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From my Perspective

Columbus' egg and the engineer's effect in forecasting *solutions* adoption

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ABSTRACT

Why is it that both complex and simple solutions that have proved to be effective have low rates of adoption? The literature on innovation (i.e., a specific category of *solutions*) management has provided some clues, identifying barriers of several types: organizational, technological, economic, human behavior and the nature of the innovation. We suggest that one reason is the misalignment between the degrees of complexity i.e., the degree of knowledge embedded, of the problem and its solution. A solution perceived to be too simple for a complex problem falls into the category of what might be called "Columbus' egg". At the basis of this effect there is the tendency to minimize expected frustration as the difference between the effort made in looking for a solution and the obtained reward. When the solution is too complex for a simple problem, this is the case of the "Engineer's effect". This effect has its cognitive underpinnings in the tendency to minimize decision-making costs. We discuss and illustrate these phenomena and propose some guidelines for technology developers and product innovation managers, as well as for forecasting solutions adoption.

1. Introduction

This perspective article introduces a new explanation of mechanisms behind the process of solution (e.g., technology, innovation) adoption, able to account not only for cases in which an effective but perceived too complex solution is not adopted, but also cases in which a low adoptions rate occurs also for effective and very simple solutions.

The proposed explanation should be considered as the medium term of an *abductive inference* (Bonfantini and Proni, 1983; McKaughan, 2008) starting from results i.e., low rate of adoption for too simple and too complex solutions. This explanation presents some degree of novelty in new associations among existing theories on innovation and diffusion adoption approaches (with respect to the case of simple but effective solutions that are not adopted), and to some existing influences and associations with cognitive and neural science perspectives, on the one hand, and theoretical frameworks/perspective (with some updating and improving) of the technology acceptance models (TAM), on the other hand. Considering the proposed explanation might be beneficial for technology developers and product innovation managers, as well as for forecasting technology adoption.

1.1. *Results as the "scene of crime"*

The "scene of crime" consists of low adoption rates for a specific solution. The "dead body" is the solution, characterized by specific dimensions e.g., shape, colors, embedded technologies, brand, complementary services, etc.; "suspected" are real and potential adopters (read the market). Suspected are heterogeneous in knowledge, competences, education and personal characteristics. The "mystery" is that many complex as well as very simple solution e.g., face mask in COVID-19 (Shelus et al., 2020; Latkin et al., 2021, see also Cobelli et al., 2021, Brem et al., 2021[1]) although proven to be feasible and effective, or those that are successfully adopted after a relative long gestation, show low rates of adoption (Jahanmir and Cavadas, 2018), and/or may be also ridiculed or underestimated at the beginning (sometimes by the same proposer) (Eisen, 1999; Ofek et al., 2016; Pursell, 2007). "All truth passes through three stages. At first, it is ridiculed. Secondly, it is violently opposed. Thirdly, it is accepted as being self-evident." (attributed to Schopenhauer) (Scheubel et al., 2018). The solution to the mystery is a law/theory able to explain which characteristics of the solution and the adopters can justify the observed low rate of adoption.

The complexity and heterogeneity of disciplines and characteristics

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[1] Cobelli et al. 2021, Brem et al. 2021 analyse factors affecting technology adoption/non-adoption during coronavirus pandemic and investigate the availability, short and long-run impact and the requirements of future technologies for improving our lives, respectively.

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of technologies, as well as skills, competences and personal characteristics of potential adopters, induce to assign a low probability for a general approach. In effect, one of the most important problems in analyzing and comparing technology, also within a specific field (e.g., standard of care with respect to radical health technologies), is the high heterogeneity and often incompatibility of dimensions and characteristics of alternative solutions that we should compare, and what drives their adoption.

What influences the adoption of an improved cooking stove may not necessary affect or influence the adoption of conservation agriculture adoption machinery[2] (see paragraph 1.2). However, the two examples above, and all the "scenes of crime" can be analyzed taking into account, not only technology specific theories and factors reported in Section 1.2 but also, to anticipate the thesis of the paper, the balance between the complexity each real and potential adopter assign to a specific problem and the complexity of the proposed solution. This approach integrates and goes beyond the necessary characterization of specific technologies and adoption drivers.

Since the dimension proposed shifts the effort to compare technologies' characteristics to quantitatively compare the levels of problems and solutions' knowledge complexity, our approach allows the comparison of alternative solutions within and among different markets (see Fig. 1). Within a specific market, for instance, the approach overcomes the difficulties emerging in comparing technologies that may strongly differ from each other, like a current solution and a radical innovation.

In Section 2 we propose the dimensions a knowledge-based measure of complexity should integrate.

1.2. Traditional explanations of the observed results

In the literature there are several explanations for low rates of adoption also for effective solutions. Most of them focus on barriers to adoption and, complementary, on barriers to diffusion (Mohr, 1969; Ghoshal and Bartlett, 1988; Warty et al., 2021), classified in organizational, institutional, technological, economical, ethical, and social/cultural categories (David, 1985; Reddy et al., 1991; Waarts et al., 2002; Loch et al., 2003; Hall, 2004; Turchetti et al., 2014; Chouki et al., 2020; Silveira et al., 2021). On one hand, these barriers are dually linked with both those sources that drive innovation -history and industry-specific problems, existing complementary technology and new technological opportunities (Dosi, 1982; Dosi, 1988; von Hippel, 1988; Taalbi, 2017), and on the other hand, with those managerial strategies that, by reducing obstacles to product market entry, improve the rate of adoption, such us user-friendly interfaces (Davis et al., 1989; Cho et al., 2006), pre-selling and support services (Evanschitzky et al., 2015; Upadhyay et al., 2017) and entry time (Kohli et al., 1999; Bayus et al., 1997; Häckel and Stirnweiss, 2019).

With respect to the literature on innovation adoption, different models emphasize components and behaviors that influence adoption. It is the case of the models of technology adoption and their empirical analyses (Aldhaban et al., 2015; Lai, 2017).

In these models, the presence and activation of a singular component is a necessary but not sufficient condition for adoption. These components are attitude i.e., behavioral beliefs and outcome evaluation, subjective norms for the Theory of Reasonable Belief TRB (Fishbein and Ajzen, 1975); attitude, subject norms and perceived behavioral control for the theory of Planned Behavior TPB (Ajzen, 1991; Bosnjak et al., 2020); perceived usefulness and ease of use for the Technology Acceptance Model TAM (Davis et al., 1989; Davis, 1989) and its updated versions that introduced different dimensions that describe usefulness perception (Venkatesh and Bala, 2008; Venkatesh, 2000); performance expectancy, effort expectancy, social influence and facilitating conditions for the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003; Williams et al., 2015).

