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A Timeline of the Risk Field: Bridging Fundamental Achievements and Modern Research

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Abstract— *An evolutionary, diverse, and complex path of the risk conceptualization has been built along with the history of mankind. The current understanding and the variety of methods available to deal with risk and uncertainty are linked to the achievements made by several academics and researchers in the past. However, very little of the risk analysis literature has attempt to explicitly bridge or recognize this fundamental construction for organizational and research purposes. This conceptual paper presents the results of a literature research in a timeline framework. The significant accomplishments that collaborated to the modern knowledge in the field of risk are organized in five distinct phases and their connections to modern research topics are discussed. The aim is to provide a condensed but comprehensive overview of the foundations and evolution of the risk field and link the different conceptual paths that currently exist in risk analysis research. The present paper contributes to a systemic view of the risk discipline, which we believe will be a helpful review from which academy and industry readers would benefit.*

I. INTRODUCTION

Risk analysis practices have been performed since the beginning of civilization. Some researchers affirm that the oldest strategy for coping with risk is insurance, a societal risk management strategy [1]. Others believe that the risk notion appeared with man's fascination with games of chance, the very essence of risk-taking [2], that seems to be nearly as old as man himself (e.g., findings of relics related to a dice game Astragali in many archaeological digs) [3,4].

Though the notion of risk existed before the concept became linguistically or mathematically defined, there is no conclusive agreement about its origin. Authors denominate risk as a problematic conceptual phenomenon due to its many views in metaphysic, epistemic and moral contexts with no common understanding and obscure origin [5,6]. The philosophical issues of risk research [7] are challenging topics permanently in debate [8–12]. Therefore, proper academic risk discipline with educational programs, journals, research groups, societies, and scientific events had emerged [8,9,13].

There is an astonishing volume of literature covering the risk and uncertainty topics, and it seems to be present in all disciplinary fields. However, fundamental matters of risk and uncertainty are mostly addressed in dedicated chapters or book introductions from related disciplines (e.g., probability theory, decision theory, social sciences) but not often in research papers.

The inspiring book of Peter Bernstein [2] gives an interesting portrait of the evolution of the risk concept up to 1960. It provides a broad view about the historical

achievements but, as the author highlights, the theme is presented using a conceptualization of risk focusing on quantification, rationalism, and probability, using either frequentist or subjective interpretations.

Covello and Mumpower [3] focused on the "neglected period" of risk analysis and risk management, the years before the 20th century, when probability theory emerged and tools for quantitative risk analyses were developed. Althaus [5] classifies the risk concepts in a disciplinary perspective using the economic conceptualization of risk. Though other authors have used this classification in the study of risk theory (e.g., [14,15]), some authors affirms that it lacks precision [16].

In [16], the author uses an approach called "thought-constructed development paths" to review the definition and meanings of the concept of risk. Nine risk definition categories are presented to encompass the many definitions of this subject in the literature. The author concludes that in the past two decades, there has been "a shift from rather narrow perspectives based on probabilities to ways of thinking which highlight events, consequences and uncertainties". Although comprehensive, it missed a historical contextualization of the leading proponents of the risk concepts considered in the classification.

Aven [13] reviews the principles and methods proposed at the beginning of the XXI Century, focusing on the fundamental ideas that form generic risk research. The author recognizes that the selection of ideas reported in his manuscript has "bias toward rather recent papers and the areas of interest of the author". Carayannis et. al, [17] provides distinction of five "risk management Eras" with briefly describing some historical accomplishments. However, it lacks connecting current research with past achievements.

The present paper provides an organized timeline with the main collaborators to the risk discipline in a phase division structure. It distinguishes the main conceptualizations of risk developed throughout history in a unified, comprehensive, and neutral view of the risk discipline. The aim is to provide fundamental knowledge and their connection to the modern risk research from which academy or industry practitioners can strength the decision-making and policy formation for RD&E management structures.

The structure of this paper is as follows. We present the method used to perform this conceptual research and the approach to developing the risk timeline in Section II. Section III presents the research findings following the proposed fundamental risk phases. Section IV outlines discussions about some modern risk research and their connections with the timeline and our view about the risk field. Section V concludes this paper with lessons learned and future topics of research.

II. RESEARCH METHOD AND TIMELINE DEVELOPMENT

This conceptual paper consists of an extensive literature research. The review began broadly, searching for review articles and generic (classic) books related to the risk topic (e.g., [2,4,18–20]). Additional relevant articles were identified in papers references using snowballing backward and forward approaches [21] (i.e., citation tracking) and browsing in specialized journals covering risk and related disciplines. Also, search strings from the area of study was performed to retrieve relevant articles from the databases of Scopus and Web of Science.

The timeline shown in Figure 1 was built from an interactive process of reading-collecting (database formation), cross-checking (information verification), selecting (prioritizing most relevant data), and organizing the most reliable information from different sources in a chronological order. The names of the main collaborators, their nationality, approximate date of publication, and short title of the achievement made to the risk field are shown in a standard form. When mention is made in the text, we use the name of the collaborator and the date of publication to make it easier to find each author in the timeline.

