HIGHLIGHTS

- A qualitative approach is presented to select strategies for emerging risk management.
- This approach is inspired by meta-learning concepts.
- This approach is based on the combination of uncertainty and the consequences.
- The uncertainty is considered as a combination of knowledge and understanding.
- Three case studies are included with different evolutionary degrees of emerging risk.
- The approach is applicable to the pre-assessment and risk communication processes.

Abstract

The emerging risk models are still scarcer and far from agreements or consensus, currently being a focus of increasing interest in the industrial context. Consequently the frameworks that deal with emerging risk management in industrial contexts are very recent or even still in the development and maturation phase. The uncertainty should be considered as the main characteristics of the emerging risk in this context.

Thereby, the main objective of this paper is to develop a qualitative approach inspired by meta-learning lessons to the selection of strategies for emerging risk management considering uncertainty as the main decision variable in industrial contexts. For this, uncertainty has been integrated, as a combination of knowledge and understanding, in a theoretical framework on emerging risk. With the results obtained an emerging risk classification scheme has been developed. This scheme allows estimating the level of emerging risk and management strategies based on the combination of uncertainty and the potential consequences of emerging risk. Such approach has been applied to three case studies with different evolutionary degrees of emerging risk, being: exoskeletons; nanomaterials; and industrial automation. The proposed approach could be considered primarily as a qualitative tool applicable to the process of pre-assessment and communication of emerging risk.

Keywords: emerging risk; management; meta-learning; risk analysis; risk characterization; uncertainty.

Approach to the selection of strategies for emerging risk management considering uncertainty as the main decision variable in industrial contexts.

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1.- Introduction

The risk definitions used in the professional and scientific fields are numerous (e.g. Aven, 2010, 2011a, 2012a), but emerging risk definitions are much scarcer and far from agreements or consensus, currently being a focus of increasing interest in the industrial context, both from a systemic and occupational point of view (e.g. Flage and Aven, 2015; Brocal et al., 2017).

From a systemic perspective, the International Risk Governance Council (IRGC, 2010a, 2010b) suggests that an emerging risk may occur under two different conditions, that is, under emerging conditions and under new or unfamiliar conditions. Under emerging conditions the risk is emerging when it is new in a broad sense, as in the case of new technologies, new materials; e.g. carbon capture and storage (Wilday et al., 2011); and the risk is emerging when being familiar or traditional, it is presented under new or unfamiliar conditions; e.g. larger volumes of LNG handled (Paltrinieri et al. 2015). Paltrinieri et al. (2019) identifies in risk emergence one of the fundamental challenges of the overall risk assessment.

From an occupational perspective, the European Agency for Safety and Health at Work (EU-OSHA) defines a new and emerging risk (henceforth emerging risks) as any occupational risk that is both new and increasing (Flaspöler et al., 2005; Brun et al., 2007a, 2007b, 2009); e.g. automated manufacturing process (Brocal et al., 2018)

Emerging risk requires specific or adapted management frameworks based on traditional risk management frameworks. There are numerous management systems in the industrial risk field, which have been classified by Brocal et al., (2019a) in three groups: (a) the systems that address risk from a general and / or systemic perspective (e.g. ISO 31000:2018 standard; CSA Q850-97 standard; NORSOK Z-013 standard); (b) the systems that deal with accident risk management, that is a major accident (e.g. Directive 2012/18/EU) and occupational accident (e.g. Directive 89/391/EEC; ISO 45001:2018 standard; ILO-OSH, 2001; ANSI/AIHA Z10, 2005;); and (c) the systems that address the emerging risk.

Emerging risk is addressed by Paltrinieri et al. (2020) through a meta-learning approach aiming at optimizing the risk analysis learning process - i.e. learning how to learn. In fact, one of the main issues is understanding how to provide a risk assessment approach adaptable enough to tackle the emergence of unexpected implications. In other words, the overall concept of meta-learning for emerging risk focuses on defining an intelligent approach (θ^*) to reach the best expected risk management performance $E(RMP)$ even in case of unseen emerging conditions (D_t) in the foreseeable future (at time $t = T + 1$), and can be expressed as (1):

$$\theta^* = \underset{\theta}{\operatorname{argmax}} \, E(RMP|D_t), \quad t = 1, \dots, T + 1 \qquad (1)$$

The frameworks that deal with emerging risk management are very recent or even still in the development and maturation phase and consequently, the number of scientific publications that collect the concepts as “emerging risk” or “emerging risk management” are still scarce regard to “risk” and “risk management”, such as shown in Table 1.

About the specifically frameworks that deal with emerging risk management Brocal et al. (2019a) point out the IRGC (2011, 2015a, 2015b) on management emerging risks linked to technology and industrial processes, the CEN (European Committee for Standardization) workshop agreement (CWA) 16649:2013 on emerging risks related to technology and the ISO 31050 standard - Guidance for managing emerging risks to enhance resilience which currently is under developing (ISO, 2018c).

Taking as reference the IRGC (2011, 2015a), the CWA 16649:2013 and especially the EU-OSHA, Brocal et al. (2017, 2018) have developed a theoretical framework inspired by meta-learning lessons, which allows modelling and qualitatively characterizing the emerging risk. This theoretical framework defines different evolutionary phases of emerging risk that should be managed with appropriate strategies which are not yet defined. For this, the uncertainty needs to be considered as the main characteristic of the emerging risk (IRGC, 2015a).

Table 1. Number of scientific publications on "risk"; "risk management"; "emerging risk"; "emerging risk management" (Results from the Web of Science. Timespan: 2000-2018; All databases; Field tag: Topic).

Year	Risk	Risk management	Emerging risk	Emerging risk management
2018	352.035	8.538	82	0
2017	328.311	8.385	89	2
2016	313.313	7.794	90	0
2015	292.314	7.230	71	0
2014	266.711	6.459	81	2
2013	249.175	6.163	74	5
2012	225.045	5.885	65	2
2011	208.029	6.056	61	0
2010	194.562	6.125	81	1
2009	180.017	5.417	48	0
2008	166.784	4.756	45	0
2007	146.619	3.817	46	0
2006	135.087	3.484	39	0
2005	123.702	2.892	44	0
2004	113.634	2.572	27	1
2003	105.014	2.268	39	0
2002	94.280	2.160	25	0
2001	85.594	1.681	11	0
2000	79.600	1.682	8	1

Thereby, the main objective of this paper is to develop a qualitative approach to the selection of strategies for emerging risk management considering uncertainty as the main decision variable in an industrial context. w

The structure of this paper is as follows: firstly, the uncertainty has been analyzed as the main evolutionary variable of emerging risk over time. For this, uncertainty has been studied as a combination of knowledge and understanding. The result has been applied to the theoretical concept of emerging risk. Secondly, criteria for the selection of strategies for emerging risk management have been defined and analyzed. For this, an emerging risk classification scheme has been developed. This scheme allows estimating the level of emerging risk and management strategies based on the combination of uncertainty and the potential consequences of emerging risk. Thirdly, such criteria for the selection of strategies have been applied to three case studies with different evolutionary degrees of emerging risk. Finally, the results obtained are analyzed and discussed, and a series of conclusions are set forth, along with suggested future research.

2.- Analysis of uncertainty as the main evolutionary variable of emerging risk

The theoretical framework on emerging risk proposed by Brocal et al. (2017, 2018) consider three typologies of emerging risks, namely: new risk (NR), new and increasing risk (NIR) and increasing risk (IR). These authors have associated these three emerging risk typologies with the evolutionary phases of the technology lifecycle (TLC) on the S-curve as shown in Figure 1.