With respect to the literature on innovation diffusion, for example, Rogers (1983) modelled the diffusion of innovations as a process driven by the relative advantages of the innovation. These include: a) the compatibility of the innovation with the technology and complementary innovation (Bucklin and Sengupta, 1993); b) the degree of complexity of the innovation; c) how the innovation can be tested, and d) how innovation may be recognized by potential adopters.

The focus of the literature on the innovation diffusion has therefore concentrated its analysis on:

(1) The characteristics of the innovation;
(2) The characteristics of actual or potential adopters in the marketplace;
(3) The contextual variables of the environment.

These categories are used in the attempt to explain differences in diffusion rates of innovation spreading. Explanations vary according to the scientific discipline of the researchers. Sociologists, for instance, stress the social environment in which solutions are diffused and how social network topologies impact on adoption diffusion, overlapping models of diffusion in management, marketing, economics (Bass, 1969; Mokyr, 1990; Liu et al., 2005; Arieli et al., 2020).

Historians and anthropologists focus on culture and the religious basis of trust and traditions (Rogers, 1983; Mokyr, 1990, see also the special issue of Technol. Forecast. Soc. on Technology and Religion and the article of Kumar et al., 2022). Economists suggest that diffusion is a lengthy process, and that its rate is influenced by the characteristics of the technology (Nelson et al., 2004) (e.g. the learning timeframe, Lynn et al., 1996), the incentives for adoption provided by institutions and markets (Gilbert and Newbery, 1982; Farrell and Saloner, 1986; Bunea et al., 2020) and by the attributes of the adopters, especially the nature of the information available to them (Dosi, 1991).

In this paper we introduce and add a complementary explanation for why (or how) solutions that had been proven to be workable, effective, and even advantageous to the adopter, may not be adopted. Our explanation differs from the current ones since it is not technology specific and it is expected to be relevant in all the processes of adoption and for all technologies/solutions. Our model proposes that a reason for this phenomenon is the incongruity between the dimensions of the problem (simple or complex) and the nature of the solution identified to solve it (simple or complex). This new dimension integrates the existing observed factors and drivers of adoption.

2. Widening the framework of analysis: the world of problems-and-their-solutions

We argue that the low rate of adoption of some solutions can be also explained by the imbalance between the level of complexity of the problem and that of the solution, so that the proposed solution is too simple or too complex for the problem it is designed to solve. We proceed to define problems and solutions.

Problems (Laudan, 1977; Popper, 1999) are propositions regarding a way of doing something, obtaining a particular condition or effect, or the framing or articulation of wishes and needs.

Problems require a certain level of knowledge. They are formulated according or against (as counter rule, Feyerabend, 1975) to the attributes of the society in which they arise and the system of knowledge available at the time. Many unsolved problems have been abandoned or ignored simply because people turned their attention to other topics they consider more relevant. Alternatively, problems may be considered important at certain times just because they have fundamental consequences for different disciplines. Therefore, those inventions designed to achieve the solution of a problem have much more important effects than the solution of the original problem per se; e.g., solutions and techniques invented by Andrew Wiles (1995) in the proof of the Fermat's

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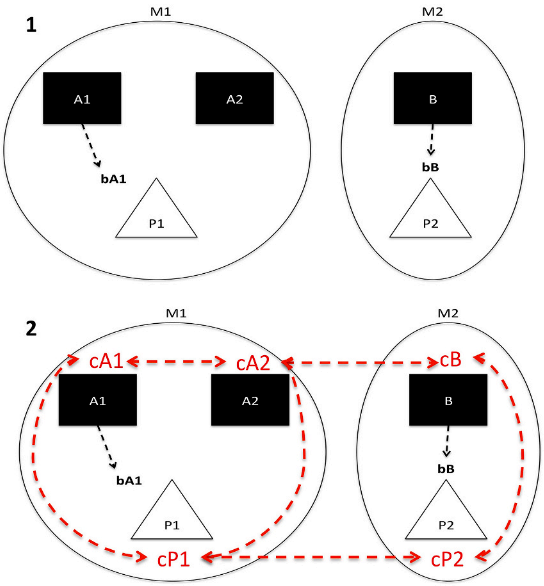
[2] We thank an anonymous reviewer for this example.



1. Technology-specific barrier/ adoption driver (bA1 and bB cannot be compared)

Let consider the cases of technologies A1 and A2 as solutions of problem P1, and technology B as solution of problem P2. A1 and A2, on the one side, and B, on the other side, identify two different markets, M1 and M2. A specific barrier that is irrelevant for technology B in M2 may affect the adoption of A1 in M1, but not A2. However, the adoption rates of A1 and A2 in M1 (and also B in M2) depend to how A1, A2 and B complexity matches with the complexity (c) assigned to problems P1 and P2. This approach is based on a unified measure of solutions' and problems' complexity that integrates, but it is not affected by, specific characteristics of technology and markets.

2. Knowledge- based problem-solution complexity (cA1-cP1, cA2-cP2, cB-cP2 but also cP1 vs cP2, cA1 vs cA2 and cB complexity can be compared) as knowledge-based adoption barrier/ driver

Fig. 1. Technology-specific barriers vs knowledge-based problem solution complexity.

last theorem (Wiles, 1995; Taylor and Wiles, 1995). Problems may be generated by practical situations, i.e., by the insufficiency of currently available technology, by new practical problems, or by theories developed and generated by similar or different questions.

Solutions are procedures, technologies, activities, products, systems, and also "theories" able to explain facts. Solutions are designed to solve a problem. Solutions can be inventions, innovations, new products, new procedures or discoveries. Both problems and solutions can be categorized by their level of complexity, defined in this paper as the level of knowledge required of and available to the problem solver. This level of knowledge can be measured by four dimensions: 1) quantity (how much knowledge is available e.g., computational complexity); 2) quality (degree of sophistication of this knowledge); 3) inter-disciplinarity (knowledge from different disciplines or scientific fields); and 4) availability (ease of access to knowledge). On this perspective, the usually accepted concept of *complexity* associated to solution as "the degree to which a solution is perceived as relatively difficult to understand and use" (Rogers and Shoemaker, 1971; Tornatzky and Klein, 1982), defines cases of negative consequences associated to a high level of knowledge required of and available to the problem solver.