Prioritizing data was simultaneously conducted with phasing formation process. We acknowledge that other authors could be added to the timeline, but consciousness and sticking to the objective of the paper is mandatory. Therefore, criteria on higher impact to each philosophical current (i.e., different risk conceptualization) was applied and the most important developments were selected to form the timeline.

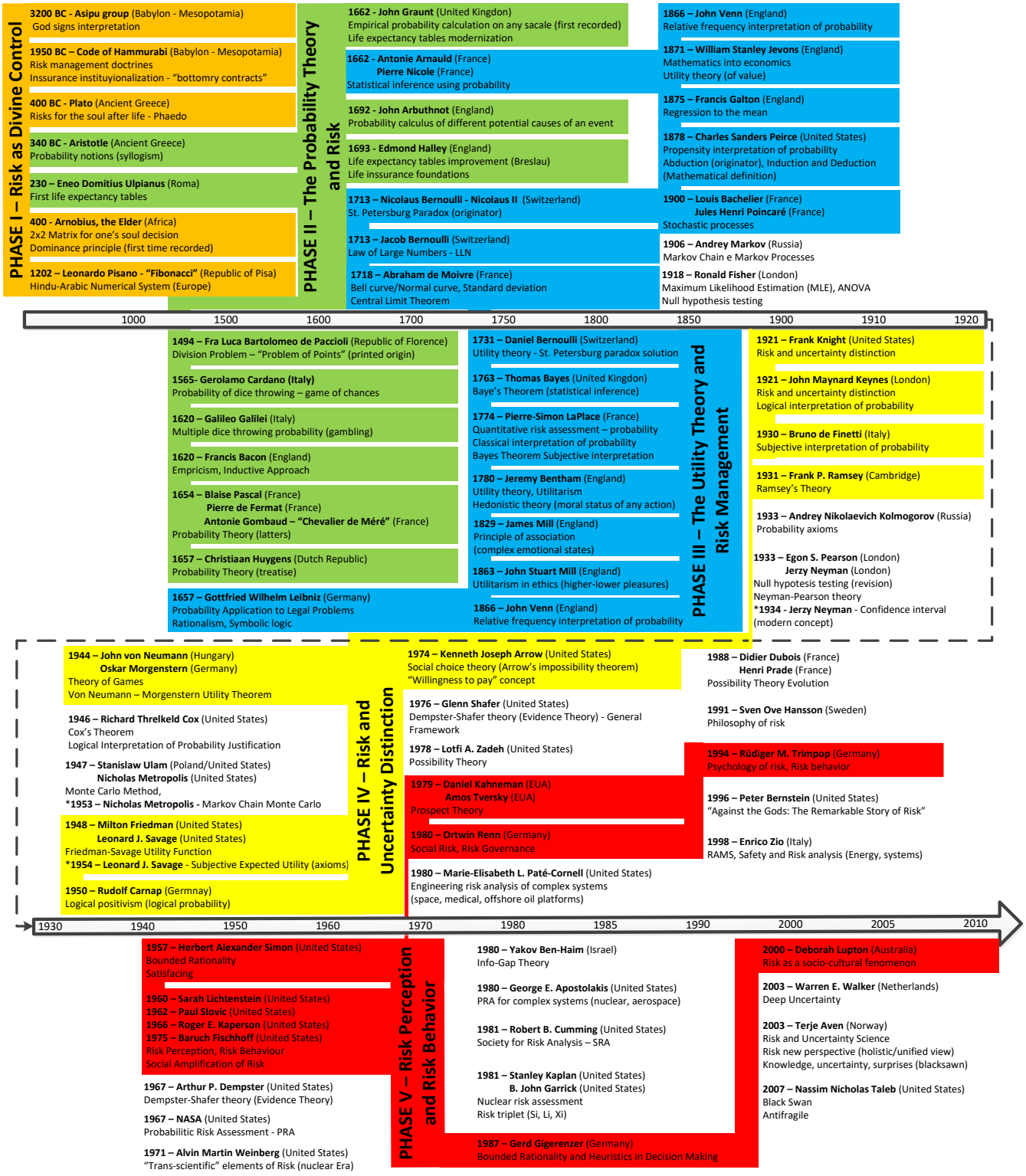

Fig. 1. The Risk History Timeline and Phase Division.

III. PHASES IN THE EVOLUTION OF THE CONCEPT OF RISK

We defined five distinct phases that organize the history of risk according to the risk fundamental conceptualizations defined over time. The proposed phases are not chronologically straightforward and do not include the utmost modern risk authors cited in the discussion topic. The phase division should not be understood necessarily as progression or an improvement view of risk fundamentals since there is no definitive or proven right conceptualization of risk broadly accepted in the research community.