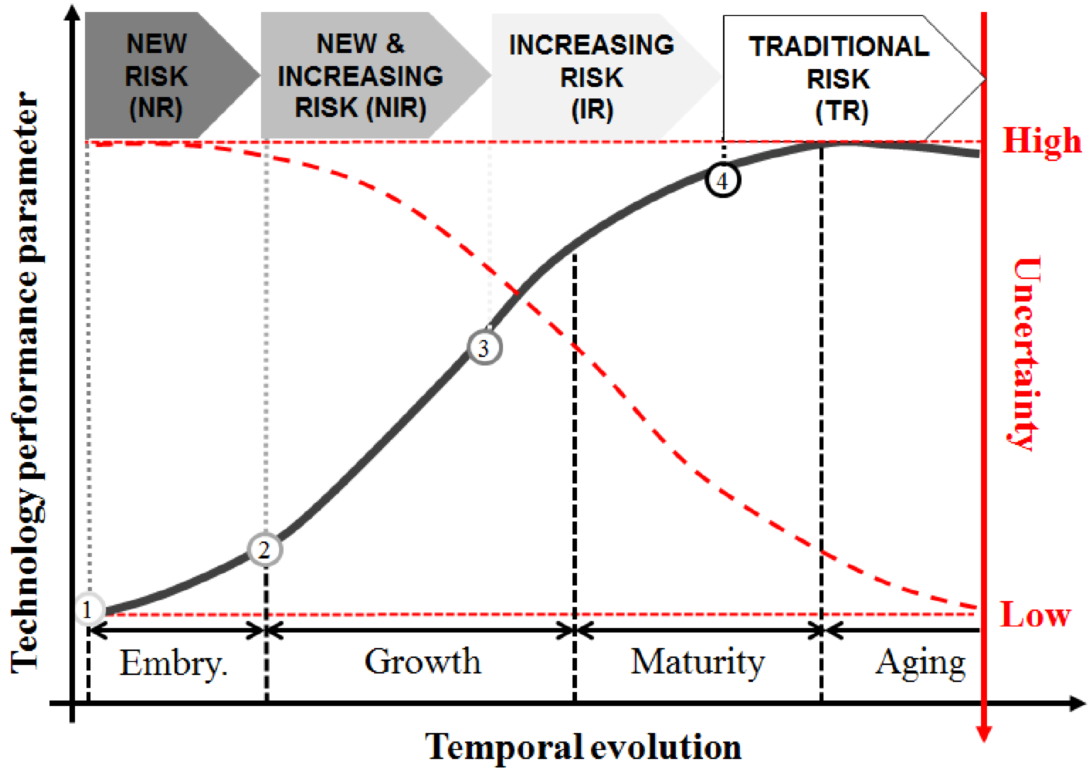

Figure 1 Integration of the evolutionary phases of emerging risk and uncertainty in the Technology performance parameter (adapted from Brocal et al., 2017, 2019a).

With this approach, the evolution of emerging risk over time can be explained through four phases. Initially, the emerging risk is a new risk (NR) during the embryonic phase of the new technology (1-2). Secondly, the NR begins to increase, that is, it is a new and increasing risk (NIR) during a part of the growth phase (2-3). Thirdly, the risk is no longer new to become an increasing risk (IR) (3-4) between the growth and maturity phases (3-4). Finally, during the maturity phase the emerging risk becomes a traditional or familiar risk.

In this process of maturation and extinction of emerging risk, Brocal et al. (2019a) have added the variable uncertainty (in red), considering for it the dynamic framework of risk management developed by Villa et al. (2016) as well as an open qualitative approach based on the point of view of Aven (2010). Thus, the uncertainty evolves inversely regarding the emerging risk. In this way, when the emerging is new (embryonic phase), the uncertainty is maximum, and when the emerging risk is extinguished, that is, a traditional risk, the uncertainty is minimal. This minimum value should be considered a "relative minimum" with respect to traditional risk. In other words, this minimum value would not be necessarily low from the perspective of a traditional risk.

2.1.- The uncertainty as the combination of knowledge and understanding

Montewka et al. (2014) consider that there is a conditional dependence between risk and the combination of knowledge (K) and understanding (N) of system behavior. These authors express this conditional relationship as (2):

$$R \sim \{A, C, Q\} | \Delta \quad (2)$$

Through this equation the risk is described by the triplet formed by the events (A), the consequences (C), the uncertainty (Q) and the conditional dependence upon the construct Δ which represents set comprising the K dimension and the N dimension (Δ ~{K,N}).

Montewka et al. (2014) propose to evaluate the degree of risk uncertainty (of each of the elements of a system and its interrelationships) through a qualitative model based on a matrix that combines the evidence of the variables K and N as shown in the Table 2. Such authors consider that in the qualitative evaluation of Q, K represents the data, models and theories, and N represents assumptions, judgments and the ability to assess the level of K about the element. That is, K is factual and N is not necessarily factual and (unlike K) is gradual.

Table 2. Degree of uncertainty (Q) (Montewka et al., 2014)

	Knowledge (K)		
	High	Medium	Low
Understanding (N)			
High	L	L	M
Medium	L	M	M
Low	H	H	H

The result of the degree of Q can be classified as high, medium or low. To obtain the result, the classifiers for quality of K and level of N shown in Table 3 will be used (low, medium, and high).

Table 3. Classifiers for Quality of knowledge (K) and Level of understanding (N) (adapted from Montewka et al., 2014)

	Quality of knowledge (K)	**Level of understanding (N)**
High	• Data is reliable and/or • Engineering model is accurate and/or • Scientific theory is broadly accepted	• Assumption is broadly accepted among peers and/or • Judgment is broadly accepted among peers and/or • Assessor can well justify the ranking of K
Medium	Conditions between those characterizing K/N as High and Low	
Low	• Data is unreliable • Engineering model is a crude estimate • Scientific theory is contested	• Assumption is contested among peers • Judgment is contested among peers • Assessor cannot properly justify the ranking of K

The variables K and N can be incorporated as two new axes to Figure 2, with the objective of comparing the evolution of the degree of Q proposed by Montewka et al., (2014) with respect to the evolution of the Q proposed by Brocal et al. (2019a). This comparison has been made as follows. Firstly, the uncertainty curve and the K-N axes have been divided into approximately three equal parts in order to graduate them to low, medium and high. Secondly, the approximate center point of each section of the uncertainty curve has been indicated with a circle (red [high], orange [medium], green [low]), which represents a coordinate with respect to K and N with the results shown in Table 4.

Table 4. Result of the incorporation of the K and N axes on the uncertainty curve.

Uncertainty curve sections	**Knowledge (K)**	**Understanding (N)**	**Uncertainty (Q)**	**Phases**
High (Red)	Low	Low	High	Embryonic/Growth
Medium (Orange)	Medium	Medium	Medium	Growth/Maturity
Low (Green)	High	High	Low	Maturity/Aging

With these results can be observed that the use of the K and N graduation can be a good qualitative approach to determine the degree of Q of the emerging risk based on its evolutionary phases.

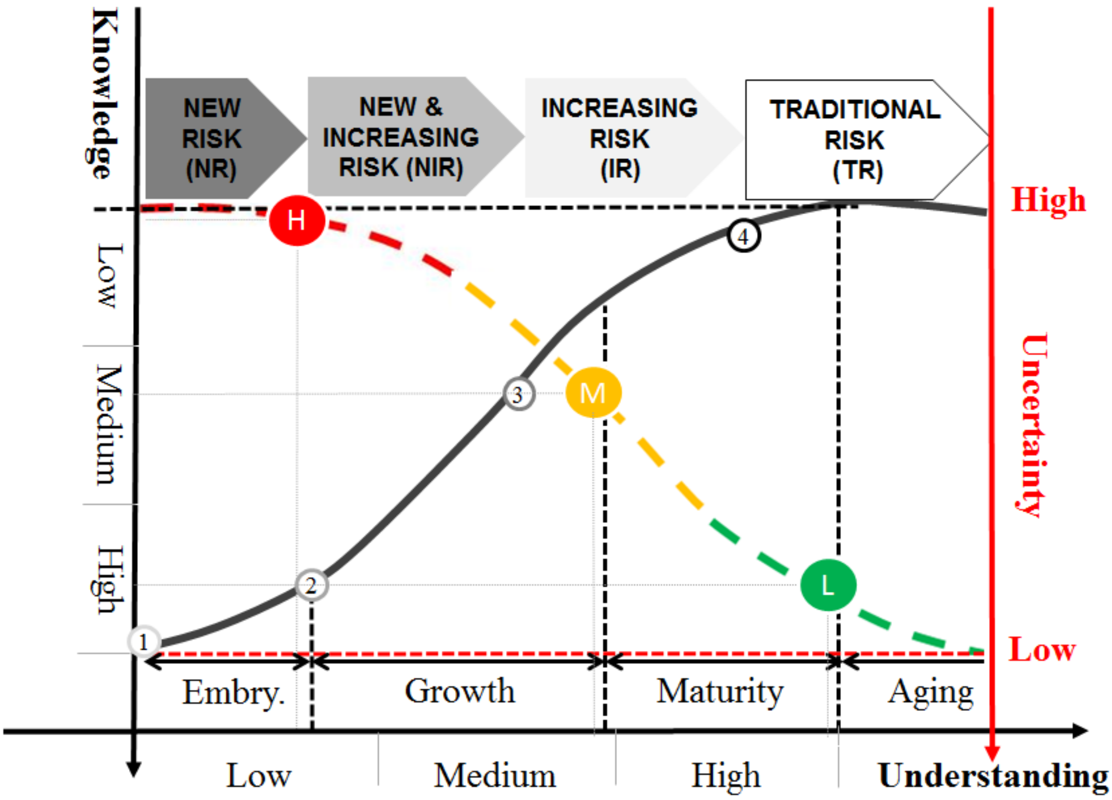

Figure 2 Incorporation of the knowledge (K) and understand (N) axes in the evolutionary phases of emerging risk and uncertainty curves (adapted from Brocal et al., 2017, 2019a, 2019b).

