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(Article begins on next page)

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The many shades of 'openness': an application of item response theory to open innovation research

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This study addresses one of the most basic research questions investigated in the Open Innovation (OI) literature: how open are firms? This question has remained partially unanswered given the challenges encountered by empirical research in assessing the relevance of specific OI practices within the OI model, as well as the types of activities perceived by managers as OI benefits or concerns. To provide an answer to this question, we suggest a framework using Item Response Theory to improve over current measures of firms' openness and test it on a sample of 383 technology-based SMEs. Our theoretical model conceives openness as an instance of how firms make decisions regarding the adoption of different OI practices based on their evaluation of OI benefits and concerns. Focusing on the relationship between firm-level differences in terms of openness and the types of OI practices adopted by these firms, we show that significantly different levels of 'OI maturity' are required to broaden the scope of external partnerships and to shift from non-pecuniary OI modes (relation-based approaches) toward pecuniary (transaction-based) practices. Our results have relevant implications for the OI literature and provide new managerial insight into OI adoption.

1. Introduction

Open Innovation (OI) was originally introduced as a phenomenon by which companies make '*use of purposive inflows and outflows of knowledge to accelerate internal innovation and to expand the market for external use of innovation, respectively.*' Specifically, the OI paradigm assumes that '*firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology*' (Chesbrough, 2006, p. 1).

Following the original conceptualization, the literature has adopted a process view of OI (Gassmann and Enkel, 2004; Enkel et al., 2009): firms practicing OI utilize external knowledge inputs within their own innovation process (outside-in OI) and allow unused ideas and technologies to extend outside the organization for others to use in their respective businesses (inside-out OI) (Chesbrough, 2017).

Different perspectives have been adopted to investigate this phenomenon. Firms' external search strategies (Laursen and Salter, 2006), the nature of technological

activities (van de Vrande et al., 2009), the forms of compensation (Dahlander and Gann, 2010), the types of partnerships (Brunswicker and Vanhaverbeke, 2015), and the changes involved in OI adoption (Ahn et al., 2015) are among the most common approaches used to characterize the large variety of modes and practices adopted by firms to implement OI.

In his latest book, Chesbrough (2019) highlights that as OI has continued to spread well beyond firm-to-firm collaborations toward the much broader contexts of supply chains, inter-organizational networks, and ecosystems, the phenomenon has become increasingly difficult to detect. To this point, Chesbrough explicitly calls for the development of new empirical research to answer the following three basic research questions: To what extent is OI generally used by firms? Are certain OI practices more relevant than others? What types of OI practices do managers perceive as OI benefits (or concerns)?

To provide an answer to these questions, we advance the application of Item Response Theory (IRT) to OI research and specify a theoretical model of how firms make decisions regarding the adoption of different OI practices given an underlying level of openness estimated as a latent trait.

Compared to alternative measures of firm openness, based on additive indexes, IRT enables the assessment of the relationship between the firm-level (unobservable) degree of openness and the pursuit of different (i.e., more or less challenging) OI practices and demonstration of the comparative relevance of OI activities for managers' decision-making process (i.e., perceived benefits or concerns).

Our empirical application is based on survey data collected from a sample of 383 Italian technology-based SMEs. Focusing on firms operating in technology markets allowed us to detect a wide range of activities and compare technology-oriented and market-oriented OI practices. As different OI practices may have different relevance within the context of technology-based SMEs (Minshall et al., 2010), such a focus may provide a clearer interpretation of managerial evaluations in terms of perceived benefits and concerns.

Using IRT, we analyze the relationship between firm-level differences in terms of openness and the types of OI practices that render the concept effective. Our findings show that along the openness continuum, firms tend to adopt more challenging OI practices. By progressing from lower to higher levels of openness, firms widen the scope of their external interactions from actors inside the value chain to external networks and are increasingly able to adopt pecuniary OI modes. Therefore, the proposed measure represents an indicator of OI maturity (i.e., firm's ability to face more challenging OI practices) rather than an indicator of OI adoption based on the pursuit of a higher number of OI practices. This measure captures the non-linearities in the process of OI adoption due to the influence of managers' perception of the OI benefits and challenges of different OI practices.

2. Theoretical background

As the OI concept theoretically evolved, empirical research has adopted increasingly detailed perspectives to provide evidence of the phenomenon, and a wide number of dimensions have been investigated in an attempt to cover the multiple aspects of the OI model.

While the use of different perspectives has added to the richness of the concept itself (Chesbrough and Bogers, 2014, p. 14), empirical research has encountered several substantial challenges.

First, as the OI model involves very different practices that are linked to firm-specific characteristics (Spithoven et al., 2013), the design and development of measures of OI adoption encountered specific methodological issues, while attempting to cover the entire spectrum of OI activities (Podmetina et al., 2014; Ahn et al., 2015). Table 1 provides a summary of the indicators developed by relevant quantitative research concerning OI published between 2000 and 2018. The selected studies were categorized according to the following three criteria: the types of indicators reflecting the definition of openness; the measures used as proxies of OI adoption; and the OI modes under investigation. While some studies adopt an in-depth perspective of specific OI practices to investigate their adoption and performance impact (Parida et al., 2012; Brunswicker and Vanhaverbeke, 2015), other studies provide a broader view by developing more comprehensive measures of openness based on the breadth/depth of firms' external search strategies (Laursen and Salter, 2006), types of technology sources (Chen et al., 2011), number of innovation partners (Drechsler and Natter, 2012) and degree of OI adoption (Burcharth et al., 2014).

Overall, empirical measures of openness largely involve the use of proxies to describe the degree to which firms draw more or less extensively and/or deeply from various external knowledge sources (Laursen and Salter, 2006), collaboration modes (Spithoven et al., 2013), types of partners (Drechsler and Natter, 2012), and their inclination (proclivity) toward OI (Ahn et al., 2016; Rangus et al., 2016).

Consequently, a common definition and comparable measurements of openness have been difficult to produce. The literature is quite diverse regarding OI definitions and research methodologies, and the existing measures are mostly based on the use of

Table 1. Summary of the main indicators developed in the quantitative empirical literature concerning OI

References		Indicators of OI adoption		
Authors and Year	Journal	Definitions	Measures	OI modes
Baum et al. (2000)	Strategic Management Journal	Alliance network composition	Number of alliances with different partners	Outside-in Inside-out
Laursen and Salter (2006)	Strategic Management Journal	Breadth and depth of external search strategies	Number of types of external knowledge sources and intensity of ties	Outside-in
Keupp and Gassman (2009)	R&D Management	Breadth and depth of OI adoption	Number of types of external knowledge sources and intensity of ties	Outside-in Inside-out
van de Vrande et al. (2009)	*Technovation*	*External knowledge exploration and technology exploitation activities*	*Types of OI practices*	*Outside-in Inside-out*
Tsai (2009)	Research Policy	Collaborative network composition	Types of partners	*No distinction*
Huang and Rice (2009)	Int. Journal of Innovation Management	Interorganizational networking	Types of OI practices	*No distinction*
Lee et al. (2010)	Research Policy	Collaboration patterns	Types of information sources and types of partnerships	*No distinction*
Parida et al. (2012)	Journal of Small Business Management	Technology scouting and technology sourcing activities	Types of OI practices	Outside-in
Zeng et al. (2010)	Technovation	Cooperation networks	Number of types of innovation partners and intensity of ties	*No distinction*
Hung and Chiang (2010)	International Journal of Technology Management	OI proclivity	Attitudes towards the OI paradigm	*No distinction*
Love et al. (2011)	Research Policy	Level of openness	Number of types of innovation partners	*No distinction*
Chen et al. (2011)	Technovation	Scope, depth and orientation of external technology sources	Number of types of external technology sources and intensity of ties	*No distinction*
Drechsler and Natter (2012)	Journal of Business Research	Level of openness	Number of types of collaboration partners and intensity of ties	*No distinction*
Classen et al. (2012)	Journal of Small Business Management	Breadth of external search strategies	Number of types of cooperation partners	Outside-in
Hung and Chou (2013)	Technovation	External technology acquisition and external technology exploitation	Types of OI practices	Outside-in Inside-out
Spithoven et al. (2013)	Small Business Economics	OI adoption	Types of OI practices	Outside-in Inside-out
Ritala et al. (2015)	Technovation	External knowledge sharing	Number of types of knowledge shared with external partners	*No distinction*
Teirlinck and Spithoven (2013)	Technovation	Research collaboration and R&D outsourcing	Types of OI practices	*No distinction*