Risk as Divine Control phase (phase I) embodies the collaborators from an epoch where the society notion of risk was based on the Divine will, people had no choice towards their future, and the uncertainty idea did not exist. The phase named probability theory and risk (phase II) comprise the precursors and the acknowledged discoverers of the probability concept. Emphasizing this revolutionary theory that made humans believe in having the power of controlling the future by mastering risks. Risk management consolidation and utility theory phase (phase III) encompass the achievements that made possible the capitalist system and the first ideas that people's interests are reflected in decision making, the fundamental essence of utility theory. The risk and uncertainty concepts distinction phase (phase IV) is characterized by the recognition that there are limitations in the normal law and the strengthening of subjectivism (degree of belief). The perception of risk and risk behavior phase (phase V) is marked by the rationality behavior questioning and the appearance of several theories in the psychology field to understand human behavior in the decision-making process.

2.1 Phase I: Risk as Divine Control

The **Asipu Group - 3200 B.C.** is recognized as the first recorded instance of risk analysis practitioners [3,6]. The group was part of the ancient Babylon civilization and served as consultants for risky and uncertain decisions [3]. They identified the problem and the alternative actions, collected data of possible outcomes by interpreting the gods' signs, and recommended the most favorable alternative with certainty, confidence, and authority [6].

According to **Rüdiger Trimpop – 1994** [6], other ancient traces of the risk notion are found in the **Code of Hammurabi - 1950 B.C.** It established several risk management doctrines within 282 clauses in the code and laid out the basis for the institutionalization of insurance by formalizing the concept of *bottomry* in maritime contracts on vessels and cargoes [2].

Even though concerns about risks had evolved, an important change just came to happen with the rise and spread of Christianity. **Peter Bernstein – 1996** [2] suggests that the single God with well-defined purposes and intentions to the future changed the humans notion of risk, the future became a matter of moral behavior and faith. Then, Christians focused their curiosity on what would happen in the afterlife.

Although the afterlife subject had already been thought by philosophers in the past, it remained as will and control of the Divine. According to Covello and Mumpower [3], **Plato - 400 B.C.** included several discussion treatises about afterlife in *Phaedo*. In the monograph *Against the Pagans*, **Arnobius the Elder – 400 A.D.** proposed a 2x2 matrix for the decisions affecting one's soul according to Christianity acceptance and God's existence [3,6]. Arnobius' argument marks the first recorded appearance of the *dominance principle*, a heuristic for making decisions under risk and uncertainty [3].

Centuries later, in the context of the cultural shocks caused by the Crusades, the handwritten book *Liber Abaci* authored by **Leonardo Pisano – 1202** (i.e., *Fibonacci*), came to be known as the introduction of the Hindu-Arabic numbering system to the western world [2]. The written calculation fostered abstract thinking and enhanced mental capabilities of humans, considered essential basis for realist and constructivist philosophical perspectives [11] of the risk discipline, and general science development.

2.2 Phase II: The Probability Theory and Risk

Besides probability is widely acknowledged as a mathematical concept, its discovery is a landmark for the risk field. Phase II encompasses the emergence of the probability theory and the beginning of changing at the Divine assignment of risk, during the Renaissance and Protestant Reformation after 1300 [2].

The nature of probability had been thought by Greeks through the word *eikos*, the old Talmudic Jewish philosophers may have come closer to quantifying it [2]. Still, the probability theory was formally defined only in the 17th century and even later associated with risk, in an epoch that society was shifting its culture from mysticism to science and logic [3].

The book *Liber de Ludo Aleae* written by **Gerolamo Cardano – 1565** (posthumously published in 1663) introduced the notion of chances with dice-throwing experiments, but the meaning of risk still remained related to the gut view of probability, with no connection to measurement [2,18]. **Galileo Galilei – 1620**, aware the achievements made from Cardano, also concluded about the frequency of various outcomes with dice throwing, but lost interest in the subject [2].

Around the same time, the philosopher of science **Francis Bacon – 1620** authored the book *Novum Organum* with the pioneering scientific method of empiricism [22,23]. It confronted the dominant deductive approach, as established by **Aristotle – 340 B.C.** in the work *Organon* (i.e., a treatise on logic and syllogism [22]). Bacon's work defined rules for a scientific method where inductive reasoning can generate scientific knowledge in a non-metaphysical approach (i.e., *eliminative induction* [24]). By acknowledging inductive reasoning as a scientific method, Bacon suggests that reason exists beyond the mythologies and religions. Consequently, it awakened the epistemological potential of human mind leading to an explosion of knowledge, innovation, and growth in science [25].

In this context, **Chevalier de Méré - 1654** invited the famed French mathematician **Blaise Pascal - 1654** to solve the "*problem of the points*", the stakes division in an unfinished game of *balla*, suggested by **Luca Paccioli - 1494** in the book *Summa de Arithmetic*. Pascal turned for help to **Pierre de Fermat – 1654**, and the outcome of this collaboration led to the development of the theory of probability [2,18,19,26].

Few years later than Pascal and Fermat letters about probability, **Christiaan Huygens – 1657** independently published his treatise on probability in the book *Calculations in Games of Chance* [26]. **John Arbuthnot – 1692** translated Huygens' publication and added generalizations on dicing games results in the book *Of the Laws of Chance* [27] what made Huygens being recognized as another originator of the probability theory.