2.2. Degree of uncertainty of the conditions that define an emerging risk

A general estimate of the degree Q of each of the conditions (Ci) that defines an emerging risk is shown in the Table 5. For this, each Ci has been analyzed based on the classifiers for K and N described in Table 3. The results of this analysis are described below.

C1 and C2 - New technological or organizational variable and New social perception: With respect to K: the level of K cannot be considered high due to under these novel conditions it is not plausible that reliable data exists in the context of risk. Regarding the availability of an engineering model is accurate and / or scientific theory broadly accepted, it will depend on each specific case (specific risk). With respect to N: once the risk is considered new, it can be understood that some of the classifiers of the high level of N will be true. The three classifiers in a new situation will hardly be true all at the same time.

C3 - New scientific knowledge: With respect to K: the level of K can be considered medium since, at least, there will be a new widely accepted theory. With respect to N: as in the previous case, once the risk is considered new, it can be understood that some of the classifiers of the high level of N will be true. The three classifiers in a new situation will hardly be true at the same time.

C4, C5 and C6 - Increase in: the number of sources of risk, likelihood of exposure and health consequences: With respect to K: The level of K can be considered medium or high since under these conditions there should be reliable data to determine that the corresponding indicators are increasing. Regarding whether the availability of an engineering model is accurate and/or the scientific theory is broadly accepted, it will depend on the specificity of the case. With respect to N: Once the risk is considered as increasing, it can be understood that one or more of the classifiers of the high level of N will be true.

Table 5. Degree of uncertainty (Q) of the conditions (Ci) that define an emerging risk

Conditions (Ci)		**Knowledge (K)**	**Understanding (N)**	**Uncertainty (Q)**
By «new» we mean that:				
C1	The risk did not previously exist and is caused by new processes, new technologies, new types of workplace, or social or organisational change; or,	L/M	L/M	H/M
C2	A long-standing issue is considered as a new risk due to a change in social or public perceptions; or,	L/M	L/M	H/M
C3	New scientific knowledge allows a long-standing issue to be identified as a risk	M	L/M	H/M
The risk is «increasing» if the:				
C4	Number of hazards leading to the risk is growing; or	M/H	M/H	M/L
C5	The exposure to the hazard leading to the risk is increasing (exposure level and/or the number of people exposed); or	M/H	M/H	M/L
C6	The effect of the hazard on workers' health is getting worse (seriousness of health effects and/or the number of people affected).	M/H	M/H	M/L

3.- Selection emerging risk management strategies

Kristensen et al. (2006) have proposed an alternative qualitative approach regarding the approach for risk evaluation and selection of risk management strategies proposed by Klinke and Renn (2002). For this Kristensen et al. (2006) propose the so-called Predictive, Bayesian Risk Classification (PBRC) scheme, which is formed by nine characteristics, being: Potential consequences, Uncertainty, Ubiquity, Persistency, delay effect, Reversibility, Violation of equity, Potential of mobilization and The difficulty in establishing appropriate performance measures. In this scheme the two main characteristics are potential consequences and uncertainty about consequences, while the other seven characteristics are used to describe aspects of these two characteristics and/or aspects of the system, event or quantity of interest.

For that, Kristensen et al. (2006) have chosen seven categories or types of risk (Ri) based on two main characteristics (potential consequences and uncertainty about consequences). These seven types are shown in the Table 6 and are arranged following a tendency of the Ri. In addition, each type is associated with one or more risk management strategies (RMSi). Such authors define a RMS as a specific set of procedures, rules and regulations that describe how one should manage the risk related to a System.

Table 6. Risk context classification scheme (adapted from Kristensen et al., 2006).

	Category		
Type of Risk (Ri)	**Potential consequences (C)**	**Uncertainty of Consequences (Q)**	**Level of risk**
1	Low	L/M/H	Low
2	Medium	Low	
3	Medium	Medium	
4	Medium	High	⇓
5	High	Low	
6	High	Medium	
7	High	High	High

3.1.- Emerging Risk context classification scheme

The approach of Kristensen et al. (2006) has been adapted to the characteristics of the emerging risks defined in this paper. The result of this adaptation is shown in Table 7. For this purpose, 6 types of emerging risks (ERi) have been considered, following a tendency of the level of emerging risk.

Each ERi type is defined by the combination of Ci, C and Q. The types that determine a NR are associated with the conditions C1, C2 and/or C3; and the three types that determine an IR are associated with the conditions C4, C5 and/or C6. The categories of consequences (C) are defined in Table 8.

To this end, the criteria “high consequences” and “low consequences” of Kristensen et al. (2006) and WBGU (2000) have been used, respectively. Likewise, for the medium category, a criterion equivalent to that adopted for the Q has been used in order to maintain a homogeneous structure between the criteria of Table 3 and Table 8. The Q corresponds to that obtained in Table 5, that is, the value of Q is the result of the combination between K and N values (categories).

Table 7. Emerging Risk context classification scheme

Type of emerging risk (ERi)		Category: Potential consequences (C)		Uncertainty of Consequences (Q)	Level of emerging risk
New risk (NR)	ER1	C1/C2/C3	High	M/H	High
	ER2	C1/C2/C3	Medium	M/H	
	ER3	C1/C2/C3	Low	M/H	⇓
Increasing risk (IR)	ER4	C4/C5/C6	High	L/M	
	ER5	C4/C5/C6	Medium	L/M	
	ER6	C4/C5/C6	Low	L/M	Low

Table 8. Categories for Potential Consequences (adapted from Kristensen et al., 2006; WBGU, 2000)

	Potential Consequences
High	• Losses and damages are difficult to bound, and • High scores are given to one or more of the characteristics: reversibility, persistency, ubiquity and delay effects
Medium	Conditions between those characterizing as High and Low
Low	• Small catastrophic potential • Low levels of persistency and ubiquity (scope in time and space) • High reversibility of potential damage, and • Low potential for social conflict and mobilization

Regarding the tendency of the level of emerging risk, it is inverse with respect to the level of risk shown in Table 6. At the beginning, the level of emerging risk is maximum when it arises as a NR. This level is reduced when it evolves towards an IR. This level is minimal before disappearing as an emerging risk and becoming a traditional risk. This evolution of Q and the phases of emerging risk are consistent with those shown in Figure 1 and Figure 2.

Like the classification scheme proposed by Kristensen et al. (2006), the intention of the emerging risk classification scheme presented in Table 7 is to make a basis for characterisation, discussion and management of the emerging risk. Consequently this new scheme should be considered as a starting point for further handling of emerging risk, and not as a technique that provides decisions of its own, as well as that it is not a management system.

3.2.- Selection criteria

Kristensen et al. (2006) establish three RMSi, the risk-based approach (RMS-1), the precautionary approach (RMS-2) and the discursive approach (RMS-3). These RMSi are briefly described in The ERi types can be associated with RMSi and examples described by Kristensen et al. (2006) following the following procedure, whose results are shown in Table 10: firstly, each ERi type (Table 7) has been associated with the Ri type (Table 6) of the same combination between the C and Q variables. For example, ER2 type is categorized with medium C and medium / high Q. This combination (medium [C]) -medium / high [Q]) corresponds to the combinations corresponding to R3 type (medium [C]) - medium [Q]) and R4 type (medium [C]) - high [Q]). Secondly, each ERi has been associated with the RMSi associated with each Ri according to Table 9. For example, R3 and R4 are associated with RMS-3 and RMS-1, respectively. Consequently, these two RMS are associated with ER2.

Table 9, where they are associated with the Ri (Table 5) and examples considered by Kristensen et al. (2006).