(Continues)

Table 1.   (Continued)

References		Indicators of OI adoption		
Authors and Year	Journal	Definitions	Measures	OI modes
Chesbrough and Brunswicker (2014)	Research-Technology Management	OI adoption	Types of OI practices	Outside-in Inside-out
Du et al. (2014)	Research Policy	OI adoption at the project level	Types of partners	Outside-in Inside-out
Burtcharth et al. (2014)	Technovation	Level of OI adoption	Number of types of OI practices	Outside-in Inside-out
Ahn et al. (2015)	Journal of Innovation Management	Breadth and depth of OI adoption	Number of types of OI modes and intensity of adoption	Outside-in Inside-out
Brunswicker and Vanhaverbeke (2015)	Journal of Small Business Management	Variety and direction of sourcing strategies	Types of external knowledge sources	Outside-in
Vahter (2015)	Industry and Innovation	Level of openness	Number of types of innovation partners	*No distinction*
Verbano et al. (2015)	Journal of Small Business Management	Variety and direction of openness	Types of partners	Outside-in Inside-out
Bengtsson et al. (2015)	Creativity and Innovation Management	Breadth and depth of OI adoption	Number of types of OI partners	Outside-in OI
Bigliardi and Galati (2016)	Technology Analysis & Strategic Management	Level of OI adoption	Number of types of OI practices	Outside-in Inside-out
Ahn et al. (2016)	Technology Analysis & Strategic Management	Level of openness	Readiness/willingness to collaborate	*No distinction*
Rangus et al. (2016)	Innovation	OI proclivity	Inclination towards OI activities	Outside-in
Ahn et al. (2017)	R&D Management	Level of OI adoption	Number of types of OI practices	Outside-in Inside-out
Bogers et al. (2018)	Research Policy	Level of openness	Number of types of external knowledge sources	*No distinction*

subjective scales that sometimes fail to follow the original definition (Schroll and Mild, 2012). If such scales better reflect the strategic importance of OI for different types of firms, the diversity of methods and measures used hindered the opportunity to perform systematic comparisons.

Therefore, the second substantial challenge concerns the development of comprehensive knowledge regarding the OI model (Chesbrough, 2019). As external knowledge sourcing and outside-in OI practices have been examined far more thoroughly than the inside-out branch of OI, this last portion of the model remains less well understood by academic research and industry practice (Chesbrough, 2017, p. 36). Furthermore, due to the limited use of inside-out OI, actual measures of OI adoption might be biased toward the outside-in process (Huizingh, 2011). More generally, empirical research has not

sufficiently considered the different aspects characterizing the OI paradigm as the model includes different knowledge paths (Chesbrough, 2006), types of approaches (Dahlander and Gann, 2010), and a wide range of technology-oriented and market-oriented practices related to external technology exploration and exploitation (van de Vrande et al., 2009). This issue is evident in the context of SMEs. Since the seminal contribution by van de Vrande et al. (2009), numerous empirical studies have investigated OI adoption in SMEs and showed that most SMEs tend to adopt only small subsets of OI practices, while strategies involving a wider range of activities are adopted by only small subsamples of SMEs with 'very open' profiles (Brunswicker and Vanhaverbeke, 2015), which are typically the most innovative (Chesbrough and Crowther, 2006). Due to this complexity and heterogeneity, it has been even

more challenging to investigate the difficulties SMEs encounter in pursuing OI, i.e., the disadvantages of specific OI practices.

As a result, the most basic research question investigated in the OI literature (i.e., to what extent is OI generally used by firms?) has remained partially unanswered. As Chesbrough recently emphasized: *'Yet I believe that most of us don't really understand OI very well. We don't agree on what it means, we don't know how to best use it, we don't think hard enough about its problems and its limits […]'* (2019, p. 29).

The third (methodological) challenge encountered by empirical research concerning OI is related to the operationalization of firm openness. To date, the most diffused measures of OI adoption are based on a formative perspective characterizing many composite indicators in the economics and management literature. In the logic of formative indicators, the measures are based on combinations of observed items (e.g., the use of external information sources and the pursuit of different OI practices), which are assumed to *form* the construct. Such an operational definition of OI adoption (Bagozzi, 1979) involves the creation of additive indexes as a linear combination of a set of proxies attempting to cover the entire scope of the construct. The implicit assumption underlying this perspective is that each OI practice is an equally good proxy; thus, firms adopting a higher number of OI practices are considered *more open than firms that do not* (Laursen and Salter, 2006, p. 140). However, giving equal weights to different OI practices is a strong assumption that is difficult to justify theoretically as certain OI modes and specific OI practices are more frequently adopted than others and are characterized by specific challenges and risks (Dahlander and Gann, 2010).

Undeniably, the adoption of OI cannot be epitomized by only the sum of single OI practices. In contrast, an investigation of the relevance of different types of OI activities within the construct could provide a more rigorous examination of the phenomenon (Chesbrough, 2019). From this perspective, the relevant questions are: How open are firms? How are specific OI practices more relevant than other practices in characterizing firm openness? What OI practices do managers perceive as OI benefits or concerns?

We argue that an investigation of the decision-making process underlying OI adoption is required to answer these questions. In this context, both the object of analysis (firm openness) and the characteristics of the OI practices adopted by these firms are simultaneously relevant.

To provide a richer theory-driven understanding of how firm openness is reflected in the adoption of different OI practices, we advance an application of Item Response Theory (IRT) to OI research.

To characterize openness, we adopt Chesbrough's view of the OI paradigm as *'the antithesis of the traditional vertical integration model'* (2017, p. 35). From this perspective, rooted in transaction cost economics, OI adoption can be studied as an instance of how firms make decisions regarding whether to conduct internal innovation activities or access, harness, and absorb external knowledge flows across their organizational boundaries (Dahlander and Gann, 2010).

Based on IRT, we specify a theoretical model of how firms make decisions regarding which OI practices to adopt given an unobservable level of openness. IRT conceives openness as a reflective measure that is determined when an observed set of behaviors (the pursuit of different OI practices) *reflects* an underlying attitude to adopt OI rather than *forming* the construct (Diamantopoulos and Siguaw, 2006). Under this framework, the types of OI practices pursued by each firm are conditional on (i.e., a function of) each firm's unobservable level of openness. Our analytical approach, which is based on the Rasch model (Rasch, 1960), produces two types of estimates: a firm-level measure of openness reflecting the attitude to pursue a set of observed OI practices and a set of item-level parameters enabling the assessment of the relevance of each OI practice within the construct. The result is a scale that places both firms and OI practices along the openness *continuum,* while separating 'open' from 'closed' firms and OI practices perceived as benefits from OI practices perceived as concerns.