With probability theory, quantified decisions and forecasts to the future became possible [26]. First, defining expected outcomes in games of chance and gradually to other applications, created a disruption for decision-making based on the degree of belief. Bernstein [2] provides an interesting view of the two sides of probability, one looking at the future, meaning the degree of belief of an opinion (i.e., the gut view, known as epistemological) and the other interpreting the past, concerned with what we actually know from experience.

After the games of chances, the mortality tables and life expectancy observations were the second formal application of the probability theory, fulfilling a large temporal gap in this topic since the **Eneo Domitius Ulpianus – 230** life tables [3]. The businessman **John Graunt – 1662**, acknowledged as the founder of the science of statistics together with William Petty [2,19], made the first recorded attempt to calculate empirical probabilities of life expectancy tables of London city in his publication *Natural and Political Observations Made Upon the Bills of Mortality*.

Although Graunt failed to generalize conclusions from the statistics available [2], he acknowledged that sampling is an essential part to predict about the future, a crucial topic to the risk field. **Edmund Halley - 1693** published an advanced probability analysis of mortality and births for the city of Breslaw in the book *Transactions*. This work allowed the insurance annuities calculation [6] and is considered the foundation of the modern life insurance system. However, the notion of risk management only effectively emerged when society could believe that they were free agents and had some influence in the outcomes of actions, according to their choices [2].

2.3 Phase III: The Utility Theory and Risk Management

Phase III addresses the risk management consolidation and the development of the *Utility Theory*, an alternative to explain human choices beyond probabilities. **Antoine Arnauld** and **Pierre Nicole – 1662**, brought the probability subject into evidence in the book *La Logique ou L'art de Penser*. They suggested a process for developing hypothesis from a set of facts (i.e., known today as statistical inference) and pioneering included the strength of desire for a particular outcome in the decision-making [18].

Among other accomplishments, the eight celebrated mathematicians from the *Bernoulli* family shown in Figure 2 had established fundamental theories related to the risk field. Advised by **Gottfried Wilhelm Leibniz – 1657**, that a "finite number of experiments would inevitably be too small a sample for an exact calculation of nature's intentions" [28], **Jacob Bernoulli - 1713** considered the linkages between probability and the quality of information for the first time in the book *Ars Conjectandi* (posthumously published by his nephew Nicolaus II) [2]. Jacob admits that "unless we can assume that the past is a reliable guide to the future", an estimate of probability after the fact is impossible. Jacob concludes that whatever data is chosen to analyze, it is only a fragment of reality, and the quality of data is crucial for generalization [2,18].

The theorem *Law of Large Numbers – LNN* [18] proposed by Jacob for calculating probabilities a posteriori states that increasing the number of trials, the probability of the observed average to reach the true average will correspondingly increase, within some stated amount of error, no matter how small. This was the first fundamental theory about the limitations using probability to measure past events (i.e., the relative frequency interpretation of probability), which was later advanced by John Venn – 1866 in *The Logic of Chance*.

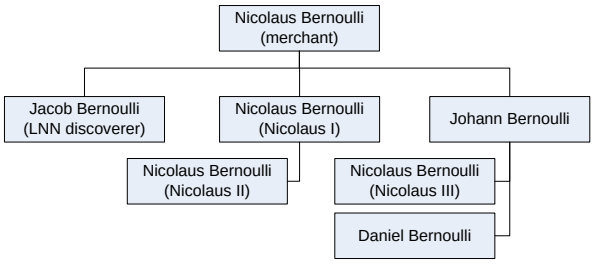

Fig. 2. The parental tree of the Bernoulli mathematicians related to the risk field.

The prominent statement that "satisfaction resulting from any increase in wealth being inversely proportionate to the quantity of goods previously possessed" was introduced by *Daniel Bernoulli – 1731* in a paper titled *Specimen Theoriae Novae de Mensura Sortis*. This conclusion came to be the first systematic process to explain how most people make choices and reach decisions using the fundamental idea of utility in the sense of desirability or satisfaction [2] - "the value of an item must not be based on its price, but rather on the utility that it yields" [29]. The solution of the *St. Petersburg Paradox* (suggested by his cousin **Nicolaus II – 1713**) [30] came to be the most famous example of proving his point.

Daniel Bernoulli criticized the dominant approach of *expected value* to explain decision-making choices since it completely ignored the decision-maker (i.e., the value assigned to each possible outcome in a decision under uncertainty). He concluded that even when probabilities are known, rational decision-makers will try to maximize expected utility rather than the expected value.

When searching if observations comprise a sufficiently representative sample of the universe, **Abraham de Moivre – 1718** suggested the structure of the *normal distribution* (i.e., the *bell curve*) and defined the concept of standard deviation in the book *The Doctrine of Chances* [2,18,28]. Today, we recognize de Moivre proposals as the core principle for risk management systems.

By investigating the inverse problem of Jacob Bernoulli (i.e., *inverse probability*), **Thomas Bayes - 1763** made a striking advance in statistics through an experiment with a billiard table. He defined a systematic way to use new information to revise probabilities based on old data (i.e., to compare posterior probability with the priors) in his famous book *Essay Towards Solving A Problem In the Doctrine of Chances*. The possibility to modifying a probability based on the accumulation of new information opened a philosophical discussion about uncertainty, which at that point was still unknown.