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Table 9. RMSi and categories according risk context classification scheme (adapted from Kristensen et al., 2006; WBGU, 2000)

Risk management strategies	**Short Description**	**Type of risk (Ri) and examples***
RMS-1: Risk-based approach (or policy)	Treatment of risk in form of avoidance, reduction, transfer and retention.	4: A process plant based on a new type of technology 5: Smoking 6: Nuclear energy
RMS-2: Precautionary approach	A policy of containment, constant monitoring, continuous research and the development of substitutes.	2: Anthropogenic effect of climate change and the loss of biological diversity 6: Nuclear energy 7: Greenhouse effect, human intervention in ecosystems
RMS-3: Discursive approach	Measures to build confidence and trustworthiness, through reduction of uncertainties, clarification of facts, involvements of affected people, deliberation and accountability.	3: Many technological risks belong to this category, such as chemical process facilities 6: Nuclear energy * category 1 is not linked to any formal RMSi

Table 10. Correspondence between type of Emerging Risk (ERi), Type of Risk (Ri) and RMSi

Type of Emerging Risk (ERi)		**Type of Risk (Ri)**	**RMSi**
New risk (NR)	ER1	6/7	RMS-2
	ER2	3/4	RMS-3 /RMS-1
	ER3	1	---
Increasing risk (IR)	ER4	5/6	RMS-1 / RMS-2
	ER5	2/3	RMS-2 / RMS-3
	ER6	1	---

The results shown in Table 10 can be analyzed in order to determine the coherence between each ERi type and the assigned RMSi. For this, the Ci linked to each ERi has been compared with the characteristics of the assigned RMSi. In this regard, as shown in Table 7, it is important to consider that the three conditions C1, C2 and C3 are applicable to ER1, ER2 and ER3. Equivalently, the three conditions C4, C5 and C6 are applicable to ER4, ER5 and ER6. Thus, the result of such analysis is described below.

- ER1: the characteristics of R6 cannot be linked to any Ci, since for example the nuclear energy is a risk that can be considered traditional. About it, the risk of nuclear accidents tends to diminish as safer nuclear technologies are being promoted (Prăvălie and Bandoc, 2018). However, other related risk factors could give other results, such as waste production. As for R7, it could be linked to both C1-C3 and C4-C6 given its new and increasing characteristics. About it, the extensive global use of fossil fuels to generate energy has led to an increase in greenhouse gas emissions and, consequently, to dramatic climate change (Pescador et al., 2019), which has become the most important human challenge in the last century (Siabi et al., 2019). Whilst data from 2014 to 2017 suggested global annual emissions of CO2 had approximately stabilized (CO2 is not the only greenhouse gas of concern for global warming and climatic change), the most recent (preliminary) data from the Global Carbon Project reported a 2.7 percent increase in 2018 (Ritchie and Roser, 2019). However, the detailed analysis of this R7 type (greenhouse effect,) is very far from the objectives of this work.
- ER2: the new and technological characteristics of R3 and R4 can be considered directly compatible with the conditions that define a NR, especially with C1.
- ER3: this type is not linked to any formal RMSi.
- ER4: the characteristics of R5 and R6 cannot be linked to any Ci, since for example tobacco and nuclear energy are risks that can be considered traditional.
- ER5: the new and technological characteristics of R2 and R3 can be considered compatible with both the conditions that define a NIR. The R2 is closely related to the R7 discussed above. The case study on nanomaterials described below can be used as an example of the R7.
- ER6: this type is not linked to any formal RMSi.

The previous results can be summarized:

- ER1 and ER2 types linked to the new conditions are compatible with all three RMSi. The ER3 type is not linked to any formal system.
- ER4, ER5 and ER6 types linked to increasing conditions are compatible with RMS 2 and RMS 3. RMS 1 is not compatible under these conditions, which is consistent considering the examples shown in Table 10, that is, this RMS 1 is only compatible with the types of ER linked to the new conditions.

4.- Study cases

Three case studies by way of examples for each typology of emerging risk (NR, NIR and IR) are shown below. Firstly, exoskeletons are studied as an emerging risk that is new (NR), secondly nanomaterials as an emerging risk that is both new and increasing (NIR), and thirdly, industrial automation as an increasing risk (IR). To this end, the emerging risks have been analyzed according the emerging risk classification scheme and the criteria for the selection of RMSi. Thus, the variables that have been analyzed are: Knowledge (K), Understanding (N), Uncertainty (Q) and Consequences (C). The Table 11 shows a summary of the main results for each case study.

Table 11. Summary of the main results for the cases studies.

Study cases	Ci	C	K	U	Q	ERi	RMSi	Observations
(1) Exoskeletons as	C1	H	L	L	H	ER1	RMS 2 RMS 3	RMS 1 does not apply to this case

new risk (NR)								study due to its characteristics.
(2) Nanomaterials as new and increasing risk (NIR)	C1	H	M	L/M	H/M	ER1	RMS 1 RMS 2 RMS 3	This case is especially compatible with the RMS 2.
	C4 C5 C6	H	M	L/M	M	ER4		
(3) Industrial automation as an increasing risk (IR)	C5	H	M/H	M	L/M	ER5	RMS 2 RMS 3	---

The number of papers included in WOS between the years 2000-2018 on the subject related to each case study has been considered as the main indicator of the evolution of the emerging risk. In all three cases, the effects on safety and health have been considered as the main consequence.

4.1.- Study case 1: exoskeletons as new risk

With the aim of reducing the risks of the lower back disorders (LBD) a new technology called "exoskeletons" (Bosch et al., 2016; Koopman, et al., 2019) is continuously being introduced into occupational environments (Picchiotti et al. , 2019).

The Figure 3 shows the evolution of the number of papers included in WOS between 2000-2018 in the field of exoskeletons, safety, industry and risk. In this figure, it is observed that at approximately from 2012 begins increase the number of papers to about 50 today, well below the 1800 results in the case of performing only search for the term "exoskeleton".

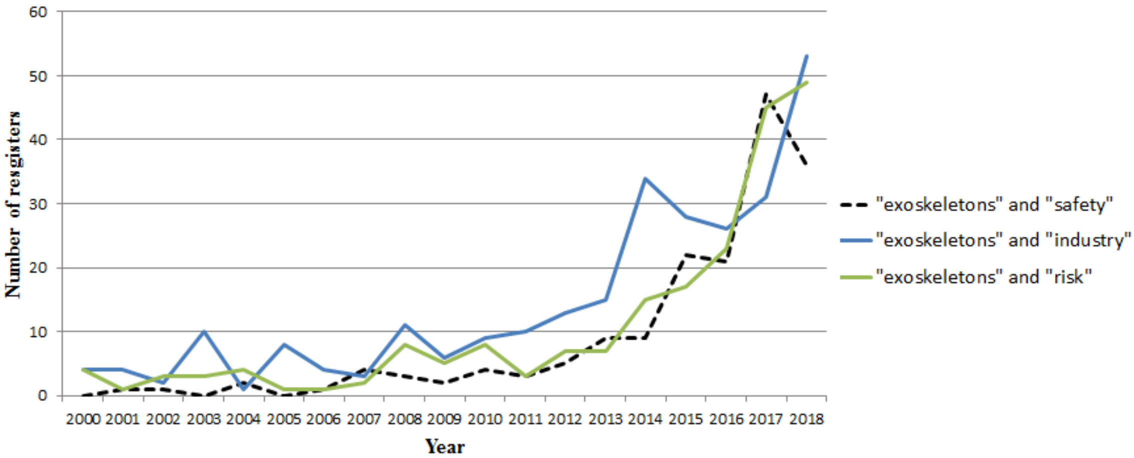

Figure 3. Number of scientific publications on "exoskeletons" and "safety"; "exoskeletons" and "industry"; "exoskeletons" and "risk" (Results from the Web of Science. Timespan: 2000-2018; All databases; Field tag: Topic).

Industrial exoskeletons are not yet fully understood and they are an emerging topic in legislation and standardization that can generate NRs because of unforeseen or unknown user behavior or because of exoskeleton performance (van der Vorm et al., 2015). In particular, long-term effects of exoskeletons on physiological, psychosocial and biomechanical parameters are unknown (Peters and Wischniewski, 2019) and there remains a void in the scientific literature relative to the effectiveness of exoskeletons intended to provide postural guidance in reducing low back injury risk (Picchiotti et al., 2019). For example, several industries including shipbuilding and aerospace manufacturing have already implemented exoskeletal interventions, though it remains unclear if these interventions simply sacrifice risk elsewhere, such as the low back (Weston et al., 2018).

Industrial exoskeleton is a clear example of an emerging risk that is new. Firstly, the technology is new, which complies with C1, and although the risk seems to be increasing (C4), it is too early to state that the risk is in a clear increase. Regarding the criteria shown in Table 3, both the level of K and level of N can be considered as low, which configure a high degree of Q.

Regarding the potential consequences could be high, because the losses and damages are currently difficult to bound. In addition, these consequences have potential characteristics related specially to ubiquity (geographical dispersion of potential damage) and delay effects (the time of latency of physical nature between the initial event and the actual impact of damage).

Consequently, considering the qualitative results of the Q (high) and the consequences (high), the level of emerging risk, in this case, is high.

