1 | .064/.098 |
| *p*-accuracy | .010 | .005 | .008 | .006 | .006 | .019 | .003 | .010 | .000 | .017 |
| Ceiling zone | 10 | 15 | 16 | 11 | 10 | 1 | 4 | 4 | 0 | 1 |

All analyses are based on the step function CE-FDH ceiling line approach. For this approach, by definition, the number of observations above the ceiling line is 0 and the c-accuracy is 100%. All confidence intervals (CI) were generated using 10,000 bootstrap resamplings. Effect size thresholds: 0.0 to 0.1 = small effect size; 0.1 to 0.3 = medium effect size; 0.3 to 0.5 = large effect size; 0.5 to 1 = very large effect size.

**Table 9.** Results for supplementary zero-inflated Poisson regression for product- and process-EI.

| | Process-EI | | Product-EI | |
|---|---|---|---|---|
| Variable | *Coef.* | *S.E.* | *Coef.* | *S.E.* |
| SCIENCE_UNIMP | .058 | 0.07 | −.076 | 0.13 |
| SCIENCE_IMP | .139** | 0.06 | .044 | 0.12 |
| SUPPLIER_UNIMP | −.165** | 0.08 | −.134 | 0.15 |
| SUPPLIER_IMP | .139** | 0.07 | .112 | 0.13 |
| B2B_UNIMP | −.094 | 0.11 | −.264 | 0.24 |
| B2B_IMP | −.119* | 0.07 | −.167 | 0.14 |
| B2C_UNIMP | .315*** | 0.07 | .065 | 0.15 |
| B2C_IMP | .276*** | 0.05 | .188** | 0.09 |
| COMP_UNIMP | .033 | 0.06 | .066 | 0.11 |
| COMP_IMP | −.098* | 0.06 | .146 | 0.10 |
| ACI | .310 | 1.05 | .398 | 1.67 |
| ACII | −.004 | 0.04 | .078 | 0.08 |
| ACIII | −.048*** | 0.01 | −.034 | 0.03 |
| EXPORT | .053 | 0.09 | .066 | 0.18 |
| FUNDING | .256*** | 0.07 | .016 | 0.14 |
| REGULATION | .351*** | 0.05 | .305*** | 0.09 |
| MARKET | .142*** | 0.05 | .243*** | 0.09 |
| INDUSTRY DUMMIES | included | | included | |
| SIZE DUMMIES | included | | included | |
| CONSTANT | 1.568*** | .114 | .994*** | .260 |
| Logit Inflation: PRESSURE | −1.734*** | .273 | −.874*** | .124 |
| $R^2$ | .132 | | .096 | |
| Wald Chi Square (df) | 313.34 (30) | | 70.16 (30) | |
| Prob > Chi Square | *** | | *** | |
| Log likelihood | −1428.29 | | −785.08 | |
| Observations | 546 | | 546 | |

*N* = 546, ****p* < .01; ***p* < .05; **p* < 0.1.

universities provides access to new technologies funded in basic research, thus supporting meaningful EI in processes. However, we did not find a positive effect of science-based collaboration on product-EI. A possible explanation for the missing association could be that this form of collaboration does not directly influence product-EI but that more proximal determinants mediate the relationship. For example, Cai and Zhou (2014) show that integrative capability mediates the association between external as well as internal factors and EI performance.

Second, we find support for our expectation of a positive impact of collaboration with suppliers on process-EI, thus confirming expectations regarding the benefits of collaborating closely with suppliers to increase the sustainability of manufacturing processes. These findings are supportive of the notion that companies can reduce the pollution, energy usage, and waste production of their manufacturing processes through collaboration with suppliers (Seuring and Müller 2008). However, our analysis does not allow for clear answers as to the question whether this improvement also reduces the overall impact of manufacturing across the value chain or if this is primarily through a shift in environmentally harmful activities from the manufacturing company to its suppliers. While De Marchi (2012) identified EI-innovators to collaborate more with suppliers than regular innovators, we do not find a direct association between supplier collaboration and product-EI. One possible explanation for the absence of such an effect could be that companies choose suppliers for collaboration within their established supplier network, thus barring them from seeking truly new technologies outside of their established sourcing scope that would enable them to implement radically new technologies for the creation of product-EI.