The model allows the detection of the types of OI practices characterizing firms with different levels of openness and the acquisition of new knowledge regarding the nature of OI practices.

3. Research design

3.1. Theoretical model

IRT is a family of methods used to assess latent constructs that, by definition, can only be determined indirectly through a set of so-called manifest variables. Based on a set of responses to questions, IRT models focus on the relationship between an unobservable characteristic of interest (a firm-level latent trait) and firms' observed behaviour (the pattern of item responses).

By applying IRT to OI research, we conceive openness as an unobservable latent attitude that is reflected in managerial decisions regarding the adoption of different OI practices. The analysis of OI adoption in terms of the underlying decision process as originally suggested by Dahlander and Gann (2010) is also consistent with research examining OI determinants from the firm perspective, particularly the role of inclinations and competencies of key individuals in the underlying decision process, e.g., the concept of OI proclivity (Hung and Chiang, 2010).

We devise a model focusing on the value (the benefit) that a firm receives from the decision to adopt (or not) a particular OI practice given the firm's underlying level of openness. As a firm's latent level of openness affects the probability of the adoption of different OI practices (i.e., the probability of the adoption of OI practice j is influenced by the level of openness of firm i), the IRT-based measure of openness is conceived as an indicator reflecting managers' evaluations of the costs/benefits of the adoption of different OI practices.

Within this framework, the benefit of the adoption of an OI practice is a function of how far the resulting OI practice is from the firm's level of openness in addition to an error term that reflects other idiosyncratic factors that may also play a role in the firm's decision. Similarly, the value (the cost) of the non-adoption of an OI practice is a function of whether the non-adoption is consistent with the firm's level of openness. Therefore, the OI practices adopted by firms with high levels of the latent trait (i.e., those reflecting higher openness) are regarded as perceived sources of OI benefits, while the OI practices adopted by firms with very low levels of openness represent perceived concerns as the loss of value from not adopting those OI practices could overcome the benefit from the adoption.

Based on a set of answers to questions regarding managerial decisions concerning the adoption of different OI practices, we specify a 1-parameter logistic IRT model (1pl IRT) of the probability of adopting an OI practice as a function of a measured firm-level latent trait (openness) and a set of item-level, i.e., difficulty or position parameters. This approach (Rasch, 1960) can be applied when multiple dimensions are present within a single overarching construct (Figure 1).

As our IRT model includes both firm-level and item-level parameters, it enables us to investigate firm openness, while simultaneously considering the different patterns of OI practices pursued by the firms in the sample.
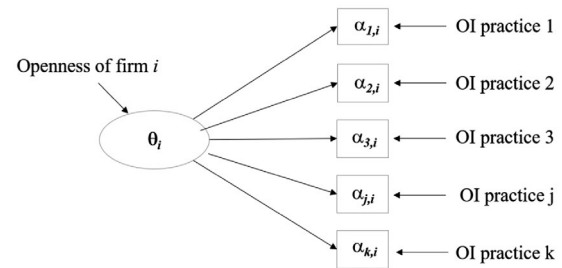

Figure 1. Theoretical model of firm openness (Rasch, 1960).

Based on a set of k observed measures, i.e., the OI practices adopted/not adopted by the firms in a sample, the 1pl IRT model allows us to estimate a firm-level continuous variable (θ_i) representing the model's assessment of the latent trait (openness) and a set of item-level coefficients (α_j), allowing us to investigate the relationship between the adoption of specific OI practices and firm-level differences along the openness *continuum*. Specifically, the difficulty parameters inform about the item properties (i.e., the characteristics of OI practices) within the construct as follows: if α_j assumes a high value, more open firms are more likely to adopt OI practice j; in contrast, if α_j assumes a low value, firms are less likely to adopt OI practice j. This approach enables us to assess *how* particular OI practices 'map' onto openness and their comparative relevance in terms of managers' evaluations of the costs and benefits of OI.

The following three assumptions of IRT models are relevant for this study:

(i)   The probability of a firm pursuing OI practice j increases as the firm's level of openness increases.

(ii)   The level of openness of firm i does not depend on the specific OI practices pursued by firm i. This assumption enables scales measuring the same construct to be linked and firms to be compared, even if they pursued very different OI practices.

(iii)   The item responses (i.e., observed OI practices) are statistically independent of a firm's level of openness as they are uncorrelated in firm i after controlling for the level of latent trait θ_i. As the position of each firm within the openness *continuum* can be estimated based on any item, the estimates are independent of the sample in use within a linear transformation. As the same mathematical function relating the latent trait to the probability of endorsing an item applies to all members of qualitatively similar populations, the comparability of the results across samples of firms with similar structural characteristics is ensured.

The general model is specified through a logistic link function for binary data:

$$P\left(Y_{ij}=1|\theta_i,\alpha_j\right)=e^{(\theta_i-\alpha_j)}/1+e^{(\theta_i-\alpha_j)}$$

$$\theta_i \sim N(0,1).$$

where the i subscript refers to a specific firm, and the j subscript refers to a specific OI practice used to assess the respondent. The function estimates the conditional probability of pursuing OI practice j as a function of a firm-level parameter (θ_i) and an item-level parameter (α_j).

θ_i represents the model's assessment of the level of openness of firm i.

α_j is the difficulty (or position) parameter assessing the conditional probability that firm i adopts OI practice j given its level of openness (θ_i).

As we are interested in evaluating the comparative relevance of different OI practices in characterizing firm openness as a result of managers' perception of OI benefits or concerns, we modeled all our available items (described in Table 2) to obtain an estimation of the latent trait. The data entered in the model were a set of binary measures indicating whether a firm adopted a given OI practice ('1') or not ('0').

3.2. Sample and data

The analysis was based on survey data collected from 383 technology-based SMEs reporting systematic innovation efforts. The data source was the 'High-Technology Firms Monitor,' which is a census database of technology-based firms with R&D laboratories localized in Italy.

Our focus on technology-based firms was motivated by two reasons. First, as most SMEs do not engage in formalized R&D activities (Vossen, 1998), the emphasis was placed on SMEs operating in technology markets to investigate managerial decisions regarding OI adoption as a result of cost-benefit evaluations related to their internal innovation processes. Although many OI concepts are used outside technology-based industries (Chesbrough and Crowther, 2006), we were interested in investigating an extended variety of OI practices, including technology-oriented modes (such as R&D collaborations or external technology acquisition) and market-oriented modes (from customer co-development to licensing activities) (Ahn et al., 2015). To ensure the comparability of our results with prior studies concerning OI adoption in SMEs (van de Vrande et al., 2009; Spithoven et al., 2013), we were also interested in investigating a range of OI practices reflecting both technology exploration and exploitation, which are more common among firms operating within technology markets. Furthermore, as SMEs tend to adopt some OI practices more frequently than other practices characterized by specific challenges (Brunswicker and van de Vrande, 2014), a focus on OI adoption in technology-based SMEs appeared suitable to better detect situations in which the pursuit of OI activities may represent both a benefit and a risk (Minshall et al., 2010; Oakey, 2013). Due to size limitations and the relevance of one (or few) technologies as the main assets, managers are forced to balance the perceived OI benefits with relevant concerns (e.g., preventing internal knowledge leakage to competitors and protecting internal technology assets), especially in contexts characterized by low appropriability conditions (West and Gallagher,

Table 2. Sample characteristics ($n = 383$)

Sectors/Industries of operation	Size classes			
	1-9 employees	10-49 employees	50/more employees	Total
Life sciences	51.3%	28.2%	20.5%	100.0%
Machinery and robotics	48.3%	39.3%	12.4%	100.0%
Chemicals	35.3%	47.1%	17.6%	100.0%
Electronics	37.8%	53.3%	8.9%	100.0%
Energy/Environment	78.9%	15.8%	5.3%	100.0%
ICT	70.9%	24.5%	4.6%	100.0%
Knowledge-intensive Services	52.2%	47.8%	0.0%	100.0%
Manufacturing industries	45.3%	41.1%	13.7%	100%
Service industries	69.4%	26.4%	4.1%	100%
Total	57.4%	33.7%	8.9%	100.0%

2006). Emphasizing OI adoption in technology-based SMEs could provide a clearer interpretation of managerial decisions regarding the adoption of different OI practices in terms of perceived benefits and concerns and a more straightforward comparison with the prior literature.