Thus, this emerging risk can be considered an ER1, so the three RMSi could be theoretically compatible with that risk. However, this risk has the special feature that it is a new technology which that aims to reduce risks of an ergonomic nature, that is, the implementation of this technology in the workplace could be considered as a risk treatment according to RMS 1.

Therefore, the management strategy of this emerging risk should be different from RMS 1, at least in this initial phase of the risk. Thus, the application of RMS 2 and RMS 3 strategies would be more appropriate, particularly considering the mechanisms of constant monitoring, and continuous research, as well as measures to build confidence and trustworthiness.

4.2.- Study case 2: nanomaterials as new and increasing risk

Environmental, health and safety aspects of nanotechnology applications and nanomaterials have been debated in the scientific and regulatory communities since the early 2000 (Paula et al., 2018). In 2009 the experts agreed that nanoparticles and ultrafine particles pose the strongest emerging risk (Brun et al., 2009). Growing production and use of nanomaterials result in an increasing number of workers and consumers exposed to nanomaterials (Kaluza et al., 2009).

The Figure 4 shows the evolution of the number of papers included in WOS between 2000-2018 in the field of nanomaterials, safety, industry and risk. In this figure it can be seen that at approximately the beginning of the century the number of papers begins to increase to approximately 400-800 today.

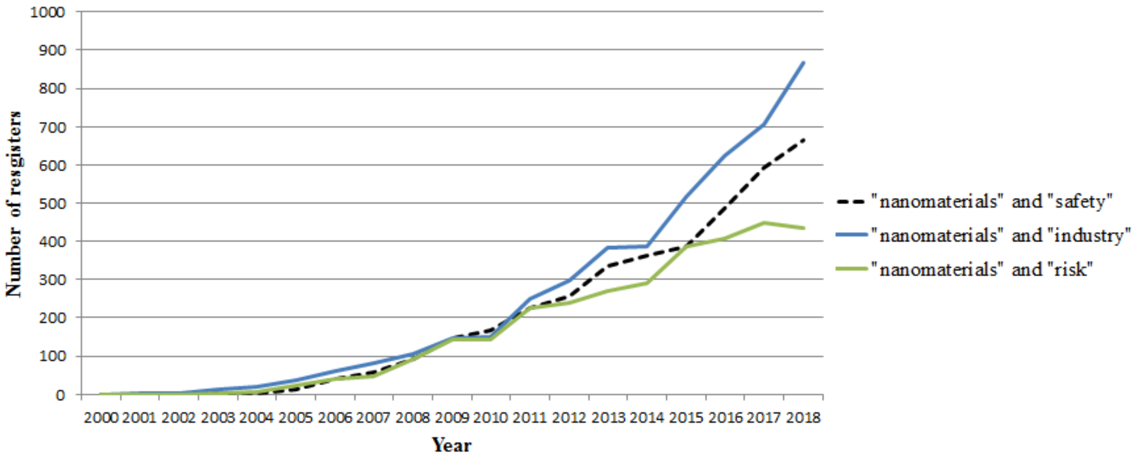

Figure 4. Number of scientific publications on “nanomaterials” and “safety”; “nanomaterials” and “industry”; “nanomaterials” and “risk” (Results from the Web of Science. Timespan: 2000-2018; All databases; Field tag: Topic).

There is considerable scientific uncertainty involved in evaluating the risks of handling engineered nanoparticles in the workplace accentuated by the constantly increasing variety of novel nanomaterials requiring assessment (Paula et al., 2018) and the great diversity of toxic potential among the nanomaterials (Schulte et al., 2019), as the actual health risks of these products remain largely unknown (Vance et al., 2019).

Such context of uncertainty is linked to reduced level of N relate with almost every aspect of nanotechnology, such as definition, characterisation, toxicity and exposure levels (Gibson et al., 2012), gaps in methodology and data availability (Paula et al., 2019), a lack of clarity on appropriate early indicators of adverse health effects (Schulte et al., 2019), and lack of global standardized methods and metrics for nanomaterial characterization and labeling in consumer products (Vance et al., 2015).

Schulte et al. (2019) have made a systematic review on current state of knowledge on the health effects of engineered nanomaterials in workers, and they have concluded that there is a state of uncertainty about it. Such authors consider that understanding the effects of nanomaterials in exposed subjects is a priority and although the number of currently available studies in occupational and epidemiological fields is quite limited, preliminary considerations regarding the possible health impact of nanomaterials and biomarkers of effect can lead future investigations.

On the other hand, Paula et al. (2018) have presented an inventory of ready-to-use and publicly available tools for the safety assessment of nanomaterials named ‘NANoREG Toolbox’, which covers a broad range of over 500 current tools, developed in Europe and beyond.

Nanomaterials are a clear example of an emerging risk that is new and increasing. Firstly, the technology is new, which meets C1. Secondly, the factors associated with conditions C4, C5 and C6 are also increasing.

Regarding the criteria shown in Table 3, K can be considered as medium and level of N can be considered as low/medium, which configure a degree of Q as medium/high. In this case, the result of K is clearer than N. In any case, this degree of Q is a global estimate of the health effects of nanomaterials, so an evaluation of specific nanomaterials could give different results.

Regarding the potential consequences could be high, because the losses and damages are currently difficult to bound (both occupational and environmental level). In addition, these consequences have potential characteristics related to reversibility (the possibility to restore the situation to the state before damage occurred would be difficult but impossible), ubiquity (geographical dispersion of potential damage), persistence (temporal extension of the potential damages) and delay effects (the time of latency of chemical nature between the initial event and the actual impact of damage).

Consequently, considering the qualitative results of the Q (medium/high) and the consequences (high), the level of emerging risk, in this case, is high/medium.

Thus, this risk can be considered a combination of ER1 and ER 4, so that the three RMS could be theoretically compatible. The combination of the three strategies is clearly compatible with this emerging risk. For example all three strategies are compatible with the Directive 98/24/EC on risks related to chemical agents at work and the directive 2004/37/EC on carcinogens or mutagens at work. In any case, in this state of uncertainty a precautionary approach is particularly applicable (Gibson et al., 2012; Schulte el al., 2019).

4.3.- Study case 3: industrial automation as an increasing risk

Industrial automation integrates processes, machinery, electronics, software and information systems with the objectives of greater production, better quality, lower costs and maximum flexibility (Mehta and Jaganmohan, 2014).

In 2005 the EU-OSHA identified emerging risks related to automation (Flaspöler et al., 2005). The Figure 5 shows the evolution of the number of papers included in WOS between 2000-2018 in the field of automation, safety, industry and risk. In this figure can be seen that in 2005 the number of results is similar to 2018 in the case of nanoparticles, and it is much higher compared to exoskeletons. The evolution of the number of papers until 2018 is clearly increasing, although unlike the previous cases, there is a broader historical data.

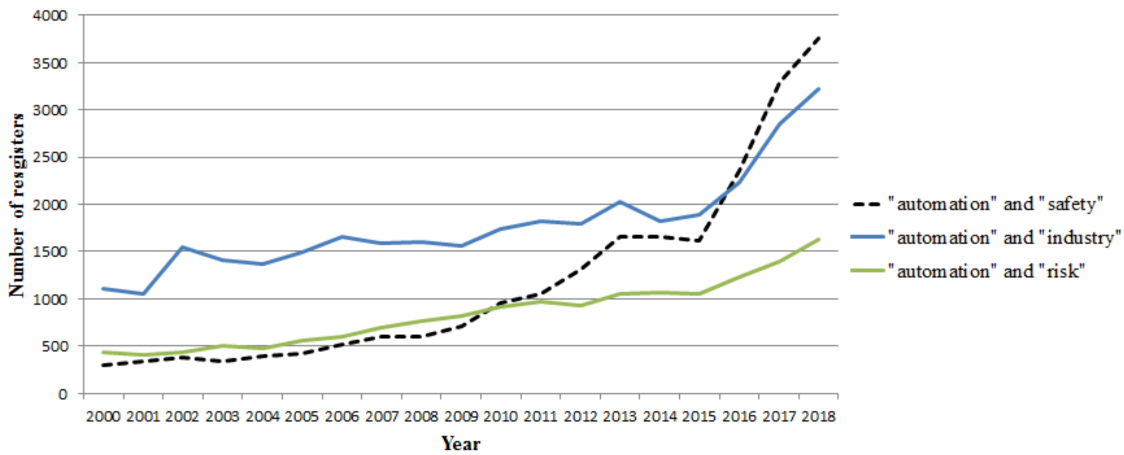

Figure 5. Number of scientific publications on "automation" and "safety"; "automation" and "industry"; "automation" and "risk" (Results from the Web of Science. Timespan: 2000-2018; All databases; Field tag: Topic).