Fig. 2 depicts the combination of these dimensions that define the problem or solution as simple or complex.

Problems which fall in the shaded area are complex because in order to solve them it is assumed that a high level of knowledge is required. *Solutions* which fall in the shaded area are complex because it is assumed that they require a high level of knowledge to be developed/designed.

In Fig. 2 we propose to widen the framework of analysis by enriching the current solution adoption models e.g., the technology adoption models, to include the relationship between the complexity of problems and the complexity of solutions (Fig. 3).

We argue that in addition to the traditional variables that drive the rate of adoption of solutions, we must also consider the balance of the level of complexity of a problem and that of the solution. If the complexity of the solution is too high vs the complexity of the problem, the solution diffuses at a lower rate of adoption. This is the *Engineer's effect*. If the solution is too simple compared to the problem it attempts to solve, the resulting low adoption rate is due to the *Columbus' egg effect.* As shown in Table 1, cells A and D are combinations of problem-solution complexity balance that contributes to a high rate of adoption.

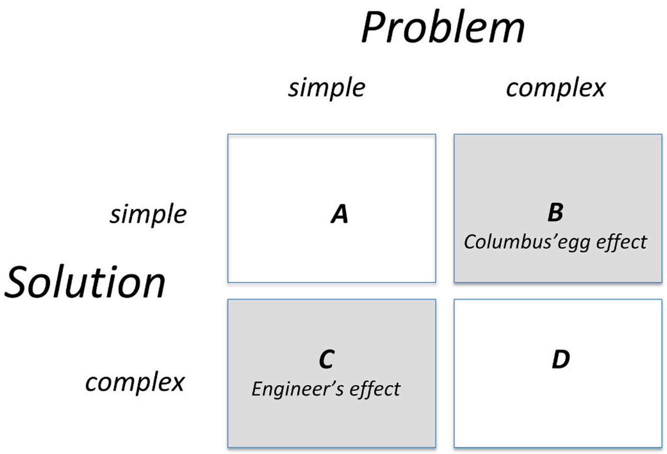


Fig. 2. Matching problems and solutions.

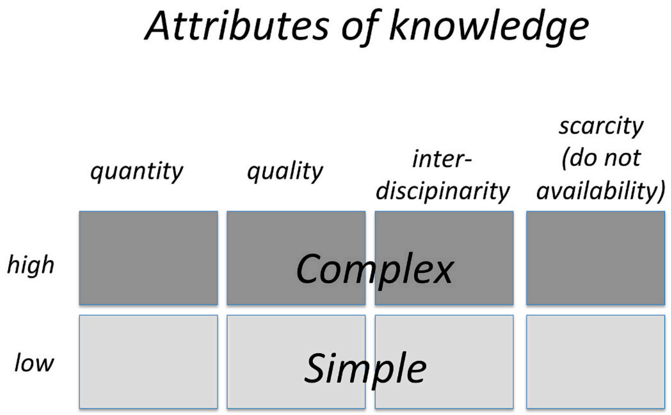


Fig. 3. Definition of complexity.

Table 1

Problems and solutions in the adoption of innovations.

Characteristics of the relationship "problem-solution"	Relationship between the complexity assigned to a problem and the actual complexity of a found solution	Effects on adoption
Aligned	A. Simple solution for simple problem	A relative high degree of adoption
Misaligned *Columbus' egg effect*	B. Simple solution for complex problem	A low rate of adoption at the first stage and a relative high speed of adoption when (if) this solution is finally accepted because of a very small "technological gap"
Misaligned *Engineer's effect*	C. Complex solution for simple problem	Rate of adoption relatively low and no effects on the substitution of old solutions: old and new solutions may cohabit for a long time because of the learning time, i.e., to make a comparison is very difficult.
Aligned	D. Complex solution for difficult problem	Relative higher rate of adoption than point C in the first stage

3. Is there a match between problem and solution? Explaining the link between complexity and rate of adoption

The mechanism of adoption is anchored in the belief that the complexity levels of problem and solution are positively correlated. Shinn (2011) for example has argued that: "radical innovation solves big problems". This is a similar argument to the De Solla Price (1963) "Little Science Big Science". He argued that modern science poses very complex problems, which need to be addressed by massive investments and complex solutions. Simple problems can be solved by currently available and simple solutions. However, the best solution for a given problem cannot be adopted as the best solution for an increasingly difficult problem. When problems regarding a given situation (e.g., production of goods and services or the development of complex military systems) become more complex, the solutions that were adequate up until then are no longer appropriate. As problems of production or the development of such systems increase in complexity, so do solutions, such as the degree of automation and the employment of inter-disciplinary knowledge (Levhari, 1965; Sraffa, 1960).

Problem-solving often appears difficult and some problems seem impossible to solve simply because we do not know where to begin (Michalewicz and Fogel, 2000). A reason for this notion is our belief that the complexity of the problem overwhelms the solutions we have traditionally applied to such problems.

Suppose that a solution is considered for adoption by the organization's decision-makers. This solution is proposed as a *solution* to a specific problem of the potential adopter. If this problem is perceived by the organization as complex and the solution is perceived to be too simple, the process of adoption will slow down and the adoption may be postponed, re-examined, or rejected. The potential adopter must perceive the solution as a *viable* solution to its problem. This viability or "match" is the balance between the complexity of both problem and solution. Similarly, if the problem is perceived by the decision-maker to be a simple one, and the solution is perceived to be complex, the process of adoption will stall. One reason is that the simplicity of the solution evokes *skepticism* in the potential adopter that such a simple solution will indeed solve the problem.

Table 1 shows the various relationships that arise from the matching of problem-solution and the impacts of the alignment or misalignment of complexity between problems and solutions. Situation C (complex solution for a simple problem) is a widely-seen phenomenon. The low rate of adoption in this situation is due to the perception by the potential adopter that very complex solutions are unnecessarily sophisticated, too expensive, and possibly futile attempts to solve a simple problem.

Situation B (simple solution for complex problem) is much less common, even if cases of "too easy to be effective" which culminated in a solution are not rare. There are several examples of simple solutions that solved problems considered to be complex: the helm; Archimedes' screw; the Westinghouse brake; the distributor; and the carburetor in internal combustion engines.