Surprisingly, our results suggest an additional positive association of collaboration with consumers on process-EI. A potential explanation could be that customers receive otherwise costly information about production processes through collaboration, thus mitigating the 'credence' character of process-EI (Darby and Karni 1973; Migliore, Schifani, and Cembalo 2015), or through the advanced knowledge of lead users undergoing a functional change (Urban and Von Hippel 1988). Our results confirm the positive effect of collaborating with private customers on product-EI. We argued that this effect could result, among other factors, from the valuable input of customers. This input is needed to ease customer adaptation to new ecologically friendly products. We did not find such an effect for collaboration with enterprise customers on either product- or process-EI. A potential explanation for absent effects could be a functional disaggregation of roles within the collaborating company, resulting in the individuals involved in the collaboration not having ecological goals or ideas on their mind. The results of the commonality analysis for process-EI show that enterprise customer collaboration needs to be aligned with both science-based collaboration and supplier collaboration to positively influence EI performance. This finding indicates that while different collaboration partners contribute in distinct ways to EI, this contribution is partially interrelated and needs to be coordinated by firms so they can take full advantage of the joint innovative forces of universities, suppliers, and enterprise customers. In light of the unique and shared effects uncovered by the commonality analysis, firms need to find a carefully balanced approach to coordinate the collaboration with different types of innovation partners: on the one hand, a coordination that allows an individual collaboration to fully unfold and, on the other hand, a coordination that fosters the collaboration of all collaboration partners.

Finally, our results indicate no effect of collaboration with competitors and other companies from the same sector on either process- or product-EI. Prior research supports both a positive and a negative effect. Competitor collaboration could further EI through common standards, shared investments in far-from-market technologies, and similar regular pressures. On the other hand, competitor collaboration has been characterised as defensive in nature.

In summary, the results of our study allow to draw implications regarding the comparative suitability of individual collaboration partners for EI. One could conclude that – in comparison to product-EI – process-EI is more strongly driven by collaboration. Furthermore, the results allow the conclusion that collaboration with private customers has the highest potential to further EI due to a positive association with both product- and process-EI.

Conducting supplementary analyses, first, we find that most observed relationships only hold true for collaborations evaluated as 'important' by firms. In line with our general assumption that such relationships are more effective, this finding could point towards the requirement for extensive collaboration to transfer and utilise the knowledge and skills required for complex, meaningful EI. Second, collaboration with consumers appears to be effective regardless of the depth of collaboration. Assuming that a primary benefit of consumer collaboration is to generate an understanding of market needs and usage behaviour, a potential explanation for this finding is that comparatively little collaborative effort is needed to further EI, as such knowledge and information is easily exchanged compared to, for example, the complex technological inputs to be expected by universities or suppliers.

Our study, through its higher level of differentiation on both the collaboration and innovation side of the analysis, primarily contributes to a more comprehensive understanding of the mechanisms within the recently established 'open eco-innovation mode'. In this realm, our contribution is threefold. First, previous research examined how top-level characteristics (breadth, depth) of firms' collaborative network relate to the emergence of EI (Ghisetti, Marzucchi, and Montresor 2015) and how collaborative networks of eco-innovators differ in their composition from those of regular innovators (De Marchi 2012). Our more-nuanced results, while generally confirming previous findings on the importance of collaboration for the emergence of EI (De Marchi 2012; Horbach, Oltra, and Belin 2013; Mazzanti and Zoboli 2005), speak towards a varying effectiveness of different partner types within the open eco-innovation mode and stress the importance of distinguishing among partner types when investigating and discussing the role of open innovation in the context of EI. Second, our differentiation between different typologies of EI showed that the impact of collaboration partners is also contingent on the EI dimension. Our study is among the first to investigate the conceptually established multidimensionality of EI (Carrillo-Hermosilla, Del Río, and Könnölä 2010; Markard, Raven, and Truffer 2012) in the context of innovation collaboration, and it confirms that it also permeates the effects achievable through collaboration. Third, previous research in this realm has been often based on non-lagged data. While these studies have provided valuable insights, the conclusions to be drawn from them are limited. By adopting a research design based on established practices from the general open innovation literature for comparable studies (Mairesse and Mohnen 2010) – specifically by allowing for a time lag between collaboration and the emergence and implementation of innovation (e.g., Belderbos, Carree, and Lokshin 2004; van Beers and Zand 2014) as well as by considering the variance resulting from different levels of collaboration intensity – we provide implications on the influence of collaboration depth on the EI performance in two dimensions of EI. Taken together, by providing this level of differentiation and by allowing for more robust implications based on time-lagged data, our study provides evidence of which types of collaboration partners are more or less suitable to promote the emergence of different typologies of EI and sheds light on the mechanisms through which different collaborations are related to EI.

