Journal of Risk Analysis and Crisis Response, 2023, 13(4), 252-272
https://jracr.com/
ISSN Print: 2210-8491
ISSN Online: 2210-8505

Article

Integrating Resilience into Risk Matrices: A Practical Approach to Risk Assessment with Empirical Analysis

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Received: October 24, 2023; Received in revised form: December 6, 2023; Accepted: December 7, 2023; Available online: December 31, 2023

Abstract: The changing and intensifying landscape of global, national, and local disaster risks, driven by socio-political, environmental, and technological shifts, underscores the critical need for risk assessment by international agencies and governments. The Risk Matrix, introduced in 1995, has been widely used for risk assessment in different contexts, lauded for its simplicity and effectiveness. This model relies on the core risk components of consequence and likelihood, making it a favored tool for risk managers. To enhance the precision of risk assessment, various adaptations and extensions of the risk matrix have emerged; while some indirectly address resilience aspects, none explicitly integrate resilience into the matrix. This paper explores the risk matrix and its extensions, advocating for the inclusion of resilience in risk assessment. It introduces an empirical approach to quantify resilience, through a survey targeting small and medium-sized businesses in Southern Ontario, Canada. By developing two types of risk matrices—one with resilience considerations and one without—our work demonstrates how resilience alters risk prioritization, highlighting the importance of preparedness. This research underscores the pivotal role of resilience in risk assessment and urges its explicit integration into risk matrices to enhance accuracy and efficacy. Through practical examples and empirical data, the paper builds a compelling case for the central role of resilience in modern risk assessment practices.

Keywords: Risk Assessment; Resilience; Risk Matrix; Disaster Risk; Survey Data; Decision Making

1. Introduction

With the changing and increasing nature of disaster risks at global, national, and local levels due to socio-political, environmental, and technological changes, risk assessment has become crucial for international agencies and governments at different levels. If global, national, regional, and local risks are not assessed properly, it would be difficult for international agencies and governments to identify the most critical risk factors and, accordingly, make appropriate risk reduction/mitigation decisions with the scarce resources that they have.

Risk is commonly described by considering both the potential consequences of an event and the likelihood of its occurrence. Hence, a risk assessment would involve evaluating uncertain future situations in terms of these two components. To assess relevant risk intuitively, many risk managers prefer to use discrete categories instead of numerical values to evaluate the components and the resulting risk.

Risk Matrix serves as a tool for assigning a discrete risk category to each combination of consequence and likelihood. It establishes a mapping between consequence and likelihood, allowing for a subjective assessment. There are no formal restrictions on this mapping, although it is typically designed to be monotonically increasing. In other words, an increase in consequence (while keeping likelihood constant) or an increase in likelihood (while keeping consequence constant) should not result in a decrease in the assigned risk. This mapping can incorporate subjective or societal factors related to risk perception, such as aversion to major hazards. For example, events with low likelihood but significant consequences may be assigned higher risk than events with minor consequences but high likelihood, even if the expected loss (calculated as consequence multiplied by likelihood) is the same [1].

The risk matrix approach has been widely utilized as a straightforward technique for analyzing risks and aiding in decision-making regarding priority actions. Researchers, engineers, and practitioners have been using this technique to assess risks in different settings and scales. Further, some national and international standards, e.g., NFPA 1600 and ISO 31000, refer to risk matrices and recommended them for risk assessment.

The widespread use of risk matrices can be partially attributed to their employment of basic risk definition (i.e., likelihood and consequence) as well as their intuitiveness and ease of use. To enhance its effectiveness, and given the application context, several variations and extensions of this technique have been developed and used in practice. While some of these extensions indirectly include some aspects of the resilience concept, none of them explicitly include resilience in the risk matrix formulation and design. This paper aims to examine the risk matrix and its extensions as well as to propose and apply a resilience-based risk matrix. Based on empirical data, risk matrices with and without the resilience component are created to illustrate the impact of resilience integration in risk assessment practices. We argue that integrating resilience into risk matrix development offers a deeper understanding of a system's ability to withstand and recover from risks, going beyond merely identifying the likelihood and consequences of those risks. Accurate risk assessment involves considering inherent system traits, including anticipation, preparedness, response, and recovery from adverse events.

The subsequent sections of the paper are structured as follows. Section 2 presents an in-depth background on the original risk matrix, including its applications, strengths, and weaknesses. Section 3 categorizes key extensions of the risk matrix approach and their underlying justifications. In section 4, the significance of incorporating resilience into risk assessment efforts is discussed and our resilience-based risk matrix method is outlined; this section also includes descriptive analyses and illustrative examples from our survey results. Finally, section 5 provides a summary and concludes the paper by providing research, policy, and practical recommendations.

2. Risk Matrix

In this section, we provide some background on the original risk matrix, followed by its applications. Then, the advantages and disadvantages of this technique are discussed.

2.1. Original Risk Matrix

The original risk matrix approach was introduced in 1995 by the United States Air Force Electronic Systems Centre (ESC) as a tool to support risk assessment [2]. It was subsequently implemented in several ESC programs in 1996 [3] and later incorporated into the military standard MIL-STD-882D in 2000.