The data collection was performed over two months (January–February 2015) through computer-aided telephone interviews with an overall population of 1,411 SMEs (defined as enterprises with no more than 249 employees) in the database. Overall, we obtained a response rate of 47% (672 firms).

The survey started with screening questions to reliably identify SMEs with systematic innovation efforts. The companies' owners or executives (CEO/CTO) were first asked to indicate if the company had developed and introduced to the market a new product/service in the previous three years. In this subsample of companies ($n = 383$), the survey continued with questions regarding the nature and characteristics of their innovation process. Drawing upon the prior literature concerning the adoption of OI in SMEs (van de Vrande et al., 2009), we asked the respondents to provide information regarding the pursuit of eight types of OI practices reflecting different knowledge paths (inbound/outbound OI) and types of compensation (pecuniary/non-pecuniary) (Dahlander and Gann, 2010).

The sample characteristics and descriptive statistics of OI adoption are reported in Tables 2 and 3. The first exploration of the range of OI practices adopted by the firms in the sample shows a prevalence of external knowledge sourcing for technology-related motives (R&D collaborations) and market-related motives (customer co-development). We observed a low diffusion of OI and high variability in OI adoption (on average, each firm adopted 1.5 OI practices with a standard deviation of 0.6) and the number of innovations (on average, four new products were introduced to the market with a standard deviation of 1.3) in the sample. R&D collaborations, users' involvement, external networking, and technology selling were more diffuse practices across industries.[1] Although our sample consisted of technology-based SMEs localized in Italy, we did not observe a major influence of the context as the characteristics of OI adoption and the positive relationship between OI adoption and the number of innovations appeared consistent with evidence from similar studies conducted in different countries (see, e.g., van de Vrande et al. (2009) regarding Dutch SMEs, Ahn et al. (2015) regarding Korean innovative SMEs and Bigliardi and Galati (2016) regarding Italian SMEs).

Table 3. Adoption of Open Innovation practices among the SMEs in the sample ($n = 383$)

OI modes	Type of compensation	OI practices	Definition	Adopted	Not adopted	Avg. number of new products
Inbound open innovation	Non-pecuniary	R&D collaborations	Conducting collaborative R&D with external partners	10.0%	90.0%	5
		User involvement	Accessing new external knowledge (ideas) from users	3.1%	86.9%	4
	Pecuniary	IP in-licensing	Buying or using the IP of other firms	0.3%	99.7%	1
		External technology acquisition	Acquisition of external technologies and expertise from the marketplace	0.6%	99.4%	5
Outbound open innovation	Non-pecuniary	Customer co-development	Involving customers in the innovation process (product development/commercialization)	14.1%	75.9%	4
		External networking/ partnerships	Collaborating with external network partners to support innovation processes (product development/commercialization)	4.0%	96.0%	4
	Pecuniary	IP out-licensing	Selling IP or offering licenses or royalty agreements to other firms	1.1%	98.9%	2
		Technology selling	Selling internally developed technologies to other organizations	2.7%	97.3%	5

4. Results and discussion

Our model is based on two theory-driven premises:

1. A higher attitude to pursue different OI practices occurs at high levels of the latent variable (openness).
2. The level of openness of each firm influences the firm-specific pattern decision process (i.e., which OI practices to pursue).
3. In the following, we report the results of our IRT model assessments.

Figure 2 displays the test characteristics curve (TCC). Using the estimates of the eight observed items introduced in the model, the TCC plots the expected number of OI practices pursued by firms with different levels of openness.

In this context, we used the TCC to compare the IRT-based measure of openness with alternative measures based on the use of additive indexes (e.g., Laursen and Salter, 2006) commonly used in the OI literature. The TCC reflects the relationship between the breadth of the OI practices pursued by the firms in the sample and the underlying openness dimension measured by our model (θ_i). The bisector line represents equality between the two measures.

Our results show that the IRT-based measure of openness is consistent with the alternative measures of OI adoption as the Pearson correlation coefficient between the two measures shows a strong positive relationship ($\rho = 0.997$, $P < 0.001$). However, while the two measures tend to overlap at their lower levels, a non-linear relationship is observed between the values of θ and the expected number of OI practices pursued by firms beyond a threshold (OI breadth = 2;

$\theta_i = 2.02$). For instance, at $\theta_i = 5.06$, the expected number of OI practices adopted by firms (i.e., the value of the additive index) is 6.

This finding reflects a fundamental difference in the theoretical conception of the two indicators, highlighting the advantage of using an IRT approach. Within an additive measure (OI breadth), each OI practice equally contributes to determine the indicator, while the assumption of giving equal weights to different OI practices is not valid when the estimation is performed with the IRT models. In the latter case, some OI practices (the more 'difficult' practices) have a higher relevance within the construct (and are adopted by sets of companies with a higher level of openness), while other practices (the less 'difficult' practices) have a lower relevance (and are far more diffuse among firms). Therefore, the proposed measure represents a proxy of firms' OI maturity rather than a measure of OI adoption based on a linear combination of OI practices. Beyond a certain threshold, a higher level of openness reflects a firms' higher attitude to pursue more challenging OI practices (rather than a higher number of OI practices).

This result is most evident in the analysis of the item-level parameters The difficulty (position) parameters are reported in Table 4, while Figure 3 displays the Item Characteristics Curves (ICCs) using the same difficulty parameters.[2]

The α coefficients in Table 4 indicate the value of θ (openness) of firm i with a 0.5 probability to pursue OI practice j. The difficulty parameter of the jth OI practice is reflected in the position of the corresponding Item Characteristic Curve (ICC) in Figure 3 along the x-axis, where the values of θ_i are reported.
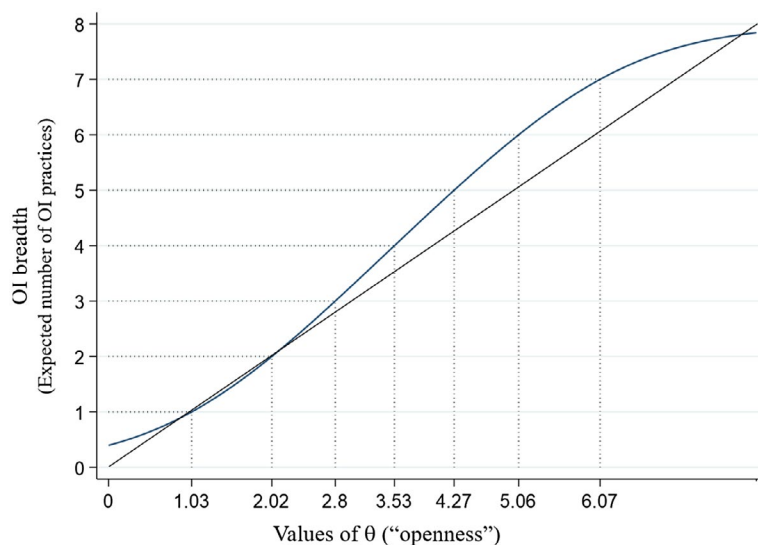