3.1. *The approach in practice: assessing technology complexity*

Moving from theory to practice (see Table 2), we need to measure technology complexity. In assessing technology complexity (TC) some approaches have been proposed. A first measure of TC (Fleming and Sorenson, 2001, 2004) refers to knowledge combination i.e., a technology is complex (simple) if the effort to combine heterogeneous knowledge is high (low). From this approach, TC is a synonymous of inventive difficulty. Starting from this perspective, Broekel (2019) introduces the concept of structural complexity i.e., TC reflects the complexity of the knowledge network properties.

Balland and Rigby (2017) define TC on the basis of three concepts: technology diversity, ubiquity and scarcity. A technology is complex if it comes from technologies that require a degree of specialization that can be found only in few places. And these specializations are observed in the same places.

Based only on interdisciplinarity and scarcity of knowledge, the above approaches are usually applied to patent data and they are not relevant for our aim and perspective.

Alternatively, and for different purposes, Jacobs et al. (2003) develop and validate a simple questionnaire for assessing the complexity of a problem (too simple, too difficult, too structured) as perceived by students. Mikkelsen (2021) assesses the perceived project complexity among managers by means of a dedicated questionnaire. Although the indicated approaches are insufficient tools for our purpose (i.e. questionnaires do not consider the four dimensions of knowledge complexity

Table 2

From theory to practice: our approach into three steps.

Steps	Description and notes
Step 1. Definition of a knowledge based technology complexity metrics (K-BC)	This metrics has to integrate 1) quantity, 2) quality, 3) inter-disciplinarity, 4) scarcity of knowledge referred to problems and solutions
Step 2. Experimental design	K-BC can be adopted as predictor of adoption rates. A sample of subjects can be recruited. Enrolled subjects may be asked to answer to a questionnaire related to a specific problem's complexity. Then a small set of alternatives can be described with the same questionnaire. Then, subjects make their choice among alternatives. It is relatively easy to estimate if the percentages of choices among alternatives reflect the differences of the complexity assigned to the problem and the complexity of the proposed solutions, and if this covariate is orthogonal to the current dimensions adopted for predicting adoption rates. This analysis can be done for different fields of application and technologies.
Step 3. Technology adoption forecasting	Starting from problems, the obtained results (Step 2) can be adopted for predicting the market adoption rate of existing and new solutions at a given point in time. Alternatively, the evolution of the differences between problems and solutions' complexity can predict the adoption of technologies over time.

and they are applied only to technology), they go on toward the direction shared by our proposal, i.e., knowledge based instead of technology based measure of complexity.

4. Relation of the concept with the existing literature

The phenomena that are here illustrated find direct footholds on some theoretical models of technology adoption, on one side, and the literature focused on the drivers of innovation diffusion and acceptance, on the other (Table 3).

Looking at the existing approaches, the dimensions introduced are in line with some achievements of the most diffused models of technology adoption (Fishbein and Ajzen, 1975).

The Columbus' egg and the Engineer's are effects linked with the TPB (Ajzen, 1991) that introduced the concept of perceived behavioral control (i.e., conditions in which the decision maker tries to control his behavior according to the expectancy of success, as the probability of "succeeding at a given task" relevant in planned actions) to improve the original dimensions of the TRA (Aldhaban et al., 2015; Fishbein and Ajzen, 1975; Ajzen, 1991) (i.e., attitude toward the behavior and subject norm). In this, too simple or too complex solutions can induce to underestimate the probability of achieving the task or overestimating the effort to obtain a success.

With respect to the TAM (Davis et al., 1989; Davis, 1989) the proposed effects are related to the expectation of the new solutions considering their perceived usefulness and ease of use, and the relationship between them. It is expected that, before adopting, the hierarchy of factors is firstly the perceived ease of use and then usefulness. However, a solution that seems too easy than expected can influence the perception of its usefulness. In other words, the perceived complexity of a solution (ease of use is usually treated as the inverse of solution complexity by innovation adoption and diffusion literature, Rogers, 1983; Davis et al., 1989; Davis, 1989) can influence the perception of its relative advantage (as synonymous of usefulness, Davis, 1989). This can be observed not only on the direction of too complex solutions, but also on the opposite corner of too simple ones. In this, empirical analysis confirms that ease of use and usefulness are highly and positively correlated (Davis et al., 1989; Keil et al., 1995, see also Sheppard and Vibert, 2019). This could be a result that does not support our idea. However, correlation between ease of use and usefulness has been obtained by collecting opinions of adopters rather than potential adopters' expectation (von Hippel, 1988; Taalbi, 2017). Therefore, empirical findings only confirm that adopted solution are characterized by a positive balance between ease of use and usefulness. This is compatible with the idea that a balanced relationship among expectations on problem characteristics and solution characteristics can drive innovation diffusion.

Table 3
Theoretical background.

Theoretical model on technology adoption	Specific concept	Relationship with Columbus' egg and the Engineers' effect
Theory of Planned Behavior (TPB)	Perceived behavioral control	Perceived too simple or to complex solutions can induce to underestimate the probability of achieving the task or overestimating the effort to obtain a success
Technology Acceptance Model (TAM)	Relationship between expected usefulness and ease of use	These effects can appear when expectation on ease of use or complexity of a proposed solution is considered by individuals as a proxy of the real usefulness of the solution and they are not balanced with respect to the complexity attributed to the problem
Unified Theory of Acceptance and Use of Technology (UTAUT)	Effort expectancy (also related to the perceived behavioral control of the TPB)	See the concept of perceived behavioral control. Effort expectancy can induce the potential adopter to reflect on the perceived frustration if a high effort in adopting a proposed solution fails in solving his or her problem

Whit respect to UTAUT (Venkatesh et al., 2003) the two scenarios are closed to the concept of "effort expectancy" (that is also closed to the concept of perceived behavioral control of TPB).

Although their influence as existing models, the above approaches have some limitations that we tried to overcome in our rule/theory for solution adoption. Among others, these models are related to individual rather than for institutional or corporate adoption (Ajibade, 2018). But their most important limitation (it is shared with alternative approaches) we tried to overcome is that they can offer strong or weak reasons for the lack of adoption of too complex solution but they do not offer explanations for the lack of adoption of very simple solutions, as in case of the Columbus'egg effect.

By contrast, our approach is far from the dimensions of the technology adoption models and alternative constructs that take into account experience or effective use of the technology (e.g., the Task Technology Fit model TFF, Goodhue and Thompson, 1995) that are closer on describing drivers of technology use rather than factors influencing technology adoption.