To facilitate the utilization of this new risk assessment methodology developed by the ESC, the MITRE corporation created a software application called "Risk Matrix" in 1999 [3]. This software, built using Visual Basic code within Microsoft Excel, accompanied by a user guide, provided a comprehensive explanation of the methodology. Its purpose was to aid programs in identifying, prioritizing, evaluating, and managing risks that may jeopardize their objectives. The MITRE Corporation and ESC collaborated to further enhance and refine the "Baseline Risk Assessment Process" [4]. This baseline process was designed to apply to any project or program requiring risk management [5].

The original risk matrix is based on the well-known definition of risk, where risk is a function of hazard likelihood (probability) and consequences (severity/impact) [6]. Peace (2017) [7] defines the risk matrix as a method of merging qualitative or semi-quantitative assessments of consequence and probability to generate a risk level or rating.

There are three common types of risk matrices: purely quantitative, purely qualitative, and semi-quantitative [8]. Risk matrices are typically composed of a two-dimensional, graphical diagram expressed in terms of event consequences on one axis and event likelihood on the other axis. Depending on the program or activity being assessed, features of the risk matrix such as size are determined. The categorization of consequence (Y) and probability (Z) will be calculated as Y × Z, respectively. For instance, if there are 5 consequence categories and 5 probability categories, this will create a 5 x 5 matrix with 25 cells, each representing a different level of risk.

Table 1. Severity and probability scales [5].

Severity	Description	Probability	Description
Critical (C)	Catastrophic effect resulting in program failure. No requirements met.	0-10%	Very Unlikely
Serious (S)	Major effect on program. Minimum requirements met.	11-40%	Unlikely
Moderate (Mo)	Moderate effect on program. Some requirements met.	41-60%	Even Likelihood
Minor (Mi)	Minor effect on the program. Most requirements met.	61-90%	Likely
Negligible (N)	Minimal or no effect on the program.	91-100%	Very Likely

To construct a risk matrix, the process involves categorizing and scaling the severity of consequences and likelihood, categorizing and scaling the output risk index, defining risk-based rules, and visualizing the risk matrix [9]. The risk matrix method employs a systematic brainstorming approach, typically guided by a team facilitator, to identify relevant risks. Once the risks are identified, the risk assessment team assigns different characteristics such as the relevant time frame, impact, and probability of occurrence to each risk. The time frame refers to the specific period within which a risk might occur, defined by its start and end dates. The team then establishes impact definitions using relative scales based on severity and probability, as illustrated in Table 1. It is important to note that the probability estimates are used in the absence of hard data; if hard data is available, estimated probabilities must be accounted for accordingly [5].

Table 2. Example of a basic risk assessment table.

Risk	Severity	Probability (%)	Risk index
Risk 1	Critical	10	Medium
Risk 2	Critical	60	High
Risk 3	Serious	95	High
Risk 4	Moderate	10	Low
Risk 5	Moderate	100	High
Risk 6	Serious	60	Medium
Risk 7	Serious	40	Medium

Using this methodology, an assigned risk rank or risk level is obtained given the corresponding likelihood and consequence, which would then enable the management to allocate resources in such a way as to prevent potentially catastrophic events instead of focusing on low-level risks [10]. Once the impact and probability of occurrence for each risk are assigned, a risk matrix is generated. The risk matrix, presented in the form of a table, contains multiple categories such as "probability," "likelihood," or "frequency" for its rows (or columns) and multiple categories such as "severity," "impact," or "consequences" for its columns (or rows). Table 2 shows a sample risk assessment table, which is then converted to a risk matrix (Figure 1).

Low (L), Medium (M) and High (H)

Critical	**1**	--	**2**	--	--
Serious	--	**7**	**6**	--	**3**
Moderate	**4**	--	--	--	**5**
Minor	--	--	--	--	--
Negligible	--	--	--	--	--
--	0.0-10	11-40	41-60	61-90	91-100

Figure 1. Example of a basic risk matrix chart.

As illustrated, the risk matrix chart ranks the risks based on their severity and probability. To complete the risk assessment process, recommended mitigation or control policies and actions are listed. Risks with higher rank would receive higher priority for treatment and mitigation. The severity and probability values can be estimated qualitatively using expert opinion; quantitatively using past data, simulation, and mathematical models; or semi-quantitatively using a mix of expert opinion and real data.

2.2. Sample Applications

The original risk matrix has been applied to risk assessment in many industries in an attempt to reduce risks and improve safety [8]. Modern governments, regulatory agencies, regulated industries, as well as organizations in public and private sectors have been paying increasing attention to risk mitigation and management. Despite potential challenges associated with risk matrices, they are currently the most widely accepted approach for risk assessment in many areas such as engineering, health and pharmaceutical, oil and gas, and agriculture industry [11].

The risk matrix approach holds significant popularity as a risk assessment and evaluation tool in engineering. Its ability to incorporate quantitative and qualitative attributes into different risk scenarios makes it a valuable technique. By adhering to the fundamental principles of matrices, the engineering industry can obtain reliable and sufficient results to support various decision-making processes [11].