Figure 2. Test characteristics curve (TCC). [Colour figure can be viewed at wileyonlinelibrary.com]

Cristina Marullo, Irene Martelli and Alberto Di Minin

Table 4. Difficulty (position) parameter estimates of the eight open innovation practices

OI direction	OI modes	OI practices	Definition	Difficulty parameters (α_j)	Std. errors (robust)	P-values
Inbound open innovation	Non-pecuniary	R&D collaborations	Conducting collaborative R&D with external partners	2.363***	0.294	0.000
		User involvement	Accessing new external knowledge (ideas) from users	2.050***	0.256	0.000
	Pecuniary	IP in-licensing	Buying or using the IP of other firms	5.823***	1.130	0.000
		External technology acquisition	Acquisition of external technologies and expertise from the marketplace	5.201***	0.878	0.000
Outbound open innovation	Non-pecuniary	Customer co-development	Involving customers in the innovation process (product development/commercialization)	1.271***	0.177	0.000
		External networking/ partnerships	Collaborating with external network partners to support innovation processes (product development/commercialization)	3.326***	0.434	0.000
	Pecuniary	IP out-licensing	Selling IP or offering licenses or royalty agreements to other firms	4.572***	0.690	0.000
		Technology selling	Selling internally developed technologies to other organizations	3.718***	0.503	0.000

*** p<0.001.

As the item-level parameters (α_j) and firm-level estimates (θ_i) are placed on the same scale, firms with different levels of openness can be compared to OI practices and vice-versa.

As shown in Figure 3, a change in the difficulty parameter shifts the ICC of the jth OI practice along the openness *continuum* as follows: for firms with higher levels of openness, the probability of pursuing less difficult OI practices increases to 1. By showing how well the pursuit of each OI practice reflects the underlying firm-level openness, the ICC can be used to comparatively evaluate more and less difficult OI practices. In this context, α_j illustrates the position of a single OI practice as the point of interest in managers' evaluations of the benefits and concerns of implementing that practice.

We observed a sharp distinction among OI practices using our measure of openness, as the difficulty parameters show that more open firms are more likely to adopt different OI practices than less open firms.

Specifically, the estimated difficulty parameters of customer co-development and user involvement have the lowest values ($\alpha_{CUST} = 1.271$; $\alpha_{USERS} = 2.050$), indicating that interactions with downstream partners and users are likely to be adopted by firms with low openness. Similarly, the adoption of practices related to sourcing external knowledge through collaborative R&D is significantly associated with lower levels of openness ($\alpha_{RD\_COL} = 2.363$). This evidence seems to confirm that relatively intense interactions with direct customers and users compared to other external sources characterize a large majority of SMEs (Brunswicker and Vanhaverbeke, 2015) as they may represent a low-risk approach to access 'sticky' market information and obtain insight into new business opportunities (Enkel et al., 2005).

Second, compared to prior results, external partnerships are more difficult OI practices ($\alpha_{EXT\_PART} = 3.326$) as the probability of collaborating with external network partners to support the internal innovation process is significantly associated with a higher degree of openness. On the one hand, for SMEs, collaborations with external network partners represent opportunities to access complementary assets (e.g., manufacturing, marketing, and distribution channels); on the other hand, such types of OI practices typically represent a managerial challenge as they require the development of trust among partners (van de Vrande et al., 2009).

Third, regardless of the direction of knowledge flows (outside-in or inside-out OI), consistently higher openness is required to adopt pecuniary OI modes ($\alpha_{T\_SELL} = 3.718$; $\alpha_{OUTLIC} = 4.572$; $\alpha_{T\_ACQ} = 5.201$; $\alpha_{IP\,INLIC} = 5.823$). Such evidence suggests that pecuniary OI practices represent the most challenging practices in
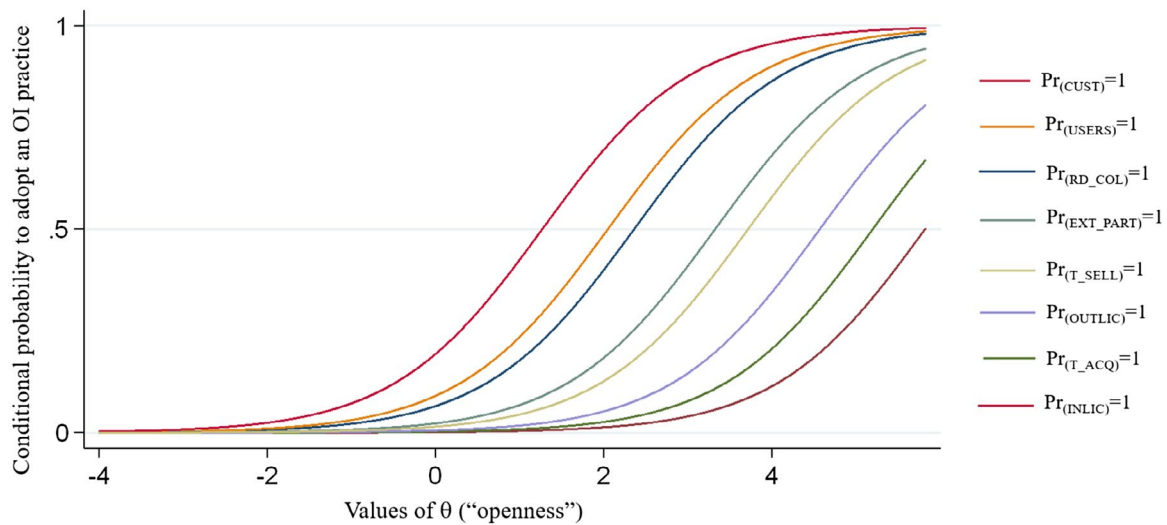
Figure 3. Item characteristics curves (ICC). [Colour figure can be viewed at wileyonlinelibrary.com]
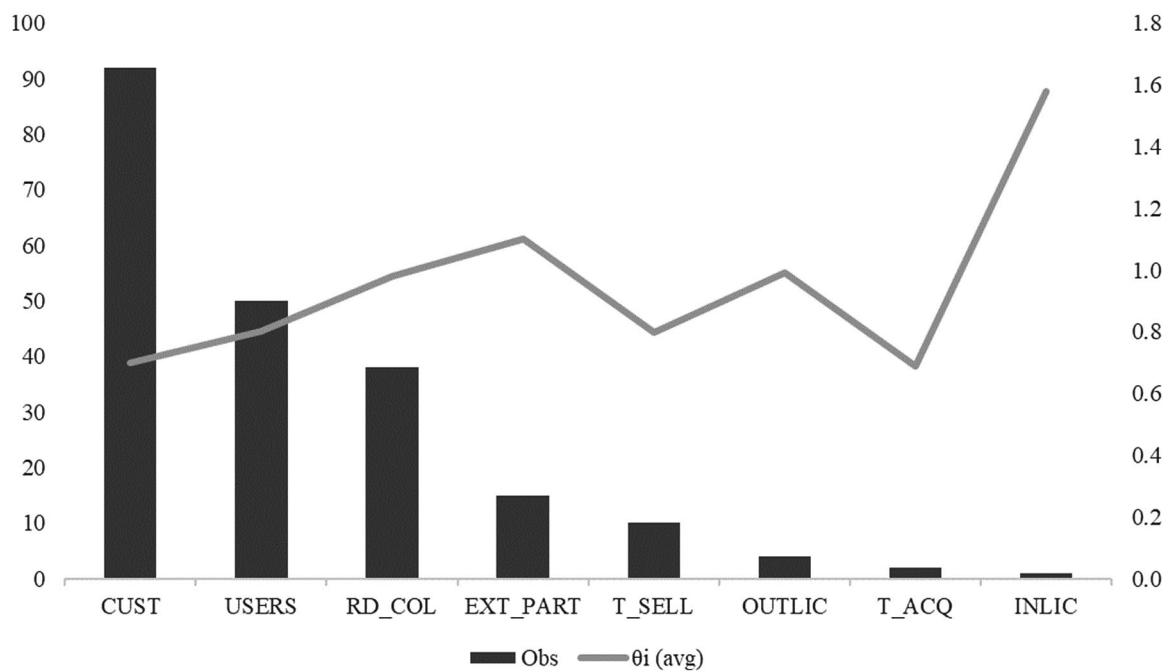