On the side of drivers of adoption related to the rate of diffusion, the first inspiration is the innovation literature, like Rogers (1983): "Innovations that are perceived by individuals as having greater relative advantage, compatibility, trialability, and observability, and less complexity, will be adopted more rapidly than other innovations". However, our perspective does not deal with the effect of specific drivers neither with innovations or inventions but on the (unbalanced) relationship among some of these drivers on the more general concept of solution adoption. Related concepts, especially on the Columbus' egg effect, are the emerging literature and empirical findings on consumer skepticism on new products (Vivekanandan and Jayasena, 2011; Obermiller et al., 2005; Morel and Pruyn, 2003) and ridiculed technology e.g., cases of technologies ridiculed at the beginning that became a market success (Scheubel et al., 2018).

A third connection with the literature is referred to the concept of institutions i.e., stable, valued, recurring patterns of behavior [60] within the evolutionary paradigm in economics (Dosi, 1982; Dosi and Orsenigo, 1988). The Columbus' egg and the Engineer's effects can be considered as institutions that guide the evolution of technological trajectories on regular patterns. The following sections describe the psychological and cognitive underpinnings of the two scenarios of misalignment in complexity between problem and solution. For each scenario, we show examples.

5. Cognitive and neural underpinnings

5.1. Psychological and cognitive underpinnings

Human beings seem to make choices as if they maximized the net expected returns under constraints of a given level of decision making cost, or minimized (expected) decision-making costs (Taylor, 1981; Vohs et al., 2008; McGuire and Botvinick, 2010) fixing a benchmark for the expected gain. Minimizing decision costs refers to reducing the quantity of cognitive effort, working memory, and task set configuration related to a specific choice (Droll and Hayhoe, 2007).

Observed phenomena such as effort-accuracy trade-off, the use of stereotypes, and reliance on fast heuristics, have been explained as effects of decision cost minimization (Allport, 1954; Payne et al., 1993; Gigerenzer and Goldstein, 1996; Shah and Oppenheimer, 2008). If expected decision costs are proportional to the complexity of the proposed solutions, expected gains are related to an additional concept that is of extreme relevance in individual behavior: frustration.

Let us consider a given problem P at time 0; let $C_t(P)$ be its level of complexity at time t as our effort in looking for a solution that is the cumulative efforts from t to 0. A solution S can be found by ourselves, or it can be offered on the market. Let's suppose that at time t two solutions S_1, S_2 are offered on the market. Understanding their degrees of complexity $C(S_1)$, $C(S_2)$ is the additional effort we need to make a decision, or in other terms, it is the decision cost $dc(C(S_1), C(S_2))$.

Let $g(S_i)$ be the gain obtained by adopting one of the two solutions, with $i = 1,2$. This gain is a function of the performances of the two solutions, which can be understood only at the decision cost $dc(C(S_1), C(S_2))$, but also of our effort made in looking for the solution; i.e., we expect that the obtained reward is proportional to the effort, and if it is not the case, frustration can emerge. Frustration can be the effect of comparing our effort and the obtained reward (it can be external or internal) as a measure of the uselessness of our past efforts (Lawrence and Festinger, 1962). The effect of frustration (Amsel, 1958, 1962) also associated with aggression (Dollard et al., 1939; Wagner, 1963; Berkowitz, 1989; Anderson and Bushman, 2002) $g(S_i)$-$C_t(P)$ is stopping search, reducing effort, and effort extinction (Shah and Oppenheimer, 2008; Wagner, 1963. See also the perspectives of Abler et al., 2005; and Dawkins and Brockmann, 1980; Ploger et al., 2021 on dissonance as the explanation for resistance to frustration).

Alternatively, effects of frustration can observed in looking for new objectives and new problems, modifying by ourselves the level of the value we expected to obtain if we solved the problem, asking for an increasing reward, or responding to new stimuli and incentives. As a consequence, the probability of adopting a too-simple but effective solution decreases with the increase in the past efforts made looking for a solution. At the basis of the Columbus' egg effect there is the process of expected frustration minimization, i.e., reducing effects of lack, or a disproportion in reward and effort, as observed in animal and human behaviors (Wagner, 1963; Dawkins and Carlisle, 1976).

Minimizing expected frustration hides a cognitive trap. Expected frustration induces not adopting too-simple solutions and continuing to look for others until the effort of problem solving has reached a relatively high level. But this induces increased expectation of frustration if a new and too-simple solution is available.

When confronted with these cases, potential adopters should require innovators to demonstrate the relationship between the knowledge embedded in the solution and the objectives to be achieved by the adoption and implementation of the innovation. This request is made in order to reduce decision costs if the solution appears too complex, or with the hope of finding errors and mistakes that reduce frustration, if the proposed solution appears too simple.

Minimizing frustration produces effects that have some analogies with the so-called Concorde fallacy effect, which induces individuals to look at past investments rather than future revenues, making subjects reluctant to abandon activities in which they have spent a lot of time, money or physical effort. The psychological basis of the phenomenon is known in the literature as the sunk cost principle: probability of switching from a solution/activity to alternatives is inversely proportional to the effort made on the initial choice (Dawkins and Brockmann, 1980), as observed in both animals and human beings (Arkes and Blumer, 1985; Arkes and Ayton, 1999).

By contrast, the effect of expected frustration on the adoption of available solutions differs from (is complementary to) the role of frustration as source of innovation. When solutions are proposed after a relatively high cumulative effort to find a solution, frustration induces individuals to reject solutions that explicitly demonstrate the uselessness of past efforts. When individuals are frustrated because they are unable to do something by applying past knowledge, frustration can induce individuals to reject past procedures and ideas, looking for alternatives that can inspire adoption (Festinger, 1961; Heinzen, 1994; Heinzen and Vail, 2003; Arbesman, 2016).

Taken independently, minimization of frustration induces one to reject solutions that seem too simple with respect to the effort made in looking for a solution (Columbus' egg effect).

Minimization of decision costs induces adopting a solution that is not too complex to be understood (the Engineer's effect), since the expected gain is reduced by the expected effort represented by the decision costs. In effect, the solution human beings adopt in this case is similar to the notion of “satisficing” (Simon, 1947). When faced with scarce resources or information complexity, managers accept solutions that are “good enough” or “satisfactory” to solve their problems, rather than searching for solutions that maximize or optimize their objectives. Managers will adopt innovations which do not require extensive and costly investment in the knowledge embedded in them and, therefore, are perceived to be necessary for “the best” solution. The “good enough” criterion is a good enough reason to adopt the innovation/solution.