Outside the realm of EI, our results also have implications for the general open innovation and knowledge sharing literature. Previous research investigated collaboration (Aschhoff and Schmidt 2008; Belderbos, Carree, and Lokshin 2004; Laursen and Salter 2006) and knowledge interactions (Powell, Koput, and Smith-Doerr 1996; Tödtling, Lehner, and Kaufmann 2009) in different knowledge settings, such as technological, organisational, and service innovation. Our study is among the first to conduct such an analysis in the context of EI, thus extending our understanding of open innovation to a knowledge context that has only more recently garnered increasing attention. Our findings regarding the impact of different partner types in the context of EI give rise to the notion that certain partner types deviate from what they were traditionally associated with in the general open innovation literature in terms of their capabilities and contribution to innovation (Faems, Van Looy, and Debackere 2005; Nieto and Santamaría 2007), e.g., when considering the impact of customers on process innovation.

Beyond the theoretical contributions, our study also has implications for practitioners. Knowledge of the differential impact of collaboration partners on different typologies of EI can inform the decision making of individuals concerned with EI. Innovation managers within firms can build upon our results when evaluating the potential of different collaboration partners contingent on the companies' EI goals. Similarly, public funding bodies, which frequently grant funding for activities directed at both EI and innovation collaboration, can rely on such knowledge in their decision making and the design of the requirements and guidelines for their funding programmes. Most importantly, policy makers should consider our findings when designing a policy mix aimed at the emergence of EI. The latter aspect is especially important due to the still present reliance of EI on regulatory incentives (Bigliardi et al. 2012) and the fact that sustainability and EI are increasingly at the centre of policy initiatives (Borghesi et al. 2013; Ghisetti, Marzucchi, and Montresor 2015).

Our study has limitations that should be considered when interpreting our results. First, we based our analyses on a sample of German manufacturing companies, thus potentially limiting validity in other countries and sectors. Previous research describes Germany as ecologically comparatively advanced in terms of policy and industry, although with a pronounced focus on end-of-pipe EI (Frondel, Horbach, and Rennings 2008; Kemp 2010), thus limiting the transferability to other developed contexts. We refrained from using a multinational sample for two reasons. On the one hand, the creation of cross-national samples with time-lagged CIS data is possible only to a very limited extent (Ghisetti, Marzucchi, and Montresor 2015). Time lags are, however, crucial to allow for a better attribution between innovation activities and permeation into EI performance. On the other hand, regulatory effects impact EI to a large degree and vary between countries and sectors. We therefore argue that excluding cross-national policy effects from our analysis is beneficial to the scope and focus of our analysis, and we follow previous studies with comparable goals and datasets (Belderbos et al. 2015; Laursen and Salter 2006) by limiting our analysis to a single country and sector.[3] A second limitation of our study is the potential for considerable sample attrition. Such attrition is plausible and common given the nature of the CIS survey as a primary instrument and the focus of our analysis on the very specific EI realm (De Marchi 2012; Ghisetti, Marzucchi, and Montresor 2015). To address the concern that sample attrition might limit the robustness of our results, we conducted supplementary analyses on different stratifications of our sample. Specifically, we reran analyses without excluding firms from the service sector as well as with a pairwise exclusion of observations to demonstrate the robustness of our results. However, despite the robustness of our findings, we cannot completely exclude a potential detrimental influence of sample attrition, of course. Third, employing time-lagged data to allow for a gap between innovation activities and the measurement of expected performance effects creates a slight overlap between periods from which measurements are taken. Specifically, dependent variables were measured for the period from 2006 through 2008, and independent variables were measured for the period 2005 through 2007, hence creating an overlap for the years 2006 and 2007. Nevertheless, we feel confident with the setup of our study because: a) no variable is measured twice and no variable can be inflated through repeated measurement, b) the setup allows for a minimal lag of one year and a maximum lag

[3]Please note that our data would allow for a comparative analysis across additional sectors, e.g., (financial) services. However, comparative analyses would require further differentiated and cumbersome hypothesis development, which would not be possible against the background of the existing literature and would dilute the focus of our study.