Pierre-Simon LaPlace – 1774 interpreted Bayes original theorem in a subjective view by modifying it to infer distribution parameters instead of searching for the probability of random variables. He published his advances in *Mémoire sur la probabilité des causes par les événements* and later in *Essai philosophique sur les probabilités* [28] and made Bayes theorem famous as the originator of the Bayesian inference. The conversion of the Bayes original theorem made possible to predict a probability distribution for a future outcome using a subjective interpretation. It assumes that the same pattern from a prior distribution would be followed, defining a fixed state of belief or state of knowledge.

According to Bernstein [2], the utility concept only became a paradigm of choice when Economists incorporated the concept in the late 18th century. **Jeremy Bentham - 1780**, the founder of modern *utilitarianism*, reinterpreted utility as a property in any object that tends to produce benefit, advantage, pleasure, good, or happiness. What he called *felicific calculus* [31] in the book *An Introduction to the Principles of Morals and Legislation*. Later, the son of **James Mill - 1829** (i.e., Bentham's collaborator) named **John Stuart Mill – 1863** modified and expanded the utilitarianism to a more liberal conception. Stuart Mill introduced a moral agent who maximized global happiness (i.e., pleasure over pain - "*The greatest happiness principle*") and separated the pleasures into higher and lower forms [32]. **William Stanley Jevons - 1871** enhanced the utility concept and believed he solved the value problem (i.e., value-laden characteristics [16,33,34]) with his publication *The Theory of Political Economy*.

The industrial revolution made a great impulse to quantification trend and scientific research growth [2]. The experience with sweet peas (*Quincunx II*) led **Francis Galton - 1875** to propose a general principle that came to be known as the *Regression* or *Reversion to the Mean*. "This is the tendency of the ideal mean filial type to depart from the parental type, reverting to what may be roughly and perhaps fairly described as the average ancestral type" [35]. Although Galton recognized that nature sometimes fails to regress to the mean, several methods are fundamentally grounded in this principle creating a direct relation to the meaning of risk (e.g., to predict tendency in the investment field).

Henri Poincaré - 1900 and his student **Louis Bachelier** attempted to explain why empirical frequencies approximately reproduce mathematical frequencies (i.e., distributions are not far from the *Normal Law* [36]). They recognized that sometimes there is not enough information to apply the laws of probability and concluded it was impossible to acknowledge with certainty how good a

sample is. This conclusion is acknowledged as the *Laplacian principle of insufficient reason*, a necessary convention for determining the value of the probability when information is missing. In this situation, they suggested to fall back on inductive reasoning and try to guess the odds using the "*method of arbitrary functions*" developed by Poincaré [2,37].

2.4 Phase IV: Risk and Uncertainty Distinction

The phase IV addresses the risk and uncertainty distinction in the Economics field and the beginning of research on how human beings recognize and respond to probability, risk management, and decision-making, arising the dilemma of measurement versus degree of belief in the rational perspective.

In the post First-World War, problems could no more be faced using strict quantified rationalism and probability under the Normal Law behavior [2]. **Frank Knight - 1921** quotes in his book *Risk, Uncertainty and Profit*: "Uncertainty must be taken in a sense radically distinct from the familiar notion of Risk, from which it has never been properly separated" [38]. Knight's proposition confronted the theory of certainty and regulation by the laws of probability [39]. He defined the term apodeictic certainty to group and characterize the events which objective probability could be assigned ("publicly verifiable" [40]) and rejected the probability assignment for other types of events.

John Maynard Keynes - 1921 published two important books addressing risk-related content in distinct moments of the history. In 1921, the book *A Treatise on Probability* explored the meaning and applications of probability. Keynes proposed the distinction of risk and uncertainty in contrast to what is definable and undefinable [41] and concluded that Galton's peapod analogy using *Regression Towards the Mean* and *Normal Law*, applies to nature but it is irrelevant to human activities [2]. Keynes advocated that objective probability does not exist: "It is not, that is to say, subject to human caprice – but our ignorance denies us the certainty of knowing what that probability is; we can only fall back on estimates". Then, Keynes suggests that: "we pass from the options of theorists to the experience of practical men" [41,42].

In 1937 Keynes published the book *The General Theory* with the explicit notion that uncertainty is unknown: "By uncertain knowledge… I do not mean merely to distinguish what is known for certain from what is only probable... there is no scientific basis on which to form any calculable probability whatever. We simply do not know" [43]. Keynes advocated the logical interpretation of probability [33], earlier originated by Bernard Bolzano's publication Wissenschaftslehre (1837) and further developed by **Rudolf Carnap - 1950** years later [44].

Motivated by the difficulties and limitations of the empiricist philosophy, the subjective interpretation of probability resurgence came from the 1930s with the philosophers **Frank Plumpton Ramsey - 1931** (i.e., *coherence principle*) and statistician **Bruno de Finetti – 1930** (i.e., *betting interpretation*). However, it was only widely restated with the publication *The Foundations of Statistics* from **Leonard Savage – 1948/1954** [18,33,44,45].