In agriculture, risk matrices serve as decision support tools for evaluating and managing risks associated with flooding and run-off, an example of which is what is known as the Floods and Agriculture Risk Matrix (FARM). The risk matrix visually ranks risks, providing farmers, policy-makers, and management with options to mitigate run-off risks and make informed decisions regarding landscape restructuring and resilience efforts [12].

In the United Kingdom, the National Health Service (NHS) employs a 5x5 risk matrix for its risk management processes. This matrix simplifies and standardizes the ranking of risks, aiding NHS risk managers, the board of directors, and other stakeholders in determining appropriate actions based on the risk scores obtained [13].

A study conducted in 2012 within the Moroccan pharmaceutical industry applies a risk matrix to its supply chain [14]. The study reveals that different stages of the supply chain (upstream, internal, and downstream) are affected by risks with varying probabilities and severities. The supply chain risk matrix proves useful not only for supply chain managers in the pharmaceutical industry but also for researchers in other sectors to identify critical risk factors.

The NASA Engineering and Safety Center (NESC), an independent organization responsible for NASA's program safety, employs a 5x5 Risk Matrix Scorecard for risk assessment [15]. This matrix provides criteria and a framework for evaluating and prioritizing individual, program, and technical issues, including safety, health, environment, mission success, and national significance.

In the realm of air transportation, whether freight or passenger operations, there are numerous and significant risk factors. For instance, to assess risks associated with air freight operations involving dangerous goods, a revised risk matrix with a continuous scale is utilized by Hsu, Huang, & Tseng (2016) [16]. The findings from this matrix contribute valuable insights to enhance safety management in air freight operations.

The oil and gas industry considers risk assessment crucial for addressing the substantial safety threats and hazards inherent in petrochemical production. Factors such as accident level, economic loss, reputation loss, and environmental pollution are among the major areas of concern. A traditional 5x5 risk matrix is employed by Tian, Yang, Chen, & Zhao (2018) [17] for risk assessment, which facilitates the determination of acceptable and unacceptable risks.

In the manufacturing domain, Turkey’s small and medium enterprises (SMEs) were surveyed, and a risk matrix approach was applied for risk assessment [18]; the findings indicated that SMEs prioritize global economic and geopolitical risks, while environmental risks rank lower in their list of concerns.

The risk matrix has found widespread application in disaster risk assessment at various levels, ranging from local to global. While most of these applications follow the traditional method with minor variations in defining hazard probability/likelihood and consequences, they often suffer from inherent limitations. Notably, many of these applications tend to overlook or insufficiently address the concept of resilience.

2.3. Advantages and Disadvantages of the Original Risk Matrix

Although the simplicity and usefulness of the risk matrix make it a valuable tool in risk management, it is subject to much scrutiny. As the use of the risk matrix approach in risk assessment expanded in different domains and levels, its advantages and disadvantages became clearer.

Some advantages/strengths of the original risk matrix are listed below:

- It is an intuitive graphical expression, which enables the combination of consequences and their likelihood to be represented graphically [2];
- It is a standard tool for risk assessment and presenting the relationship between consequence and probability [9];
- It is easy to understand and apply [2];
- It is well-received in practice [2];
- It Complies with and is recommended by international standards such as ISO (2002), ISO 31000 (2009), IEC 60812 (2006), ISO (2010);
- It has the capacity to be standardized for the entire organization in corporate settings [19];
- It is used as a guide for engineers [20];
- It is based on the accepted and standard risk definition, i.e., Risk=Probability × Consequence [1];
- It enables improvements in operational decision-making abilities by mitigating resource and distribution losses [20];
- It provides an easily understood representation of different levels of risk [7];
- It can be implemented in a short period of time [7];
- It aids risk-related decision-making process [7];
- It promotes effective discussion in risk workshops [7];
- It enables decision-makers to focus on the highest-priority risks with some consistency [7];
- It enables quick ranking and comparison of risks [7];
- It can be used to help develop a common understanding of levels of risk across an organization [7];
- Its communication within an organization requires no special expertise in quantitative risk assessment methods or data analysis [21];
- It graphically shows whether a risk is outside the risk appetite of an organization, i.e., the amount and type of risk that an organization is willing to pursue or retain [22, 23]; and,
- It graphically shows risk criteria, i.e., the terms of reference against which the significance of a risk is evaluated [22].

The disadvantages/weaknesses of the original risk matrix can be generally classified into four categories as discussed below.