If the solution can be shown to satisfy one objective, so that the adopter is comfortable with this solution, the rate of adoption will increase. For example, if the innovation contributes to reducing operational costs, but does not necessarily also contribute to improving performance and increasing market share, the cost criterion would be a “good enough” reason to adopt it. The innovator must be able to ascertain that additional investments in knowledge embedded in an innovation are not necessary for a “satisficing” solution.

Another effect of decision-making cost minimization is the negative effect on consumption of too many choices that has been analyzed under the label of “the paradox of choice” (Schwartz, 2004). It has been observed that too many choices increase decision costs, demotivating potential adopters; this phenomenon has been observed in many markets such as financial products (Iyengar et al., 2004) and food (Iyengar and Lepper, 2000). As a consequence, firms try to reduce the number of versions of the same products (Osnos, 1997; Goldstein et al., 2007).

To summarize, decision-making in problem solving is: maximization of expected reward or minimization of possible frustration, and minimization of expected decision costs. If there is no balance among these goals, Columbus' egg and the Engineer's effect can reduce the rates of adoption of too-complex or too-simple solutions.

5.2. *Neural underpinnings*

Activity in the lateral prefrontal cortex is associated with cognitive control and registration of decision costs. Frustration seems to involve different brain regions such as the basal ganglia, right insula, bilateral post-central gyrus, bilateral middle frontal gyrus, right SII, posterior cingulate cortex (PCC), right inferior frontal gyrus, and right precuneus (Bierzynska et al., 2016). The hypothesis that frustration is compensated for by anger and aggression induces scholars to associate frustration with the area of the brain that controls these reactions as decreased activation in the frontal brain regions and the dorsal anterior cingulate cortex (DCC), with less amygdala activation (Pawliczek et al., 2013). Alternative studies on frustration in early childhood evidence the role of the prefrontal cortex in controlling emotion during frustration (Perlman et al., 2014), but all these studies are related to frustration’s effects, regulation and control, once it occurs. If this mechanism is confirmed, activation (decreased activation) of the left lateral prefrontal cortex should be accompanied by decreased (increased) frustration control, and a lesser (higher) probability of observing Columbus' egg effects.

The mechanism that regulates expected frustration is still unclear, although the mechanism of expected reward is known in the literature. The medial frontal cortex appears sensitive to the increasing level of reward expectancy, if the reward is expressed in money, (Rowe et al., 2008; Rolls et al., 2020) and anterior striatum and midbrain are activated in case of non-monetary rewards such as verbal rewards (Albrecht et al., 2014).

6. The Columbus' egg effect

Benzon (1565) tells us that Christopher Columbus was dining one evening with some nobles. He asked for a whole egg to be brought to him and said: "my lords, I will lay a wager with any of you that you are unable to make this egg stand on its end like I will do without any kind of help or aid". The nobles tried without success. Then Columbus tapped the egg on the table, breaking the end slightly and with this, the egg stood on its end. His behavior provoked disapproval and none of the nobles seemed to accept his solution. Notwithstanding the nobles' reaction, that very simple idea solved a very complex problem, a problem that seemed unsolvable because of the shape of an egg.

The lesson from this anecdote is that difficult or complex problems can be solved by simple solutions, which are misaligned with the level of complexity of the problem. Because of this perceived misalignment, such simple solutions will be seldom accepted or adopted due to the skepticism of people who are faced with the problem. They expect complex problems to be solved by complex solutions. The diffusion and adoption of the simple solution is slowed until the asymmetry of the simple-complex relationship is resolved in the perception of potential adopters. The following examples illustrate this phenomenon.

6.1. *The longitude puzzle*

Determining longitude for navigating ships on the high seas was considered a very complex problem. A slight error meant sailing miles off course. In the 18th century public opinion was traumatized by the October 22, 1707 tragedy when an English fleet of four warships and 2000 sailors were lost near the Scilly Islands because their navigators miscalculated their longitude position. This episode prompted the British Parliament to adopt the Longitude Act of 1714. Parliament offered a £20,000 (nearly £6 million in today's currency) reward for the discovery of a workable method to measure longitude.

Many bizarre solutions were submitted. Finally, a clockmaker named Harrison proposed placing a clock that showed the Greenwich Mean Time (GMT) on board ship. Longitude would be calculated by the difference between local time and the time shown by the Harrison clock (Sobel, 1995).

Harrison's solution proved very effective, but the Royal Commission did not immediately accept it. It was deemed to be too simple! The Royal Commission believed that because of the complexity of the problem, the solution should involve astronomical science and include the accurate measurement of the periodical motion of the planets.

6.2. *Daylight saving time (DST)*

The idea of saving energy by a DST system was known for at least a hundred years before Franklin first suggested it in 1784 (Franklin, 1784; Hudson, 1784; Willett, 1907). The idea was so simple that Franklin initially proposed it as a joke. This idea was proposed to the British House of Commons by Robert Pearce in 1908. Although the first DST bill was drafted in 1909 and submitted to the House of Commons several times, many members opposed the proposal. In 1916 German legislators approved the first national DST bill. Afterwards, similar bills were introduced and approved in other countries.

6.3. *The checklist manifesto*

In 2009 Atul Gawande, a professor of surgery at Harvard Medical School, published "The Checklist Manifesto: How to Get Things Right", a New York Time Bestseller in which he summarized several lines of evidence in support of adopting a rather simple solution. The pernicious problem of central line-associated bloodstream infections (CLABSI) is responsible for an estimated rate of 41,000 deaths in U.S. hospitals each year. Despite the complexity of these infections, a five-point checklist virtually eradicated central line infections in intensive care units (I.C.U.) at Johns Hopkins Hospital, and greatly reduced them in I.C.U.s in Michigan. The adoption of the checklist over the period of the formal validation probably saved more than 1500 lives within a year and a half.

The idea of a checklist was born in 1935. US military aviation organized a flying race reserved for the future generations of fighter-bomber suppliers. Since the Boeing 299 had surpassed all rivals, the race was considered a formality. However, the Boing 299 rolled on the track, got off the ground and stalled, then crashed to the ground. The Army Air Corps declared Douglas's smaller design the winner and Boeing nearly went bankrupt. Mechanical failure was excluded: it was a case of human error. Although the pilot was an expert, the greater complexity of the Boeing 299 with respect to the classic aircraft induced the pilot to forget to deactivate a new steering wheel lock mechanism. A commission of experts decided to create a checklist to help both beginners and expert pilots (paradoxically, problems resolved by the checklist are actually more pertinent to mistakes made by experts than by beginners) to reduce simple but dangerous mistakes in complex processes (Gawande, 2011).