Figure 4. Incidence of the adoption of different OI practices ordered by difficulty (α_j) among the firms in the sample and corresponding average estimates of 'openness' ($\bar{\theta}_i$).

the context of SMEs as very high levels of OI maturity are required to exploit OI opportunities through market transactions. These findings support the theoretical argument that acquiring external valuable resources through OI requires relevant managerial expertise in searching and evaluation and a high degree of control of internal processes (Dahlander and Gann, 2010). Consistent with the prior literature, an increasing level of openness in technology-based SMEs is characterized by increasing management challenges, especially when OI practices involve actors outside the value chain

(Brunswicker and Vanhaverbeke, 2015) and/or market transactions (Dahlander and Gann, 2010). In the context of SMEs, higher levels of OI maturity could imply the development of managerial expertise in searching for external partners, setting proper interaction channels, and pursuing effective appropriation strategies, which have been proved to be crucial for overcoming OI challenges (Marullo et al., 2020).

Figure 4 provides further empirical evidence emerging from the IRT model, allowing us to discuss how the proposed approach improves over alternative

measures in terms of contribution to OI research. We report the incidence of the adoption of different OI practices ordered by difficulty (α_j) among the firms in the sample and the corresponding average estimates of openness (cc). Figure 4 separates the less challenging OI practices (those with lower α_j values) from the more challenging OI practices (those with higher α_j values).

Proceeding from the left side to the right side of the graph, the difficulty parameter (α_j) of each OI practice increases, while the rate of adoption decreases. Our results show a non-linear increase in the average values of openness ($\overline{\theta}_i$) with more challenging OI practices; for instance, customer co-development, which is a largely diffused OI practice, is associated with a lower average value of openness ($\overline{\theta}_i = 0.70$) than less diffuse and more challenging OI practices, such as external partnerships ($\overline{\theta}_i = 1.10$) and IP out licensing ($\overline{\theta}_i = 1.58$). Notably, in the case of additive measures, and by definition, the difficulty parameters of all OI practices included in the index should be equal, and discrimination among OI practices would not be possible (the average value of OI breadth is 2 in all the categories). Therefore, alternative approaches do not allow the assessment of how different OI practices map onto the openness construct and the separation of the types of OI practices pursued by firms with different openness levels.

5. Conclusions

Since its initial formulation, the OI concept has attracted considerable attention from both scholars and practitioners. However, as OI has progressively spread across contexts and different types of firms, the development of empirical knowledge related to the multiple aspects of the phenomenon has encountered substantial challenges. Despite several attempts to develop comprehensive measures of firm openness, OI adoption has primarily been analyzed in terms of outside-in (knowledge sourcing) OI practices as inside-out practices and pecuniary OI modes are far less diffuse. Consequently, the extent of OI adoption, the comparative relevance of different OI practices, and the most challenging types of OI practices have not been sufficiently clarified (Chesbrough, 2019).

To provide an answer to these questions, we suggested an alternative framework for openness measurement using IRT to improve over current approaches. Our theoretical model conceives openness as an instance of how managers make decisions regarding the adoption of different OI practices based on their evaluations of the related benefits and concerns. Adding to the measure of openness, a set of item-level parameters were estimated to assess

the comparative relevance of different OI practices within the construct.

This study has several implications.

As IRT conceives openness as a latent attitude that is reflected in the pursuit of more or less relevant OI practices, our measure represents a proxy of firms' OI maturity rather than an indicator of OI adoption based on the number of OI practices. Specifically, a higher level of openness can be interpreted as an increased ability of a firm to face more challenging OI practices rather than the pursuit of a higher number of OI practices. Thus, the proposed measure captures the non-linearities of the process of OI adoption and/or psychological challenges or hesitations experienced by managers in SMEs when implementing OI (van de Vrande et al., 2009). Therefore, this study significantly contributes to the OI literature.

This study also adds to the literature concerning OI in SMEs. First, this study shows that the heterogeneity in OI adoption might be due to different levels of SMEs' OI maturity. We demonstrate that technology-based SMEs with similar breadths of OI adoption have different levels of OI maturity depending on the types of OI practices adopted. As relational approaches involving actors within the value chain (R&D collaborations, customer co-development, and user involvement) represent diffuse OI practices, they *also* characterize SMEs with very low openness in our measure. In contrast, OI practices involving external networks and pecuniary OI modes assume the highest relevance in characterizing SMEs' openness as they represent the most challenging OI practices to adopt. Second, as the IRT-based measure of openness can capture different challenges in OI adoption, its application to SMEs is particularly relevant. Consistent with the prior literature concerning SMEs' management challenges in OI adoption, the proposed measure confirms that significantly higher levels of OI maturity characterize SMEs' ability to follow more challenging OI paths (Brunswicker and van de Vrande, 2014).

This study also has relevant managerial implications.

First, by evaluating how firm openness is reflected in the pursuit of different OI practices, we were able to assess the comparative relevance of OI practices in characterizing openness and provide more comprehensive knowledge regarding the multiple aspects characterizing OI adoption with a clear focus on managerial challenges.

Second, based on IRT, we conceived openness as an unobserved (latent) trait that is manifested in managerial decision-making related to OI. Therefore, our measure of openness appears to be more consistent with managers' evaluations of the benefits of OI

adoption than its academic definition (in which the concept is defined by or is a function of its measures) (Podmetina et al., 2014). Thus, the application of IRT could facilitate the communication of OI research results to practitioners, enabling academics to better inform managerial choices concerning the development of OI strategies.

Finally, this study contributes to a methodological perspective.

To the best of our knowledge, this study is the first to apply IRT to research concerning OI. This study demonstrates the potential of IRT in improving measures of firm openness by allowing a more rigorous, theory-driven interpretation of the phenomenon. The design of an instrument allowing an evaluation of how firm openness is reflected in observed behavior and obtain information regarding a large variety of OI practices (difficulty parameters) enabled us to thoroughly investigate the multiple aspects of OI adoption in SMEs rather than rely on the most used OI practices.

The main limitation of the study concerns the sample selection.