- *Theoretical / Conceptual Issues*
  - It does not clearly address the concept of uncertainty [9];
  - It does not consider the risk attitudes/preferences of the decision-maker;
  - It has an ambiguous definition for the consequence component [1];
  - It has an ambiguous definition for the inputs and the outputs [21];
  - It has an implicit major hazard aversion [1];
  - It leads to risk aggregation, where the scope affects risk ranking [1];
  - Its level of risk tolerance depends on the jurisdictional levels, e.g., it may show a risk as tolerable at the corporate level but intolerable at a departmental or unit level [7];
  - Its risk assessment is limited to identified hazards only [9]; and,
  - Its mapping of consequence and likelihood attributes can produce subjective risk analysis/perception biases [24].
- *Methodological Issues*
  - Its symmetry between low-probability, high-consequence events, and high-probability, low-consequence events is a poor representation of how impacts are systemically experienced by people, institutions, and communities [25, 26];
  - It uses the same qualitative rating to describe very different quantitative risks;
  - It may result in risk ties given the limited resolution [21];
  - It often uses the same words for the level of risk as for the consequences [7];
  - It is often designed without reference to the risk profile of the organization or risks being analyzed [7];
  - It has no or inadequate alignment between risks with different consequences, e.g., financial, safety, and reputational [7]; and,
  - As a simple matric with few categories, it does not capture certain complexities such as the non-linear relationship between hazard frequency and consequence [27].
- *User Issues*
  - It may involve overestimating or underestimating the likelihoods and consequences by the user [7];
  - It is insufficient in many cases due to the complexity of assessment problems and diverse requirements [2];
  - It has a shortage of calculation logic when it comes to making full use of the data available and interfaces to integrate with other risk assessment models [2];
  - There is little rigorous empirical/theoretical study of how well it succeeds in actually leading to improved risk management decisions [21];
  - It does not take into consideration variations in vulnerability of exposed people such as age, gender, and health factors [1];
  - It may lead to the misrepresentation of risk levels due to inappropriate scales [28];
  - It can be challenging to ascribe meaningful consideration to the probabilities under examination due to their small magnitudes [29]; and,
  - Its value is affected by the presence of human bias and subjectivity [30].
- *Assumption Issues*
  - It assumes that the probabilities and consequences are well-understood and measurable [26];

- It assumes that the risk as defined by this model is a suitable construct for public decision-making [26];
- It assumes risk as a multiplication of likelihood and consequence, which generates risk-equivalent lines that cannot be accurately represented by a matrix [30]; and,
- It assumes that resilience can be ignored when assessing risk.

3. Risk Matrix Extensions

To address the limitations and enhance the practicality of risk matrices, alternative approaches such as the Borda Method have been developed to improve the accuracy of risk assessment. However, the Borda Method does not eliminate the possibility of risk ties completely since different inputs can yield the same output. Another approach called the fuzzy risk matrix (FRM) has been proposed by Markowski & Mannan (2008) [9], which utilizes fuzzy logic to handle safety analysis in various applications. The FRM includes three types: low-cost, standard, and high-cost matrices. The application of risk matrix analysis has also been extended to supply chain risk evaluation [2]. Despite these advancements, these methods still rely on the traditional risk matrix approach and may not be sufficient in complex assessment scenarios with diverse requirements. For instance, managing supply chain risk complexities involving detectability and recoverability concerns can be challenging. Some researchers have explored domain-specific risk assessment methodologies. Bekiaris & Stevens (2005) [31] develop a common risk assessment approach for driver assistance systems, but their treatment of detectability is simplistic, considering it merely as a prerequisite for applying mitigation strategies; they also propose recoverability as a measure of mitigation strategies.

In the following subsections, we discuss main risk matrix extensions under seven categories.

3.1. Extensions on Risk Definition

Some methods focus on extensions related to the definition of risk. The following are some examples of risk equations used at the state, country, and/or provincial levels [26]:

- Risk = Hazard + Vulnerability
- Risk = Probability × Impact
- Risk = (Hazard Exposure × Vulnerability)/Coping Capacity
- Risk = Probability × Mitigation potential
- Risk = Frequency × Consequence × Changing Risk
- Risk Factor Value (RF Value) = [(Probability × 0.30) + (Impact × 0.30) + (Spatial Extent × 0.20) + (Warning Time × 0.10) + (Duration × 0.10)]
- Risk Score = Probability/frequency + Magnitude/severity (includes economic impact, area affected, and vulnerability) + Warning time + Duration of loss of critical facilities and services

Also, Ni, Chen, & Chen (2010) [32] investigate the resulting risk profiles given each of the four basic combinations of probability and consequence, i.e., multiplication, division, subtraction, and addition.

3.2. Extensions on Scale

In the existing literature, there are various approaches toward the quantitative scaling of the categories [1]. These approaches include equidistant categorization of likelihood and/or consequence [21], bell-shaped category definition [32], and logarithmic scaling [1]. These types of extensions, while recognizing some of the basic issues with the risk matrix, try to enhance the approach to obtain better results. One of the main scale-based extensions is the logarithmic extension.

The implementation of a logarithmic scale in the risk matrix is a straightforward improvement to its structure. It effectively addresses the issue of compressed range and simplifies the categorization of risks, which many analysts struggle to achieve in a defensible manner. Logarithmically scaled risk matrices have been utilized in various applications, as demonstrated by the assessment of sewer systems in Copenhagen [33] and emergency prioritization in Victoria [34]. Vose (2008) [35] advocates for the use of logarithmic axes when constructing risk matrices, and Jarrett, Westcott, & others (2010) [36] develop a generic logarithmic risk matrix and provide guidelines for its interpretation. Also, Levine (2012) [37] presented the creation of a robust and feasible logarithmically scaled risk matrix using letter codes.