The old belief that people would know all the information and that certainty would prevail had vanished with the World Wars, opening the opportunity for risk management research [2]. Nobel laureate **Kenneth Joseph Arrow - 1974** (i.e., inventor of modern *social choice theory*) focused to understand how people made decisions under uncertainty and how humans behave with their decisions [46]. Arrow developed the "*impossibility theorem*", stating that although individuals may have preferences, groups do not. The "social choice" is governed by a single global societal preference order (i.e., the social welfare function) resulting from the set of individual preferences [46,47].

John von Neumann - 1944 and **Oskar Morgenstern – 1944** made significant progress in understanding risk and uncertainty in the *Theory of Games*. Their book *Theory of Games and Economic Behavior*, represented a disruption from earlier efforts to incorporate mathematics into decision-making [48]. In essence, the theory consists of two or more elements trying to maximize their utility simultaneously, each aware of the other's concerns. That is, uncertainty lies in the intentions of the others [48,49]. This approach follows the classical model of rationality, assuming that people clearly understand and constantly apply their preferences [2,6].

The Game theory induced many ideas and applications, strengthening the rationalist view for governing risk and maximizing utility [5]. However, the rationalist triumph had a dramatic break in the early 1970s with the research works criticizing the rational behavior principle.

2.5 Phase V: The Risk Perception and Risk Behavior

Phase V addresses the rationality questioning period. Although discussions had emerged in the 1960s and the world had changed in so many forms, this is still an open research topic. The rational perspective believes that humans make decisions following a pattern of behavior that enables predictability. On the other hand, Psychologists had proven that people are prone to distortions during decision-making process [2,5].

Herbert Alexander Simon - 1957 challenged the rationality perspective (i.e., main economics orthodoxy [50]) by suggesting the *theory of bounded rationality*. It assumes that human "computational abilities" and memory has limitations to absorbing and processing information to reach conclusions. Simon concluded that human intuition consists of a "subconscious pattern recognition" process. Then, he proposed a model in which the maximization of utility is replaced by *satisficing* [24]. It occurs when associations or patterns automatically retrieved in the mind (i.e., based on experiences stored in memory) satisfy the decision-maker goals. Simon did not consider intuition irrational, but a complementary cognitive mode [50] without a conscious analytical method [51].

The research psychologists **Sarah Lichtenstein - 1960**, **Paul Slovic - 1962**, **Baruch Fishoff - 1975**, and others developed the psychometric paradigm (i.e., pioneered by **Chauncey Starr** [52]) and introduced the notion of perceived risk [5,6,53–55]. These early research produced "*cognitive maps*" of hazards that explained how laypeople perceive risks but neglected individual differences in risk perception [56]. **Roger Kasperson – 1966**, **Ortwin Renn - 1980** and colleagues suggested the concept of social amplification of risk and demonstrated by empirical studies that hazardous events interact with psychological, social, institutional, and cultural processes in ways that can attenuate individual and social perceptions of risk [57,58].

Daniel Kahneman - 1979 and **Amos Tversky - 1979** made one of the most important contributions to risk management and uncertainty fields. They defined the *Prospect Theory* (2002 Nobel Prize winner) in a critique about the expected utility theory [5,59,60] while exploring the psychology of intuitive beliefs and choices under bounded rationality [61]. Some of their conclusions are summarized as follows:

- People display risk-aversion, and risk-seeking behaviour for the same choices put in different settings called a failure of invariance.
- People tend to ignore the common components of a problem and concentrate on each part in isolation.
- People have trouble recognizing how much information is enough and too much.
- People pay excessive attention to low-probability events accompanied by high drama and overlook routine events.
- People are not risk-averse; the major driving force is loss-aversion. People do not hate uncertainty, they hate losing.

Daniel Bernoulli advocated that the final wealth state (i.e., the "final state of endowment") influences the value of a risky decision. However, Kahneman and Tversky had proven that value is determined by attitudes with reference to gains or losses and dependent on a reference point [2]. Kahneman [61] calls it the Bernoulli's error, that prevailed as the accepted understanding for 300 years.

Kahneman and Tversky [62] concluded that people use computational shortcuts and editing operations when faced with a complex problem. People rely on a limited number of heuristic principles (e.g., representativeness, availability, and anchoring [53,54]). Human mind automatically replace the complex mental effort by simpler judgmental operations (i.e., heuristics) that sometimes leads to severe and systematic errors (i.e., biases) [60,61].

Gerd Gigerenzer – 1987 proposed the fast and frugal heuristics program as an alternative theory to the heuristics and biases program (from Kahneman and Tversky). The fast and frugal heuristics relates to the ecological rationality, suggesting that humans develop a repertoire of cognitive strategies for solving judgment and decision tasks in an adaptative way (i.e., adaptative box). Differently from the heuristics and biases program, the fast and frugal heuristics does not rely only in the human cognitive architecture, it also addresses the environment structure (i.e., the pair of scissors from H. Simon)[63].

The research about the flaws of the rational model made society realize that the risk perception, risk behavior and decision-making result from a complex interaction between conscious, subconscious, and emotional (internal) aspects constantly moderated by the environment and socio-cultural influences (see Deborah Lupton - 2000 and **Ortwin Renn - 1980** [64]).