Although the focus on technology-based SMEs may represent a source of potential problems in terms of the generalizability of the results, the aim of this study was not to provide a new interpretation of the concept of OI adoption; in contrast, we intended to demonstrate the potential of IRT in enhancing current OI measurement approaches and offer new insight for the OI literature. Focusing on technology-based SMEs allowed us to investigate the comparative relevance of technology-based and market-based OI practices and ensure the comparability of our results with prior studies concerning OI in SMEs. Devising a measure of openness as a reflective indicator provided some advantages in this respect. As one property of IRT indicators is that pairwise item-level responses (observed OI practices) are statistically independent in each firm after controlling for its level of the latent trait, the measure of openness can be estimated based on any item and, therefore, is independent of the sample within a linear transformation. As our evidence of OI adoption in technology-based SMEs does not appear to be specific to the Italian context, the results of this paper might be extended to similar populations of technology-based SMEs in other countries.

Future research should consider using IRT models to develop comparative studies. For instance, IRT could be applied to CIS data to compare to Laursen and Salter (2006)'s measures (breadth and depth of firms' search strategies). More broadly, further applications of IRT to OI research (e.g., IRT 2pl models including item-level discrimination parameters)

could allow the refinement of the openness construct and improvement in its external validity. As such, IRT could inform contingency studies related to OI with relevant insights into the relationship between openness and innovation performance.

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Note

[1]Detailed statistics of OI adoption are reported in the Appendix (Table A1).

[2]The ICC curves for the single items are reported in the Appendix.

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APPENDIX

Table A1. Adoption of Open Innovation practices among the SMEs in the sample by industry (n = 383)

| OI practices	Definition	Life sciences	Machinery and robotics	Chemical	Electrical/Optical	Energy	ICT	Knowledge-intensive services
R&D collaborations	Conducting collaborative R&D with external partners	5.1%	10.1%	5.9%	11.1%	10.5%	12.6%	0.0%
User involvement	Accessing new external knowledge (ideas) from users	10.3%	9.0%	5.9%	15.6%	21.1%	16.6%	4.3%
IP in-licensing	Buying or using the IP of other firms	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%
External technology acquisition	Acquisition of external technologies and expertise from the marketplace	0.0%	1.1%	0.0%	0.0%	0.0%	0.7%	0.0%
Customer co-development	Involving customers in the innovation process (product development/commercialization)	25.6%	16.9%	17.6%	28.9%	36.8%	23.8%	34.8%
External networking/partnerships	Collaborating with external network partners to support innovation processes (product development/commercialization)	10.3%	4.5%	0.0%	2.2%	5.3%	2.6%	4.3%
IP out-licensing	Selling IP or offering licenses or royalty agreements to other firms	2.6%	0.0%	5.9%	0.0%	5.3%	0.7%	0.0%
Technology selling	Selling internally developed technologies to other organizations	0.0%	2.2%	0.0%	2.2%	0.0%	4.6%	0.0%
Total		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
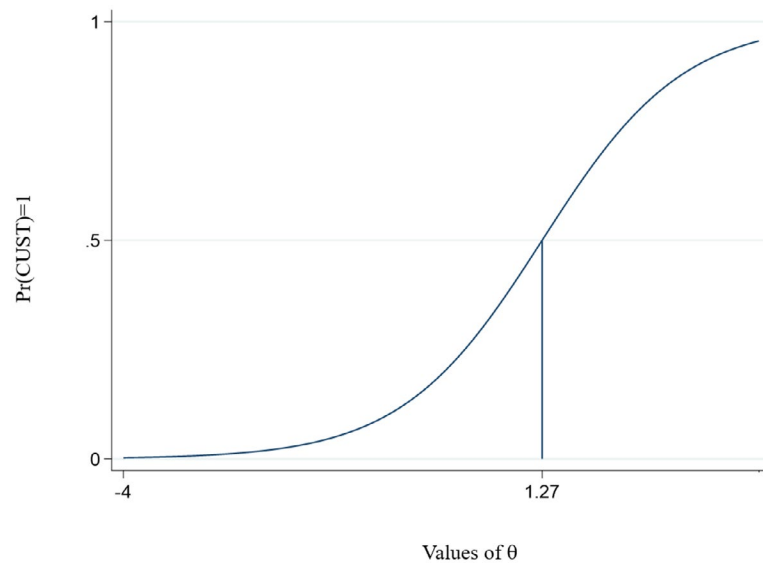
Figure A1. Item characteristics curve (ICC) – Customer co-development. [Colour figure can be viewed at wileyonlinelibrary.com]
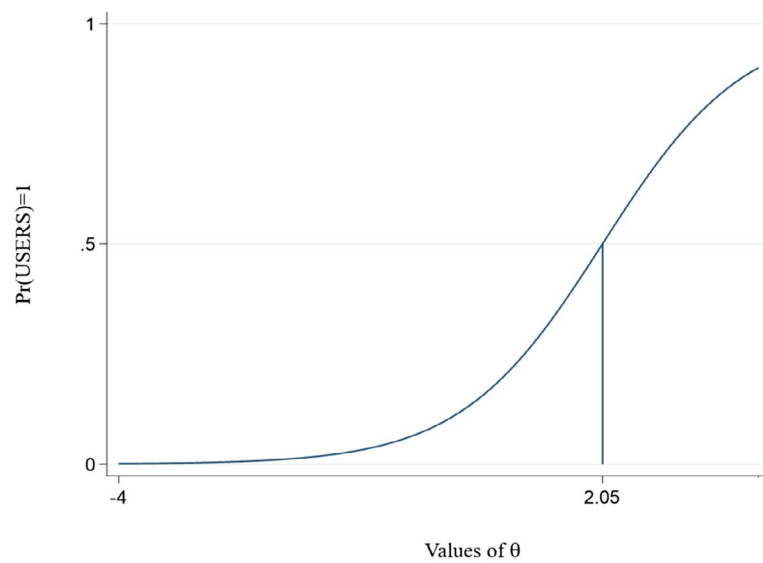