After 80 years, the idea of a checklist for reducing human error in complex operations such as surgical operations is still not completely diffused, and some skepticism is observed among healthcare professionals (some scholars still "believe that a surgical safety checklist fails to show a subjective, clinically important improvement" (Dharampal et al., 2016).

6.4. *Hand-washing. The case of Ignac Semmelweis*

In the first half of the 19th century and before Pasteur's concept of bacterial transmission, many women died of childbed fever. The clue appeared as a complex puzzle and very complex hypotheses were formulated. Ignac Semmelweis observed that his colleague Jacob Kolletschka died after an autopsy carried out on a woman who died from childbed fever. He presented the same signs as the deceased woman. He presumed that the childbed fever was transmitted to other women by professionals who were in contact with women who died. To reduce deaths, he simply suggested that professionals should wash their hands and change sheets. Although this solution was effective, it appeared too simple with respect to the complexity associated with the apparently unresolved problem, and it was generally adopted only 40 years later (Hanninen et al., 1983).

7. The Engineer's effect

The Engineer's effect arises when a problem is considered simple with respect to the degree of knowledge that should be embedded in its solution. It induces a low rate of adoption of technology perceived as too complex. Some cases of Engineer's effect are hereby offered to the reader.

7.1. *E-voting and technology in elections*

Although in some countries (e.g., Estonia from 2005 to 2015) electronic voting has been officially adopted (Vassil et al., 2016) and the list of programs and pilot studies for introducing e-voting is rapidly increasing, riding the wave of citizens' direct participation, why has e-voting (and other forms of technology-assisted solutions) not become more widespread in public elections?

Let consider the case of some EU countries (analysis based on underdeveloped countries can be influenced by the quality of available technology). Heterogeneous countries such as Ireland, Norway, Germany, and Austria have abandoned the use of electronic voting (McCormack, 2016). In other countries like Italy, up to 2015, electronic voting has been experimented with in limited areas, and without large-scale initiatives. Up to 2015, Internet voting (i.e., legally binding and also associated with other technology) has spread in only in a few countries: Canada (used in part of the country), Brazil, France, Swiss, Estonia and India (McCormack, 2016).

The answer is that e-voting is still a too complex solution compared to the traditional ones. The complexity inherent in e-voting technology merely involves the voting process, and the risk that e-voting technology might exclude some citizens is now overcome by the wide diffusion of internet, ICTs, except for security guarantees and the need to avoid electoral fraud. By attempting to resolve this problem via new technologies, the complexity of structuring e-voting for official elections could rapidly increase. In detail, the increasing use of technology for improving security paradoxically induces new problems of security that require new technologies, and so on, so that one solution for reducing security problems is to reduce the complexity of technology. Although it could make it easier for citizens to vote, e-voting could become too complex for the government to be adopted, widening the difference between the complexity associated with the problem and the expected complexity of the solution, and thus supporting traditional and less technological solutions.

7.2. Automatic lectern

While singers usually have their hands free when they sing, this is not true for musicians. An automatic lectern has been developed for automatically turning the pages during performances. The observed almost lack of a market (or very low adoption) for these technologies is due to the fact that they offer a too-complex solution with respect to the problem they try to resolve. In effect, for most musicians automatic lecterns are useless simply because musicians play by heart (so there is no problem needing a solution). For those performers who use both hands and need printed scores, multiple pages on a single page or a rapid movement of the hand is the level of complexity required to resolve the problem instead of a system that is usually bulky. In fact, it requires a battery, which usually produces noise that can be reduced only by increasing the technological complexity; also, it can automatically turn pages according to the personal interpretation and tempo of the performer only by employing complex technological systems and subsystems.

7.3. Iridium

Iridium was Motorola’s satellite phone system developed from 1985 to 1998. In 1985, Bary Bertiger, an engineer at Motorola Inc., developed the concept of Iridium when trying to resolve a problem of his wife’s: how to communicate by phone with her customers while vacationing in the Caribbean? His solution was a system of 77 LEO (Low Earth Orbit) satellites (77 is the atomic number of Iridium; the system actually consisted of 66 satellites) and a cumbersome phone. In 1992, Robert Kinzie, Chairman of Iridium, Inc., declared “This is not just a phone; it is a vision” (Collins, 2005). But Bertiger's wife, and most potential adopters, would have considered a phone to be a solution to their problems: they were not looking for a relatively complex vision.

Despite (or because of, as suggested by the Concorde effect) the enormous investment, the project was not abandoned. The complexity of the technology’s development and realization required more than 10 years of work. Meanwhile, the diffusion of mobile phones rapidly increased worldwide and made Iridium a too-complex (and too-expensive) solution (McCormack and Herman, 2001). Iridium did not widely diffuse. However, it is currently adopted as the only available, and costly, solution, for specific users like, for instance, governments, soldiers and scientists, and for communication with and from remote areas like the pole scientific stations.

7.4. Too complex to be really useful

John Naish (2008) suggested the creation of the annual Landfill Prize, awarded to the most complex consumer items created to solve simple problems. Some examples are: the digital refrigerator magnet on which you can record a 30-second video message through a digital screen, a rechargeable battery system, a computer and a camera, the bra dryer, the ear dryer, and the operatic pasta timer. Other examples include complex organizational restructuring programs designed to solve simple problems of performance or productivity of selected departments. The re-engineering phenomenon of the 1990s illustrates this Engineer's effect (Geisler, 1997).

These solutions generally have a very slow rate of adoption and diffusion. Some of them stay in the condition of inventions. They offer a very complex and usually overly expensive solution to a simple problem. Potential adopters generally are aware of this effect and choose not to adopt the solution.

8. How to accelerate the rate of adoption in case of misalignment between problem and solution

Product developers and designers as well as managers involved in developing strategies for bringing new products into the market can be oriented to overcoming the expected and “classic” barriers to adoption. However, the complexity of a product can still be misaligned with respect to the complexity expected by the market.