3.3. Rezoning of Matrix Cells

The process of rezoning matrix cells allows for a more precise classification of risk indices by rearranging the distribution of various levels. This rezoning approach effectively reduces the ambiguity in the results of risk assessments. To rezone a risk matrix, the severity and probability factors are first divided into more levels, resulting in an increased number of matrix cells. Subsequently, all the cells are rezoned in accordance with the fundamental principles of risk matrices [9].

3.4. Borda Method

The Borda method is employed to prioritize risks based on multiple evaluation criteria, ranking them from most critical to least critical. This method employs a multi-voting technique, where each team member is given a number of votes approximately equal to half the total number of risks [5]. Individually, team members cast their votes for the items they perceive as having the highest priority. The votes are then aggregated, and the top risks are selected and ranked accordingly. This method has the potential to significantly enhance the precision of the traditional risk matrix approach by effectively reducing the occurrence of risk ties through its quantitative calculation.

3.5. Fuzzy-based Approach

The concept of a fuzzy-based risk matrix acknowledges that risk analysis and assessment cannot solely rely on deterministic approaches due to various uncertainties [9]. Risk assessment is influenced by both objective and subjective uncertainties. Objective uncertainty arises from the inherent randomness in the assessment process, while subjective uncertainty stems from limited knowledge and information. Fuzzy risk assessment (FRA) aims to address these uncertainties in the risk assessment process through several steps [32]. This approach has been applied to diverse fields, particularly in industrial risk assessments [38, 39].

3.6. Utility-based Risk Matrix

The utility-based risk matrix is developed to address the limitation of traditional risk matrices in incorporating the risk attitudes of decision-makers [11]. This approach aims to provide a more comprehensive evaluation of risk by integrating risk attitudes using the Utility theory; this theory is widely used in decision-making models under risk and uncertainty, with the utility function serving as a means to demonstrate and quantify risk attitudes. For instance, a linear utility function is employed to represent a risk-neutral attitude, while an exponential utility function, the inverse of the logarithmic function, indicates a risk-prone attitude.

The utility-based approach connects risk attitudes with the risk matrix through the utility function. In this expected utility framework, risk values are presented as probabilities and losses, visualized in a two-dimensional space using utility indifference curves, which bear resemblance to the risk matrix approach; each point on the same utility indifference curve represents the same expected utility value [11]. This approach has been applied to different settings, such as supply chain risk management [40].

3.7. Indirect Consideration of Resilience

Several alternative and innovative approaches have been proposed to enhance the traditional risk matrix, modifying or expanding its common definition (i.e., Risk= Probability × Consequence) to include additional factors beyond probability and consequences. These approaches emphasize that risk analysis and hence the risk matrix should consider other elements in order to provide a comprehensive risk assessment. Although these methods may not explicitly refer to themselves as resilience-related approaches, they can be classified as such because they incorporate certain aspects or elements of resilience in their risk definition and the risk matrix development. Some of these extended versions are described below.

Detectability and Recoverability: Li et al. (2013) [2] propose an extended risk matrix that, while retaining severity and probability, includes two additional dimensions in risk definition: detectability and recoverability. Detectability refers to the ability to sense the occurrence of a risk event, assess its consequences, and take measures to avoid or minimize its impact [41]; the argument is that risks that are difficult to detect should be ranked higher compared to other risks with similar probability and consequence levels. Recoverability is defined as the system's ability to return to an acceptable level of operation after a risk event has occurred [2]. The ability to recover from an altered state is a common aspect found in resilience definitions [42]; in general, risks with lower levels of recoverability would be ranked higher than those with higher recoverability.

Vulnerability and/or Coping Capacity: Vulnerability refers to the underlying condition of an element that makes it susceptible to negative impacts resulting from a threat [43]. Coping Capacity is the collective term used to describe the methods employed by individuals or organizations to utilize their existing resources/capabilities (before, during, and after the occurrence of a disaster) to effectively manage the associated adverse consequences [44]. While vulnerability primarily directs attention toward communities and individuals, coping capacity serves as a measure encompassing prevention/mitigation, preparedness, response, and recovery efforts [45]. Several formulas have been developed to include these elements in evaluating risk, which can be used in the development of risk matrices. One such formulation is "Risk = (Hazard × Vulnerability)/Coping Capacity", where hazard refers to the likelihood of a specific threat occurring within a defined timeframe, such as the spatial-temporal forecasting of a threat.

Changing Risk: Factors such as mitigation actions and climate change can influence the frequency and consequence of risk events. To accommodate these changes, the concept of Changing Risk is introduced, which comprises the combined effects of changes in both frequency and vulnerability. In other words, "Changing Risk = Change in Frequency + Change in Vulnerability", and the two components are calculated based on answers to a series of questions about frequency and vulnerability dynamics for a given hazard [46].

While the abovementioned extensions indirectly include some aspects of the resilience concept, they do not explicitly incorporate resilience into the risk matrix formulation and design. Given that this paper uses a resilience-based approach in risk matrix development, we provide further relevant details in the following section.