The increase in automation implies an increased risk of accidents from human errors, (Flaspöler et al., 2010) due to a lack of sufficient understanding of the underlying process (Stacey et al., 2017), as well as complacency and over-reliance are often reflected in insufficient monitoring and checking of automated functions and decisions (Chidambaram, 2016). Regarding this complacency can be assumed that this issue is a widespread problem involving the understanding and control of risks (Årstad and Aven, 2017). The process error management in the context of human-automation interaction is not well understood (McBride et al., 2014).

Much research has been carried out in human factors, such as task complexity and ergonomics, and yet the influence of variability on the automatability and complexity of a process is still poorly understood (Goh et al., 2019). Future research should emphasize understanding how to improve human–automation system integration (Marquez and Gore, 2017).

Brocal et al. (2018) determined through the TICHNER technique that the automation of manufacturing processes is an increasing risk due mainly to its relationship with C5.

In relation to the criteria shown in Table 3, K can be considered as medium/high and the N can be considered as medium, which configure a degree of Q as low/medium. In this case, the result of K is also clearer than N. In any case, this degree of Q is a global estimate of the safety and health effects of accidents from human errors in the context of human-automation interaction, so an evaluation of specific automation process could give different results.

Regarding the potential consequences could be high, because the consequences of automation error can thus be severe, and may be irreversible (Wickens and Hollands, 2000). Thus, the losses and damages are difficult to bound, especially as consequence of the accidents from human errors in the case of high-risk industries have the potential for serious consequences beyond the operator to include fellow workers, the community at large and the environment (Flaspöler et al., 2010). In addition, these consequences have potential characteristics - especially when they are linked to chemicals - related to reversibility (the possibility to restore the situation to the state before damage occurred), ubiquity (geographical dispersion of potential damage) and persistence (temporal extension of the potential damages).

Consequently, considering the qualitative results of the Q (low/medium) and the consequences (high), the level of emerging risk, in this case, is low/medium.

In this way, this risk can be considered an ER5 compatible mainly with RMS 2 and RMS 3. The combination of the two strategies is compatible with this emerging risk. The RMS 2 implies continuous research, which is aligned with Marquez and Brian (2017). The RMS 3 implies measures to reduction of uncertainties in many technological risks, as is the case with industrial automation.

5.- Discussion

The main objective of this paper has been to develop a qualitative approach to the selection of strategies for emerging risk management considering the uncertainty as the main characteristic regarding the consequences. The approach is inspired by meta-learning concepts.

The structure of the said approach is configured by two blocks. With the first block the uncertainty model proposed by Montewka et al. (2014) has been integrated in the selection of risk management strategies model proposed by Kristensen et al. (2006). The second block is the result of integrating the first block with the theoretical framework on emerging risk proposed by Brocal et al. (2017, 2018).

The result of the first block can be applied to any risk. However, this result does not allow differentiating between a traditional risk and an emerging risk. For this, the second block has been developed, whose results configure an approach that qualitatively estimates two sequential and interrelated aspects: (1) the type and level of emerging risk through the emerging risk classification scheme; (2) the selection of strategies for emerging risk management through the criteria established. Both aspects are discussed below.

5.1.- Type and level of emerging risk

The determination of the type and level of emerging risk can be considered a qualitative tool for characterization (a qualitative picture of the risk [SRA, 2018]) and graduation of emerging risk, respectively. The results obtained can be used essentially in two directions that can be complementary to each other. The first direction as a previous stage of the risk assessment process, that is, as a risk framing or pre-assessment (the initial assessment of a risk problem [SRA, 2018]). And the second as the basis for the emerging risk communication through the characteristics that confer the emerging qualities, that is, through emerging risk characterization.

The degrees of Q linked to the type of emerging risk (ERi) have been limited according to the evolutionary phase considered. For new ERi and increasing ERi, the “low” and “high” values have been limited, respectively. These limitations are consistent with the results obtained with the incorporation of the K and N axes in the evolutionary phases of emerging risk and uncertainty curves. They are also consistent with the results obtained with the case studies.

Thus, the medium degree of Q defines the boundary between NR and IR. In other words, the Q could be high when risk is new (NR) or when it is new and increasing (NIR), but not when it is only increasing (IR). This criterion is not necessarily valid in a different context from the one studied in this work, that is, any risk with a qualitatively high Q must not necessarily have any novel and/or increase feature.

In any case, this approach is based on evolutionary models and typologies of emerging risk linked to the TLC on the S-curve as proposed by Brocal et al. (2017, 2018). However, there could be other curves with different behaviors. These curves could be linked to technological or other factors, such as epidemiological ones. These variations could give rise to other behaviors of Q that have not been analyzed in the present work. The terms linked to the emerging risk typologies (NR, NIR and IR) have also not been analyzed in order not to modify the original names. However, these terms could improve, considering, for example, aspects related to risk awareness. These considerations undoubtedly also point to future research.

5.2.- Selection of strategies for emerging risk management

The final application of the two blocks described above configures the qualitative approach for the selection of strategies for emerging risk management. With this approach has been established a correspondence between the ERi and RMSi. This correspondence is consistent with the results obtained with the study cases. In this study cases, the results of the WOS have been used as indicators. As a complement or alternative, other indicators related to Ci, C and Q could be used. The criteria for selection of indicators should be that which will facilitate the evolutionary analysis of the emerging risk.

In any case, the flexibility for the selection of these criteria can be considered a limitation of this approach, since with different indicators different results could be obtained. These results may be complementary. However, this hypothesis should be studied through actual formalization based on meta-learning theory, while encompassing the recent research grounded in resilience management and normal work operations (Patriarca et al. 2019).

Nevertheless, this approach is only an indicative starting point for the selection of risk management strategies with three main characteristics to consider. Firstly, the proposed approach and its application in the three case studies are theoretical. Secondly, the selection and development of one or more strategies should only be understood as a risk management approach that in turn must be properly integrated into a risk management system such as those cited in the introduction section. Thirdly, the analysis of other emerging risks under specific circumstances could give other consistent results in relation to the type of RMSi. This circumstance is due to the fact that this approach should be understood as a process aimed at the selection of the priority strategy instead of the appropriate one.

Regarding the third consideration above, it should be taken into account that the process of characterization and graduation of emerging risk can be approached from different scenarios. As a proposal, each scenario could be configured by the combination of the dimension and context of the risk.

The risk dimension could be considered general when it includes all its known variants. For example, the risk dimension associated with nanomaterials could be general, and the risk dimension associated with multi-walled carbon nanotubes could be specific. The context dimension could be general when the risk may exist in one or more industrial sectors, or in one or more geographic areas, etc. And the context dimension could be specific when the risk exists in a specific industrial process. Endonde por ejemplo, las medidas preventivas existentes serína univariable determinante

In this way, four types of possible scenarios could be defined: (1) General - General (e.g. nanomaterials - industrial processes); (2) General - Specific (e.g. nanomaterials - manufacturing processes for automotive components); (3) Specific - General: Multi-walled carbon nanotubes - industrial processes); (4) Specific - Specific (e.g. Multi-walled carbon nanotubes - manufacturing processes for automotive components). In the scenarios with some specific risk dimension, the possible existing reduction measures could condition the results obtained, especially regarding to the consequences variable (C).

The three case studies presented with this work would be examples of the General-General scenario. The types of scenarios proposed are only a proposal that could help through future work to improve the process of the emerging risk analysis (risk assessment, risk characterization, risk communication, risk management, and policy relating to risk [SRA, 2018]).

6.- Conclusions

The qualitative approach proposed in this work allows using uncertainty as the main decision variable on the level of emerging risk. With this approach it has been observed how the level of uncertainty evolves inversely over time regarding to the evolution of the levels of knowledge and understanding of emerging risk. This behavior combined with the potential consequences of risk allows that the level of emerging risk can be graded according to its evolutionary phases. Such dynamic link between uncertainty and novelty could be the subject of future research through dynamic and machine learning approaches such as that proposed by Paltrinieri et al. (2014, 2019), with which new risk notions and early warnings are monitoring and to systematically update the related emerging risk issues.

The graduation of the emerging risk level allows that one or more of the management strategies considered can be selected. The process of characterization and graduation of emerging risk can be approached from different scenarios. As a proposal, each scenario could be configured by the combination of the dimension and context of the risk. In this way, four types of possible scenarios have been defined.

The selection of management strategies should be understood as a proposal to prioritize the management approach while reaching the best expected risk management performance even in case of unseen emerging conditions. In any case, this result must be properly integrated into a risk management system in order to design a complete risk management. This integration should consider uncertainty as the main emerging risk management variable.