of three years between innovation activities and measurable effect and hence has the power to detect the majority of effects and c) gaps as well as overlaps between different periods in studies based on CIS data have not been regarded as problematic in this context (cf.Aschhoff and Schmidt 2008; Mairesse and Mohnen 2010; van Beers and Zand 2014). However, the overlap potentially allows for the effects of collaborative activities conducted prior to 2005 affecting performance measurement in the periods 2006 to 2008 or collaborative activities conducted between 2005 and 2007 going unnoticed if they enter only after 2008. This could lead to an over- or underestimation of the effect of collaboration on EI. While the data represents the most recent data including EI-related aspects, the age of the data is a limitation as the importance of collaboration for EI and of specific collaboration types may have changed during the last years. Fourth, and closely related to the previous point, our study employed a lagged research design to come closer to drawing causal inferences regarding the effects under investigation. While a lagged design can to some degree mitigate reverse causality, other issues inhibiting causal inferences, such as unobserved heterogeneity, can remain present in the analyses. Fifth, the correlation between process-EI and product-EI raises concerns of a potential dependence of the estimations reported in the different models. While the simultaneous estimation of models rendered robust results and, thus, we feel confident that the results are unaffected by this issue, this potential limitation has to be considered when interpreting our results. Sixth, in our study, we focused on process- and product-EI. Previous studies argued that organisational EI is another important dimensions of EI (e.g., Klewitz, Zeyen, and Hansen 2012; Triguero, Moreno-Mondéjar, and Davia 2013) as EI might also be related to internal organisational routines and business practices. Based on the dataset we utilised, we are not able to examine the influence of collaboration on such routines and practices or the organisational structure as whole. Seventh, the focus of the present study was on the assessment of the relation between depth of collaboration and the two EI performance outcomes. Previous studies theoretically argued and empirically examined the role of collaboration breadth in generating EI (Cainelli, De Marchi, and Grandinetti 2015; Christensen, Hain, and Nogueira 2017). The interplay of collaboration depth and breadth may be a fruitful future research avenue as this could provide insight on the question with how many partners to collaborate and how intensive this collaboration should be. Eights, due to data limitations, our study is unable to adequately differentiate between 'end-of-pipe' and 'cleaner technology' types of innovations (cf. Frondel, Horbach, and Rennings 2007; Hammar and Löfgren 2010). While such a differentiation would be valuable in the context of EI, specific datasets and surveys would be required to address this limitation. Finally, our findings have to be interpreted with care due to potential endogeneity problems. Such endogeneity problems arise because we rely on CIS data solely, and thus, use strictly endogenous variables in our analyses. While relying on CIS data is common in the literature (e.g., Christensen, Hain, and Nogueira 2017; Ghisetti, Marzucchi, and Montresor 2015; Horbach, Rammer, and Rennings 2012), to address such concerns, we encourage future research to create a dataset that allows matching endogenous and exogenous variables. For example, future research might consider variables such as market or funding as exogenous variables.[4]

Our study gives rise to several additional avenues for future research. Future studies should address the further limitations of our study, for example, by extending the analysis to other sectors and countries and by conducting comparative research to identify how

[4]We thank an anonymous reviewer for this valuable suggestion.

different sectoral structures and policy frameworks influence results. Moreover, in-depth research into the mechanisms and processes within EI collaboration is required to better understand how and when the observed surprising and counterintuitive effects can be explained. Specifically, qualitative and mixed-method research approaches could be employed to investigate how and through which channels individual collaboration partners contribute to EI activities. The characteristics of knowledge interactions (Sammarra and Biggiero 2008) as well as concepts relating to changes in functional roles as embodied in the lead-user approach (Urban and Von Hippel 1988) could serve as theoretical vantage points for such examinations. We argue that collaboration with customers, both private and enterprise, is an especially worthwhile avenue for such future studies. Moreover, our study is among the first to distinguish relevant dimensions of EI, thus endorsing the multifaceted nature of EI. Future research should expand on this approach, both in depth and breadth, by further differentiating product- and process-EI and by considering the organisational and management practices dimension of EI.

## Disclosure statement

Please note that the authors used CIS data in the following article, too, to investigate the effect of project-level collaboration breadth (i.e., the number of collaboration partner types) and collaboration depth (i.e., the intensity of the interactions with these partners) on the incremental and radical innovation performance of innovation projects: Kobarg, S., J. Stumpf-Wollersheim and I. M. Welpe. 2019. "More Is Not Always Better: Effects of Collaboration Breadth and Depth on Radical and Incremental Innovation Performance at the Project Level." *Research Policy* 48(1): 1–10.

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