4. A Resilience-based Risk Matrix: Importance of Resilience and Survey Results

4.1. Resilience and Risk Assessment

The term "resilience" was initially introduced by Holling (1973) [47] to describe the capacity of systems to endure and absorb changes and disturbances while preserving the same relationships among populations or state variables. Since then, various definitions have been provided for resilience in the existing literature, which could vary depending on the context. For instance, in the engineering domain, Bruneau et al. (2003) [48] put forward a framework for resilience that focused on reducing the impact on structures; they emphasized concepts from engineered systems such as robustness, redundancy, resourcefulness, and rapidity. Another definition, this time from a geographic viewpoint, characterizes resilience as the ability to withstand losses during a disaster and to recover afterward within a specific area and timeframe; it recognizes the potential for loss as well as the response from both the natural and social aspects of the affected area [49]. To provide one last example, we note the definition of resilience in the supply chain context, which refers to the capability to prepare for, respond to, and recover from disruptions [50].

An important concept related to resilience is vulnerability. According to Matyas & Pelling (2015) [51], resilience should not be seen as the direct opposite of vulnerability. While there are areas of overlap between them, it is important to recognize them as separate concepts. Certain characteristics/qualities can contribute to both vulnerability and our ability to adapt; for example, old age can make us more vulnerable in certain ways, but it can also enhance resilience through the wisdom gained from experience, learning, and the ability to reflect on past challenges. Lei, Wang, Yue, Zhou, & Yin (2014) [52] argue that vulnerability directs attention to the condition of a system prior to a disaster, encompassing elements such as exposure and sensitivity. On the other hand, resilience is a process that primarily concerns the stages of preparation and recovery following a disaster; it aims to strengthen the system's capacity to withstand and bounce back from hazards.

Several metrics/measures have been proposed for resilience, which again, could be different depending on the domain. Bruneau & Reinhorn (2007) [53] present metrics to evaluate resilience by measuring the expected degradation in infrastructure quality; they account for factors like robustness, redundancy, resourcefulness, and the speed of recovery. Attoh-Okine, Cooper, & Mensah (2009) [54] examine various scenarios of infrastructure performance, including normal operation and unexpected events, and introduce an index for resilience measurement. Ayyub (2014) [55] proposes a quantitative resilience model that can be applied to a wide range of systems, including buildings, structures, facilities, infrastructure, networks, and communities; however, this model requires information on several variables such as failures duration, recovery duration, and residual performance of the system. Recognizing technical, organizational, social, and economic dimensions, Platt, Brown, & Hughes (2016) [56] favor quantifying resilience in terms of failure probability, failure consequence, and time to recovery. The interested reader is invited to refer to [57], who performed a synthesis analysis by systematically reviewing 174 scholarly articles on the measurement of disaster resilience between 2005 and 2017.

In this study, we use an empirical approach to measuring resilience, followed by the development of a risk matrix. To this end, we conducted a survey, and the participants from various businesses answered questions including their evaluation of resilience. More details are provided in the subsequent subsections.

4.2. Empirical Data

In pursuit of our objectives, we undertook a research initiative aimed at gathering and examining data pertaining to resilience and risk assessment. The primary focus was to comprehend the effects of operational risks on small and medium-sized enterprises. The ultimate goal of this endeavor was to formulate a risk matrix rooted in resilience principles, incorporating novel extensions to account for resilience considerations. The preliminary analyses were conducted by Asgary & Jones (2020) [58] and the results were presented as a research poster.

The businesses surveyed provided their assessments regarding the likelihood, consequences, and resilience levels associated with 23 major operational risk events expected in the next five years. A questionnaire consisting of five parts was designed and used for data collection. Part 1 pertained to general questions about the business such as its type, size, and location. For example, a question posed was "*What is the size of your business?*" with the following choices: *One full-time employee*; *2-5 full-time employees*; *6-10 full-time employees*; *11-20 full-time employees*; *21-50 full-time employees*; *51-100 full-time employees*; and *more than 100 full-time employees*.

Part 2 revolved around hazard assessment, asking the participants about the perceived likelihood of major risk events (e.g., supply risk, technology breakdown, natural disasters, and loss of key staff) for their businesses within the next 5 years; these questions used a Likert scale (*Very Unlikely*, *Unlikely*, *Moderately Likely*, *Likely*, and *Very Likely*). Part 3 centered on consequence assessment, asking the participants about their perceived consequences of those major risk events for their businesses; these questions also used a Likert scale (*Very Low*, *Low*, *Moderate*, *High*, and *Very High*). More specifically, the participants provided their perceived *likelihoods of risk events occurrences in the next five years* under hazard assessment and their perceived *consequences of risk events occurrences in the next five years* under consequence assessment.

Part 4 aimed to assess business resilience, where participants were asked to provide their resilience evaluation for each risk event, i.e., their level of preparedness, coping capacity, adaptation possibilities, ability to absorb the consequences, and fast recovery in case the risk even occurs; a Likert scale (*Very Low Resilience*, *Low Resilience*, *Moderate Resilience*, *High Resilience*, and *Very High Resilience*) was used in this part too. For instance, the participants evaluated whether their resilience against *technology breakdown* was *very low*, *low*, *moderate*, *high*, or *very high*.