As a final conclusion, the proposed approach could be considered primarily as a qualitative tool applicable to the process of pre-assessment and communication of emerging risk. Hence this new approach should be considered as a starting point for further handling of emerging risk, and not as a technique that provides decisions of its own. Consequently future research is recommended in order to continue studying the proposed approach.

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8.-Appendix

Abbreviations	**Description**
C	Consequences
Ci	Conditions
ERi	Emerging risk type
IR	Increasing risk
K	Knowledge
N	Understanding
NIR	New and increasing risk
NR	New risk
Q	Uncertainty

Ri	Risk type
RMSi	Risk management system

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Figure 4

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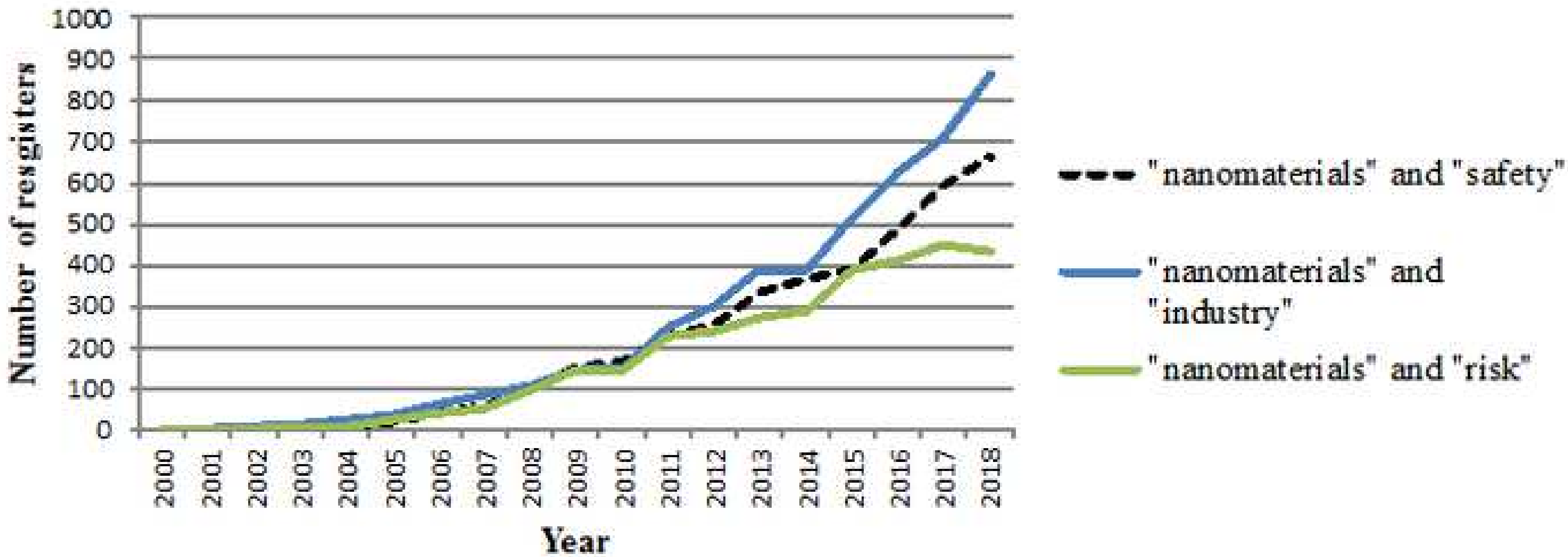

Figure 1

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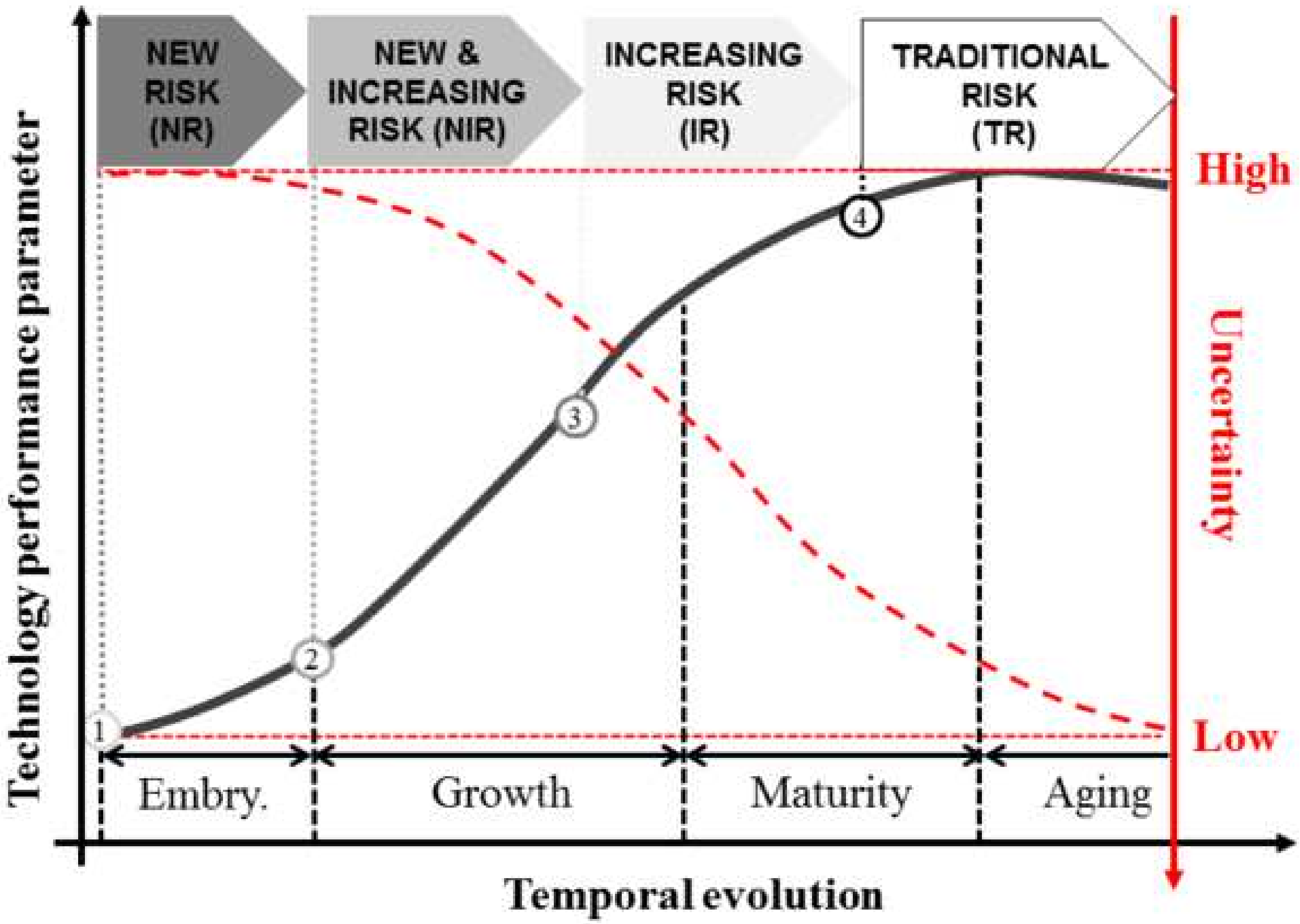