Of course, if the product is in its early stage of development, it is easier to modify the program in case of a too-complex solution. By contrast, the Columbus' egg effect could be, in case of innovation, a signal of disruptiveness (Rosenbloom and Christensen, 1994; Christensen and Rosenbloom, 1995; Christensen, 1997, 2003), so that the most important barrier is not the expected market behavior but the barriers and pitfalls within the company. Based on criteria that firms adopt to allocate resources over alternative programs, a potential and effective program that appears too simple may be abandoned or underfunded. In this, the same effects of misalignment of problems and solutions that affect adoption in the market are reproduced inside firms. Christensen (1997) offers solutions to overcoming the initial skepticism of disruptive solutions induced by allocating resources on the basis of the expected market share and current dimensions and characteristics of products the market recognized as drivers of adoption. Often a viable solution cannot be obtained within the firm and the Columbus' egg effect can be by-passed through a dedicated spin-off and small firms (Walsh et al., 2002). Alternatively, an informal and less hierarchical environment may be useful: working in a team in which effort is shared among individuals and rewards are not monetary, can reduce the gap between individual effort and reward, or can share frustration among individuals, increasing group solidarity.

How to cope with Columbus' egg and the Engineer's effect when products are in the early commercial phase? Which strategies are in the hands of a product launch manager?

The psychological and cognitive underpinnings of the effect of a perceived misalignment between the level of complexity of the problem and the level of complexity of the solution suggest solutions for accelerating the rate of solution adoption in cases of “Columbus' egg” and the “Engineer's effect”. Too-complex though effective solutions are not accepted because of too-high expected decision costs. Too-simple though effective solutions are not quickly accepted because of too-high expected frustration.

The Engineer's effect, as the consequence of the satisfaction approach induced by too-high expected decision costs, can be reduced by investing in easy interfaces that can increase the perception of easy to use (Davis et al., 1989; Hauser and Shugan, 1980; Larcker and Lessig, 1980; Swanson, 2007), supporting decisions with pre-selling services, and counseling by experts, who explain the technology’s performance and its potential to resolve not only a specific and de-contextualized problem, but new potential problems correlated to the original one that an easier solution may be unable to resolve in the future.

Alternatively, a product launch manager looks at those markets in which the proposed solution reflects the complexity of sophisticated consumers.

Reducing the Columbus' egg effect (the Engineer's effect) can be pursued by reducing expected frustration (reducing the expected decision costs).

Reducing expected frustration (reducing the Columbus' egg effect) appears as a more complex effort: in competitive environments among innovators or between innovators and potential adopters, reducing the Columbus' egg effect could be very difficult.

However, in the case of the Columbus' egg effect, a product launch manager can look at those markets in which the proposed solution is congruent with a relatively low sophistication of needs (e.g., emerging markets, Agarwal et al., 2017), invest in the potential implications of the simple solution to overcome its existing limits, if possible announce updated versions of the solution that was considered too simple, in order to transform it into the basic module of a more advanced system, or present the solution as disruptive since it actually resolves a problem considering dimensions that differ from those believed at the moment by the market.

The indicated strategies may mitigate the problems and solutions' complexity misalignment by promoting better communication of the properties and potential of the proposed solution, reducing or better clarifying the complexity inherent in the solution. However, the same effect can be obtained by acting on the original problem, showing that its complexity or simplicity may be underestimated (overestimated) and why.

In cases of the Columbus' egg and Engineer's effects, the complexity of an effective but too-complex or too-simple solution can be mitigated by modifying or recalibrating the message, the purchasing process and the communication channel (e.g., if the purchasing process is relatively easier and fast, the product could be perceived as less complex). We should emphasize the role of the communication channel in modifying the perceived complexity of a proposed solution, since the medium could be the most important message (McLuhan, 1964).

9. Conclusions and limitations

The results of the paper are twofold: first, we extended the theoretical framework of solution (e.g., invention, constructs, theories, innovation, technologies, procedures, methods) adoption by introducing the concept of alignment between the complexity of the problem and the complexity of its solution. We argued that among the different reasons that impact the solution adoption is the perception by potential adopters that there ought to be a balance between the complexity of a problem and the complexity of its solution. Secondly, we suggested that there are cases of misalignment, which are strongly rooted in the perception of potential adopters.

We illustrated cases with the Engineer's effect and the Columbus' egg effect. In these cases the rate of adoption of innovative solutions is negatively impacted. When there is a misalignment between the complexity of the problem and the solution, we suggest an approach to increase the rate of adoption. We also suggest conditions and strategies to decrease the expected decision costs involved in the Engineer's effect, and decrease the expected frustration involved in the Columbus' egg effect.

Our aim was to introduce paradigmatic, but hopefully sufficiently convincing, examples that could support our perspective and that could represent a useful baseline to design and empirically test the robustness of our hypotheses.

Although the effects of drivers such as decision-making costs and frustration in decision-making are well-observed and reported in psychological, cognitive and neuroscience literature, in fact, further research is needed to empirically explore the feasibility of our approach. This calls for studies of successfully adopted innovations and/or accepted inventions and evaluation of the degrees of complexity of the problem and the solution offered. In the case of misalignment, we should study the attributes of the criteria used by adopters, such as "satisficing" switching in the objectives of the adopters due to expected too-complex solutions, the presence of frustration in cases of low rates of simple solution adoption, and whether there are decreases in the Columbus' egg effect associated with mechanisms that regulate and control frustration.

The main limitations of the proposed approach are twofold. First, in order to test the contribution of differences in complexity of problems and solutions in explaining adoption rates, the sample size adopted for validating the questionnaire on knowledge complexity could be not sufficient. This effort will need a deep profiling of potential adopters' characteristics, and deep profiling means large sample sizes.

Second, a fundamental problem and some limitations could emerge in how to define stimuli (i.e., problems and solutions) that will be presented to the respondents. In effect, stimuli's complexity can influence the perception of content's complexity. A way for avoiding this bias could be, in case of text, to adopt highly readable sentences where readability could be measured by means of the Flesch–Kincaid readability tests (Kincaid et al., 1975). Zanette (2018) proposes an interesting way for assessing the complexity of black and white images. Alternatively, these two metrics can be adopted as measure of complexity.

In conclusion, as anticipated, new analyses and empirical studies should be run based on the proposed explanation, as we envisage the potential benefit for technology developers and product innovation managers, as well as for forecasting technology adoption.

Validated with current solutions that highly or very low diffuse in the market, the method will predict the success of new products, services, technologies, as a valid and general tool for developers and marketing managers.

Data availability

No data was used for the research described in the article.

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