IV. DISCUSSION AND RECENT RESEARCH

The risk field is wide-ranging, interdisciplinary and includes several philosophical issues in epistemology, philosophy of science and psychology topics. The distinction between know-how and know-that [13,65], the meaning of knowledge as the "epistemically most justified beliefs" [66], the risk field as a scientific discipline [8,10,67], the influences of human cognitive system [61,68,69] and behavior [70–72], and the implications of the probability interpretations [33,73] are some examples of the fundamental topics of research.

The tension between subjective (constructivism) and objective (realism) conceptualizations of risk is present in all the way through the history of risk field and numberless cited in the literature [74,75].

The realist perspective acknowledges that risk events are produced by physical and natural processes in ways that can be objectively quantified [76]. Then, the technical estimates of risk constitute true representations of

observable events regardless of the beliefs of assessors [77]. In contrast, the constructivism perspective acknowledges that risk is inherently subjective and it does not exist independently of human minds and cultures [76]. In this perspective, decisions are mental constructions subject to degrees of belief and constantly moderated by socio-cultural influences [77].

Next subsections introduce some of the recent advances in the risk field (since the 1950s) and discuss their links to the past achievements described in the paper.

4.1 The Risk Field and Probability Theory

The risk concept is often linked to the probability concept due to the interpretation of chance [33]. Probability was the first way researchers encountered to understand the randomness nature of events in gambling. Although probability is a well-defined mathematical concept, it has philosophical limitations when used for measuring risk and uncertainty [78]. Fundamental issues often occurs due to the lack of consistency about probability interpretation as classical, frequentist, logical, or subjective [33,73].

Several industries and engineering sectors (e.g., energy, transportation, aerospace, military, and construction) widely adopt Probabilistic Risk Analysis (PRA) techniques. PRA even became regulatory and normative in many of these fields to support decision-making [20,79]. However, its origin is often neglected.

PRA was first developed for safety goals but soon got widely adopted for other purposes. It formally originated in the aerospace sector at **NASA - 1967** [20,80] with the investigation of the Apollo testing accident [81]. However, PRA only proved to be an essential tool for assessing risks after 1979, with the Three Mile Island accident investigation [12,20,81]. Foundations of the PRA can be traced back to the first applications of probability as a measure of risk since the probability theory definition in the 17th century by Pascal, Fermat, and de Méré. However, it just became a reality due to the support and mathematical coherence provided by the axioms of probability established by **Andrey Nikolaevich Kolmogorov – 1933** and the computational modeling advances. **Alvin Weinberg - 1971**, Marie-Elisabeth Paté-Cornell – 1980, **George Apostolakis – 1980**, **Stanley Kaplan** and **John Garrick – 1981**, and **Enrico Zio - 1998** are also recognized by their important contributions to PRA in the context of engineering.

Most applications of PRA aim to support activities related to complex systems since they need for systematic ways to deal with reliability and safety, and often rely on the availability of great amount of data. Criticism of the probabilistic approaches to measure risk and uncertainty (i.e., often due to the philosophical orientation or probability interpretation issues) triggered the development of non-probabilistic methods. Researchers argue against the use of PRA in situations with little knowledge to support the representation of uncertainty [82]. *Evidence Theory* also known as *Dempster-Shafer Theory* or *Theory of Belief Function* firstly introduced by **Arthur Dempster - 1967** and generalized by **Glenn Shafer - 1976** [83,84], *Possibility Theory* developed by **Lotfi Zadeh - 1978** [85] and advanced by **Didier Dubois** and **Henri Pade – 1988**, and *Info-Gap Model* defined by **Yakov Ben-Haim - 1980** [86] are some of the non-probabilistic theories most adopted in the literature.

4.2 The Uncertainty Era and Risk Governance

Judging uncertainty as part of risk characterization is only possible due to the uncertainty and risk distinction made by Knight and Keynes in the 1920s. Recent events faced by society and the way they have been predicted or surprised us emerged new challenges to risk research. **Nassim Nicholas Taleb - 2007** made the *black swan* concept [87] well-known and widely discussed in the risk field research. Through this concept, authors emphasized the need for evidencing knowledge and surprises in risk management approaches [13,88]. Some disciplines were already familiar with the idea of unknown-unknowns (i.e., one type of black swan [89]) well before getting popular [24]. However, extreme events such as climate disasters, terrorism, global pandemics, and economic crises incited the need for exploring how to deal with such risks (e.g., deep uncertainty).

The *deep uncertainty* concept [90] was popularized by **Warren Walker – 2003** in the academic environment (see [91–93] for precursors). Deep uncertainty research raised many questions about the efficacy of the traditional approaches for risk management and risk policy when decision-makers cannot agree upon appropriate models or how to represent uncertainty [94,95]. Authors concluded that deep uncertainty situations should be treated differently from "normal" situations [96,97]. Therefore, deep uncertainty and black swan research resulted new developments about precautionary, robustness, and resilience principles [98,99] for risk management, and new methods to deal with emerging risks (i.e., characterized by the weak knowledge related to known/unknown [13,100]).