In Part 5, utilizing the same Likert scale as in Part 3, respondents were asked about the contribution of several factors (e.g., effective and empowered leadership, business culture supportive of business resilience, and shared information/knowledge) to their business resilience. For example, the participants rated whether "*effective and empowered leadership (under a range of conditions and circumstances, including during periods of uncertainty and disruptions)*" had a *very low*, *low*, *moderate*, *high*, or *very high* contribution to their business resilience.

The survey was conducted during the summer and fall of 2020. Data were collected from a sample of 60 small and medium-sized businesses (ranging from 1 to 100 or more employees) across diverse industries in Southern Ontario, all of whom filled out the questionnaire. They were recruited using a combination of convenience and snowball sampling. Our analyses include descriptive analysis and risk matrix development, which we discuss in more detail in the following subsections.

4.3. Descriptive Analysis

The most frequent business categories that participated in our survey were from restaurant and retail industries. The business sizes ranged from one full-time employee (18.33%) to more than 100 full-time employees (6.67%). The average number of years the businesses were in operation was about 17 with a median of 2 years. Participants represented local (68.33%), regional (43.33%), national (16.67%), and international (28.33%) businesses. Around 43% of the businesses had a risk management or business continuity plan in place. Almost half of the businesses reported that they were significantly or very significantly affected by the COVID-19 pandemic.

Encoding the Likert scale answers to numbers 1 through 5, descriptive statistics were calculated for each survey item. Table 3 shows the mean (μ), median (η), and standard deviation (σ) for each risk event, considering hazard, consequence, and resilience aspects. Under the hazard component, loss of key staff, rapid and massive spread of infectious disease, staff sickness/absence, and non-delivery of goods/services seem to be among the more likely events. In terms of perceived consequences, supply-related risks, human error, loss of key staff, rapid and massive spread of infectious disease, and non-delivery of goods/services are among the main categories. Finally, risk events associated with the highest resilience on average, as reported by the participants, are insufficient training, human error, and machinery failure.

Table 3. Descriptive measures for hazard, consequence, and resilience assessment.

Assessment of	**Hazard**			**Consequence**			**Resilience**		
Risk Event / **Descriptive**	**μ**	**η**	**σ**	**μ**	**η**	**σ**	**μ**	**η**	**σ**
Supply risks (e.g., under-resourcing, unexpected demand)	2.58	3.00	1.01	2.63	3.00	1.13	3.18	3.00	1.02
Inadequate processes and procedures	2.15	2.00	0.97	2.27	2.00	0.84	3.25	3.00	1.04
Inadequate systems (e.g., technology)	2.07	2.00	0.99	2.25	2.00	0.86	3.22	3.00	0.96
Insufficient training	1.98	2.00	0.97	2.36	2.00	1.00	3.48	3.50	1.20
Human error	2.58	3.00	1.10	2.64	3.00	1.00	3.37	3.00	1.10
Technology breakdown	2.48	2.00	1.08	2.35	2.00	1.02	3.10	3.00	0.99
Machinery failure	2.30	2.00	1.21	2.43	2.00	1.21	3.42	3.00	1.15

Information technology (IT) risk	2.17	2.00	1.11	2.18	2.00	1.03	2.87	3.00	0.98
Failure of utilities (e.g., water and power outages)	2.42	2.00	1.08	2.45	2.00	1.20	2.90	3.00	1.23
Extreme weather events and natural disasters (e.g., blizzards, floods, earthquakes, wildfires)	2.30	2.00	1.12	2.53	2.00	1.35	2.72	3.00	1.26
Unforeseen events "Force Majeure" (e.g., terrorist attack, expropriation of assets)	2.12	2.00	1.11	2.34	2.00	1.25	2.33	2.00	1.16
Loss of key staff	2.62	3.00	1.18	2.83	3.00	1.21	3.15	3.00	1.18
Failure to attract or retain top talent	2.43	2.00	1.09	2.58	2.00	1.18	3.12	3.00	1.11
Rapid and massive spread of infectious disease	2.61	2.00	1.07	2.73	3.00	1.26	2.72	3.00	1.18

Table 3. Descriptive measures for hazard, consequence, and resilience assessment (continued).

Staff sickness/absence	2.80	3.00	1.10	2.57	3.00	1.18	3.07	3.00	1.30
Cyber risk (e.g., cyber-attacks, cyber-crimes, security breaches, data breaches)	2.17	2.00	1.06	2.23	2.00	1.09	2.97	3.00	1.28
Theft of product(s) and/or information, patents, etc.	2.25	2.00	1.11	2.20	2.00	1.02	3.08	3.00	1.20
Political instability	2.00	2.00	1.15	1.97	2.00	0.99	2.62	3.00	1.28
War and military conflicts	1.67	1.00	0.90	2.03	2.00	1.16	2.27	2.00	1.25
Cross-cultural risk	1.73	2.00	0.84	1.80	2.00	0.87	2.83	3.00	1.19
Labor action/strike	1.70	1.00	0.93	1.97	2.00	0.96	3.03	3.00	1.27
Building fire	1.95	2.00	0.75	2.53	2.00	1.41	2.50	2.00	1.21
Risk of non-delivery of goods/services	2.78	3.00	1.18	3.17	3.00	0.99	2.59	3.00	0.91