Figure A2. Item characteristics curve (ICC) – Users involvement. [Colour figure can be viewed at wileyonlinelibrary.com]
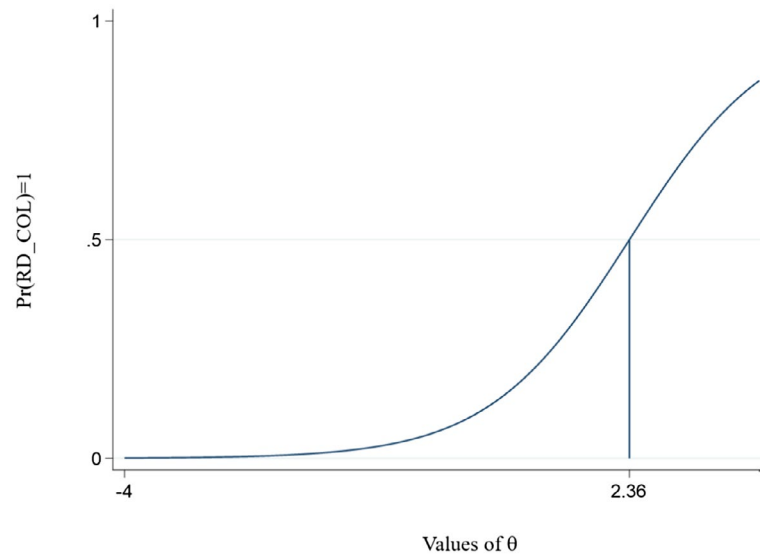
Figure A3. Item characteristics curve (ICC) – R&D collaborations. [Colour figure can be viewed at wileyonlinelibrary.com]
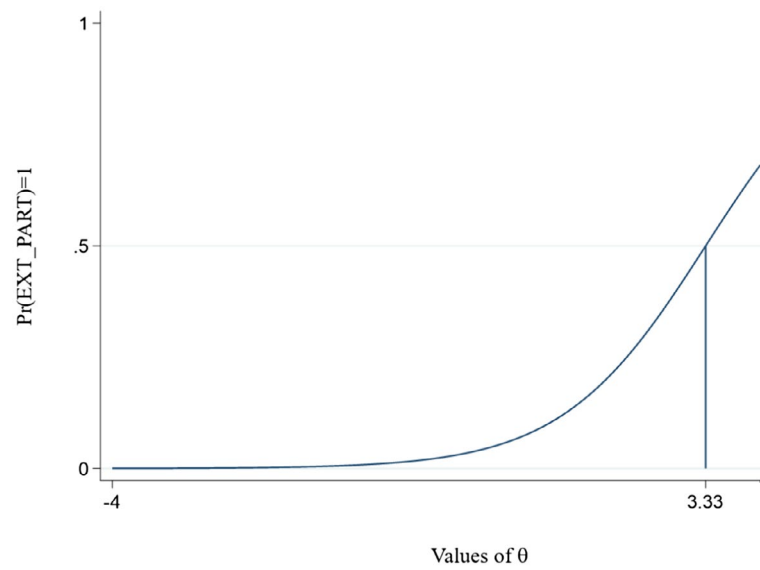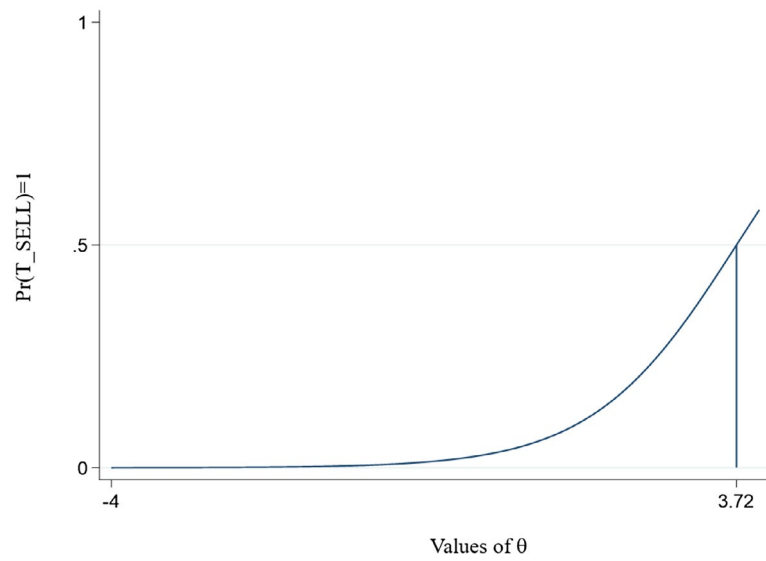

Figure A4. Item characteristics curve (ICC) – External networking/partnerships. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure A5. Item characteristics curve (ICC) – Technology selling. [Colour figure can be viewed at wileyonlinelibrary.com]
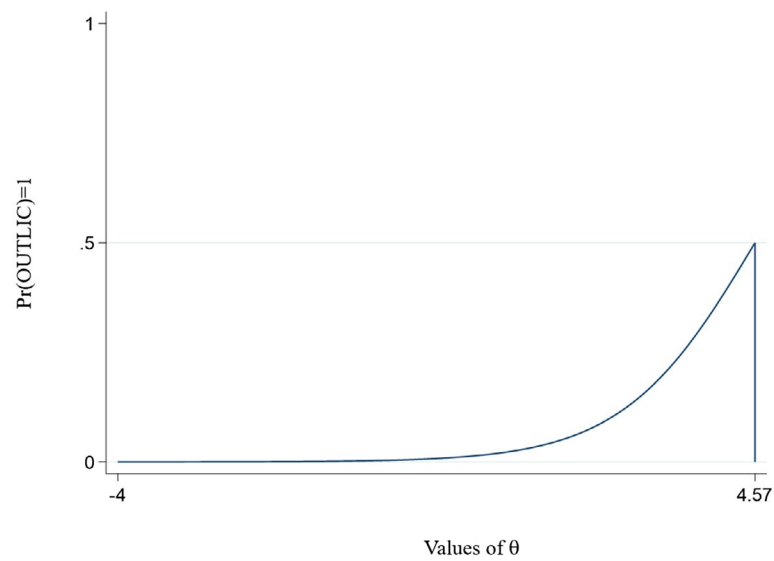

Figure A6. Item characteristics curve (ICC) – IP out-licensing. [Colour figure can be viewed at wileyonlinelibrary.com]
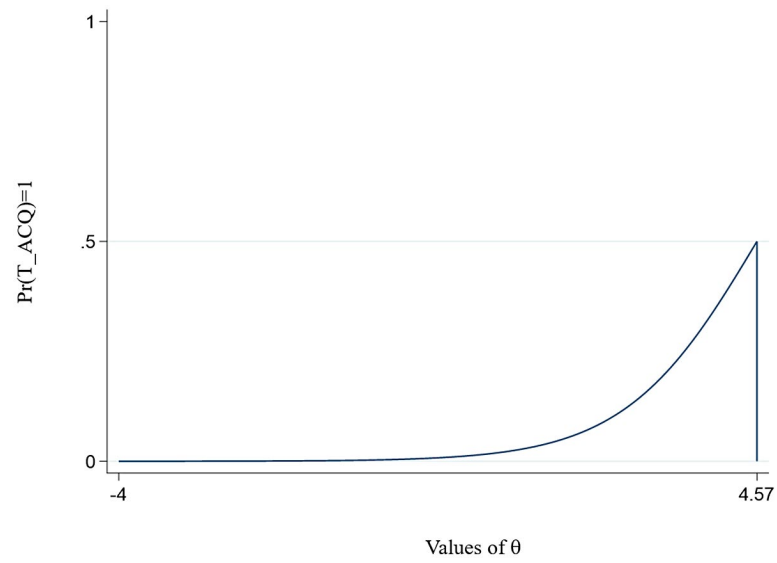
Figure A7. Item characteristics curve (ICC) – External technology acquisition. [Colour figure can be viewed at wileyonlinelibrary.com]
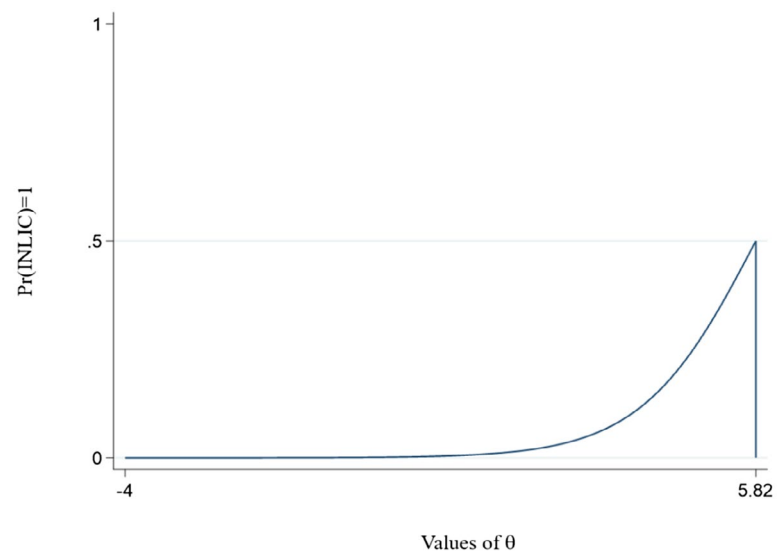

Figure A8. Item characteristics curve (ICC) – IP in-licensing. [Colour figure can be viewed at wileyonlinelibrary.com]