In this context, we see similarities in the risk field history with the first attempts to explain the Normal Law flaws made by Poincaré. Francis Galton suggested a pattern of behavior for natural events with the bell curve, but the complex and random events resulted from the interactions between society and natural environment insistently proves its unteamed character. Then, researchers move back attentions to improve managing

strategies (i.e., risk governance). Ortwin Renn, one of the most influential researcher on the topic, defines risk governance as the various ways in which many actors of society respond in the context of risk-related decision-making, including systemic risks [101]. The risk governance research topic has been in debate [102,103] since its formalization in political science in 2001 as an opposite approach to the classical notion of risk assessment and risk management [104].

Terje Aven – 2003 is an important researcher of the risk field that advocate the science of risk with **Sven Ove Hansson - 1991** [9,66]. Aven presents a "new perspective" of risk based on knowledge (i.e., "epistemically most justified beliefs" [66]), scenarios, and surprises, in opposition to "narrow perspectives" (e.g., accurate risk predictions based on probability and expected values). Aven [88] advocates the need to focus on the aspects outside *Mediocristan* [87], what Taleb refers to as *Extremistan*, which includes improved risk assessments, better capture of the knowledge dimension, adaptive and resilient thinking, and the antifragility characteristic [13,101,105].

Aven is a strong supporter for a unified vocabulary and fundamental principles definition as the basic pillar of the risk science in the context of the Society for Risk Analysis – SRA (i.e., founded by **Robert Cumming – 1981** and others [106]). These efforts seek to allow communication between the specific knowledge areas in a common language of risk [9,13,34,66].

4.3 The Dynamic and Computational Methods for Risk Analysis

Current general research focuses on dynamic and real-time risk management rather than static or traditional risk assessment [13,107]. These methods have been possible with the improvement of the fully integrated data systems, computational capability, sensors technology, prognostic techniques, and programming strategies (e.g., AI [9,107,108], blockchain [109]).

The origin of computational aid for risk analysis can be traced back to *Monte Carlo Method* (MCM) development by **Stanislaw Ulam – 1947**, during the development of the first electronic computer ENIAC [110]. The MCM allowed statistical sampling to estimate uncertainties before testing and made disruptive advances in hypothesis testing and design of experiments (i.e., the core of inductive reasoning), since first developments by **Ronald Fisher – 1918**, **Egon Pearson** and **Jerzy Neyman - 1933**.

Other remarkable achievement led by **Nicolas Metropolis – 1947/1953** was the *Markov Chain Monte Carlo* (MCMC) algorithm [111]. The MCMC merges MCM and the *Markov Chain Theory* developed by **Andrey Markov – 1906**, and the algorithm improvements (e.g., combined with *Gibbs sampler*, *Metropolis-Hastings* [112]) have been extensively applied for estimating posterior distributions using Bayesian inference to model dependence within samples in dynamic analysis [111,113].

The Bayesian inference using MCM and MCMC relates back to the Bayes Theorem interpretation made by Laplace. From this point, posterior probability with a prior distribution for unknown parameters became possible, assuming that the same behavior is maintained. Similar subjective interpretation of probability as a degree of belief supports the *Cox theorem* introduced by **Richard Cox – 1946**. It establishes a set of conditions under which abstract reasoning (i.e., degrees of plausibility, belief, confidence, credibility) is equivalent or isomorphic to probability theory [114].

Strongly related to the risk analysis is the inference process consists in moving from premises to logical conclusions. Current knowledge recognizes three types of logical reasoning: induction, deduction, and abduction. For **Charles Sanders Peirce – 1878**, the scientific method involves a spiral interplay among the reasoning methods (i.e., abduction – creating hypotheses, deduction – inferring what should be the case, and induction – testing hypotheses) [115]. Though reasoning categories are conceptually and mathematically well-defined, the mapping process for risk conceptualization is not straightforward, mainly due to human factors.

V. CONCLUSION

This paper elaborated on the main achievements made by academics, philosophers and researchers that shaped the risk field (knowledge area) and the different risk conceptualizations advocated so far. It provides a general overview of the risk discipline in a condensed form and suggests a logical separation of the collaborators according to the risk conceptualization they advanced.

A timeline with a phase division guides the paper content and summarizes the results from an extensive literature review. The timeline dates to the first acknowledged practices of risk analysis in the ancient civilization up to the contemporary research. We address the revolutionary transitions of the risk conceptualization along the history and the knowledge building blocks achieved by researchers up to the most recent research topics.

Links are built between the past and modern research topics to highlight the importance to understanding the origins of the current methods for risk analysis. It is acknowledged that the remarkable collaborators to the risk

field from our time will only be recognized in the future as the risk field continuously evolve. From the extent and the continual research about the fundamental pillars and philosophical issues addressed, we acknowledge that the risk science has much more to evolve in a continuum path alongside the changes of the society.

We see further research from the presented review as discovering additional links among the contributions of the authors presented in the timeline since just few are briefly introduced in the paper. Future research should also focus on contributions to the risk field from philosophers of science, which is punctually covered in this paper.

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