Figure 2

Click here to access/download;Figure;6_2_Figure _2.tif

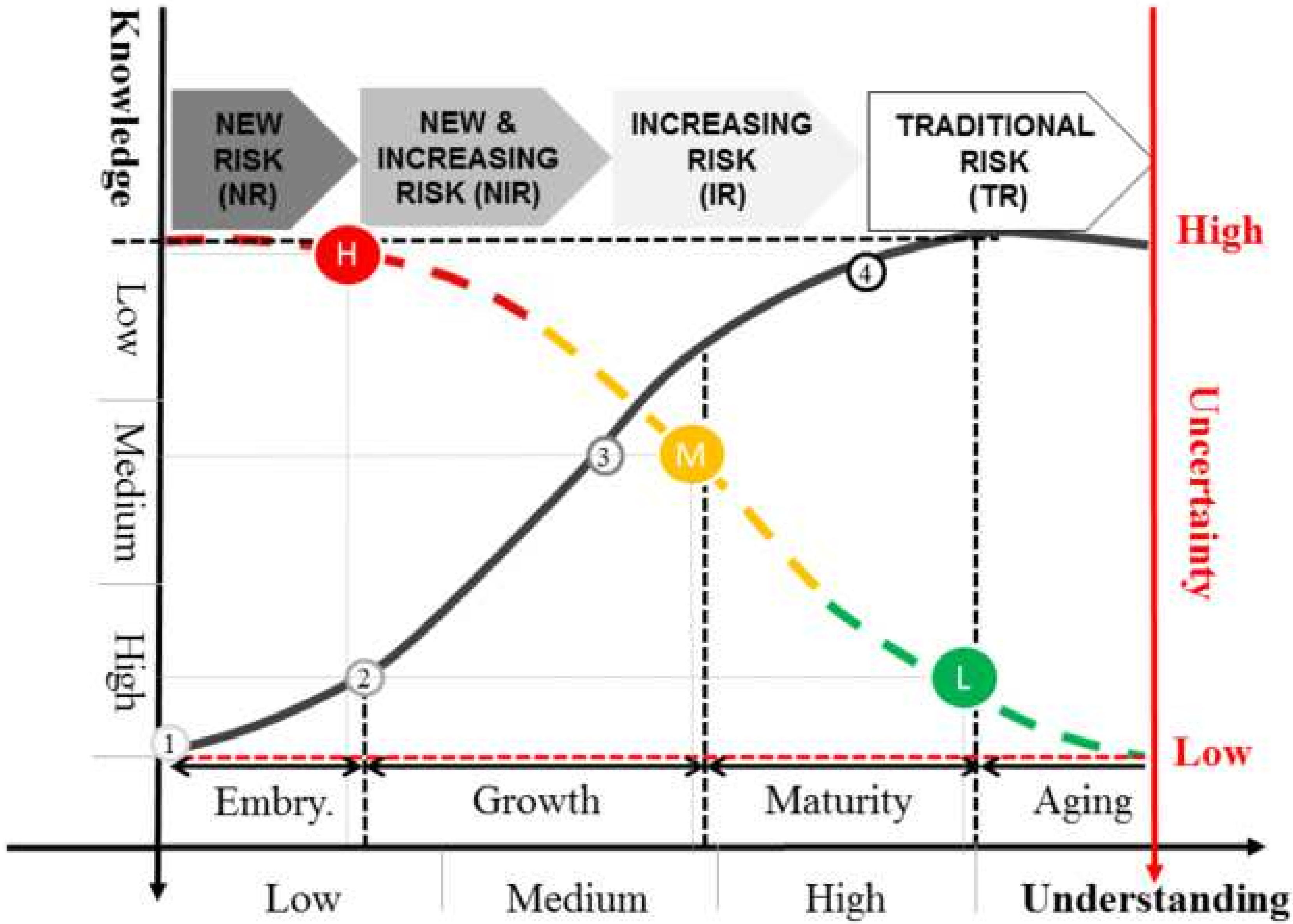


Figure 3

Click here to access/download;Figure;6_3_Figure_3.tif

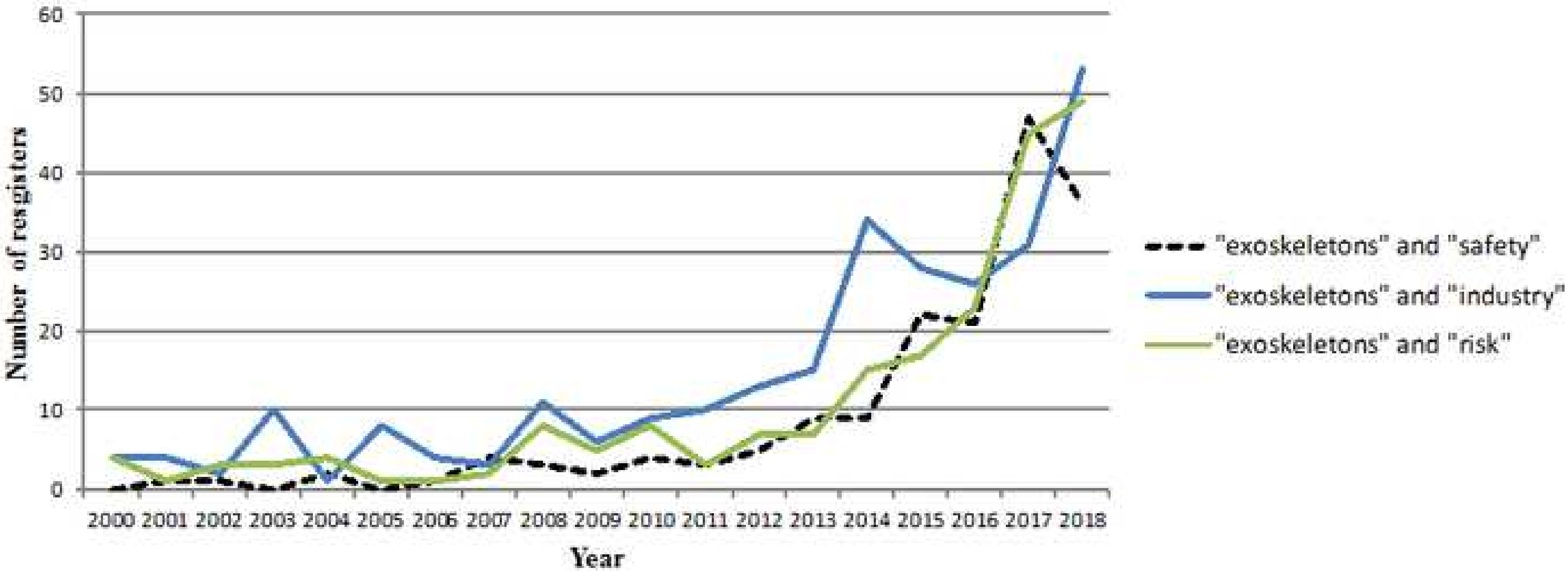
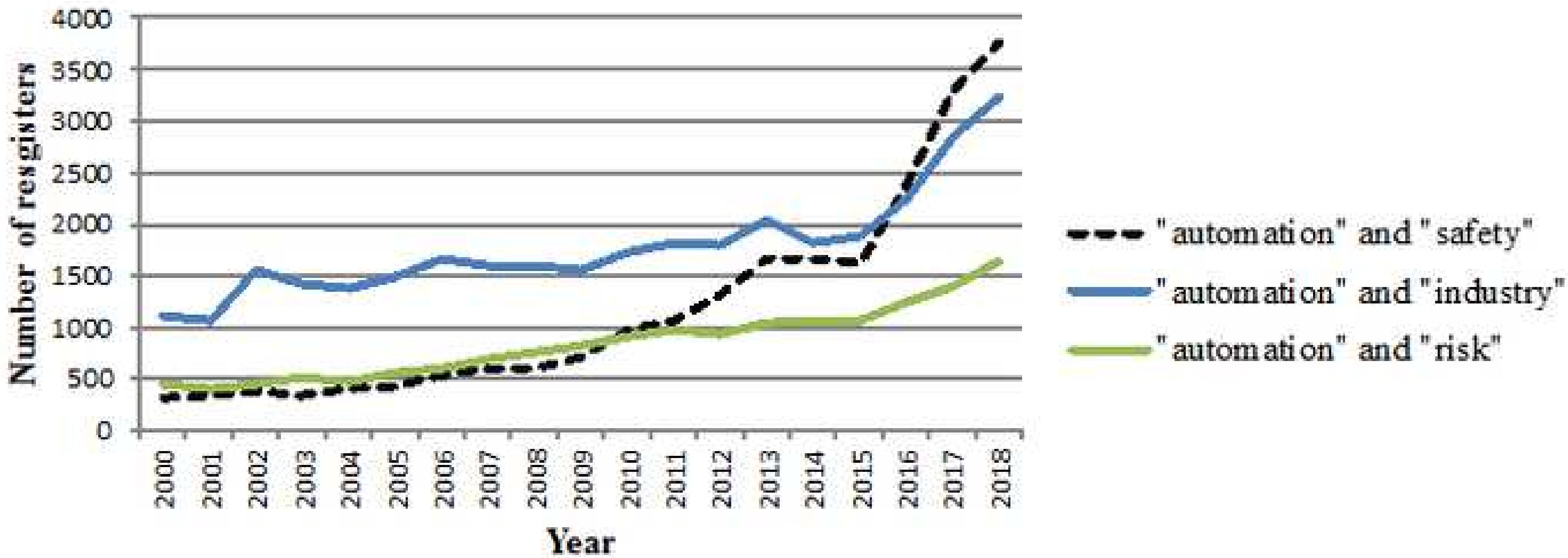


Figure 5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3500
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2500
2000
1500
1000
500
0
Number of resgisters
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Year
"automation" and "safety"
"automation" and "industry"
"automation" and "risk"