Based on mean and median measures, the following factors had the highest contribution to business resilience:

- Business culture supportive of business resilience (commitment to, and the existence of, shared beliefs and values, positive attitudes and behavior)
- Shared information and knowledge (knowledge are widely shared and applied in the business, learning from experience and learning from each other is encouraged)
- Shared vision and clarity of purpose across all levels of the business

- Effective and empowered leadership (under a range of conditions and circumstances, including during periods of uncertainty and disruptions)

4.4. Risk Matrix, With & Without Resilience

Based on average values, we created risk matrices *with* and *without* the resilience component. In essence, we aimed to assess risk using two approaches: one based on the Likelihood multiplied by Consequences, and another where we multiply Likelihood by revised Consequences, i.e., "Consequences divided by Resilience". Figures 2 and 3 show the corresponding risk matrices. It is important to note that the different y-axis scale in the latter case is for better readability only.

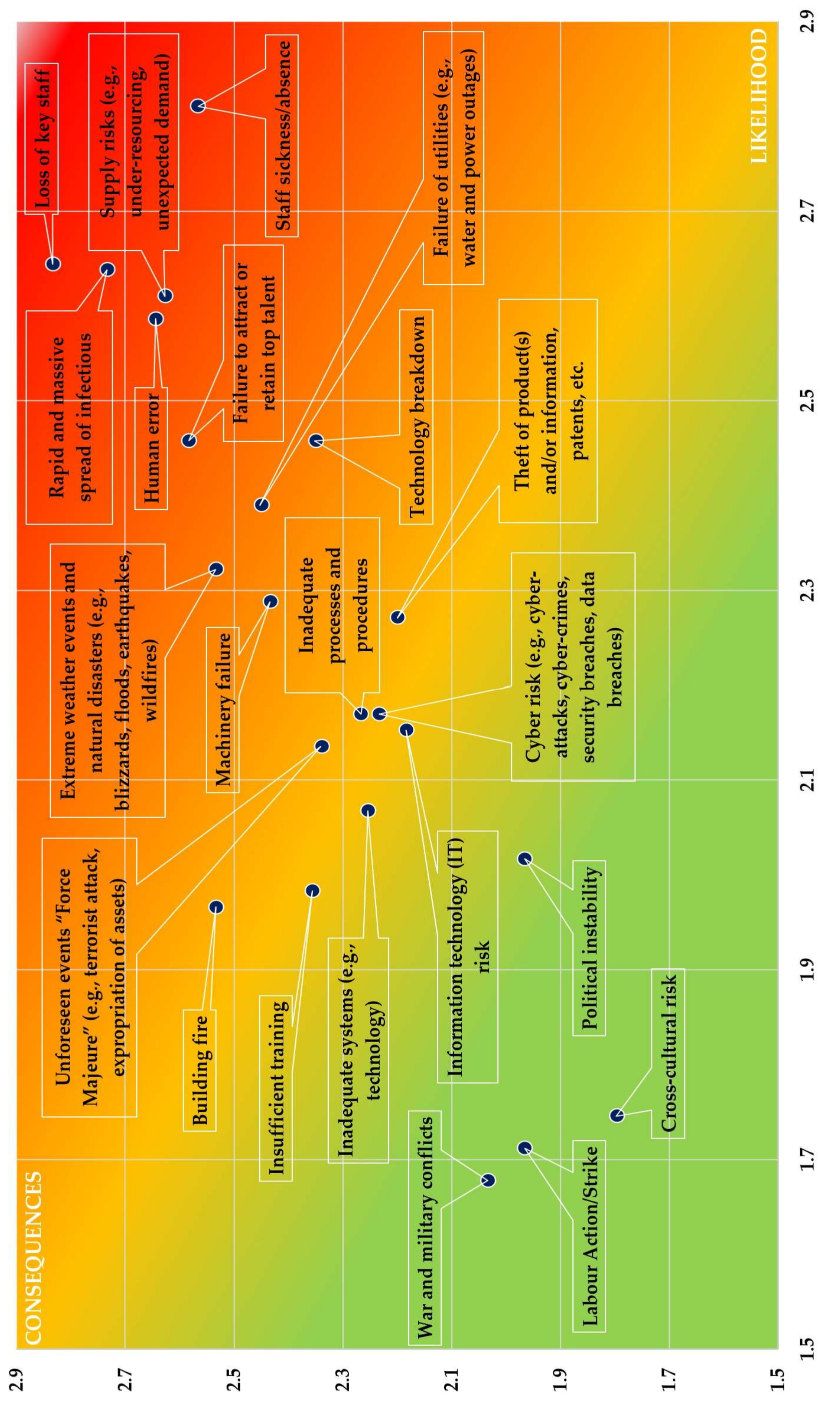

Figure 2. The developed risk matrix without the resilience component.

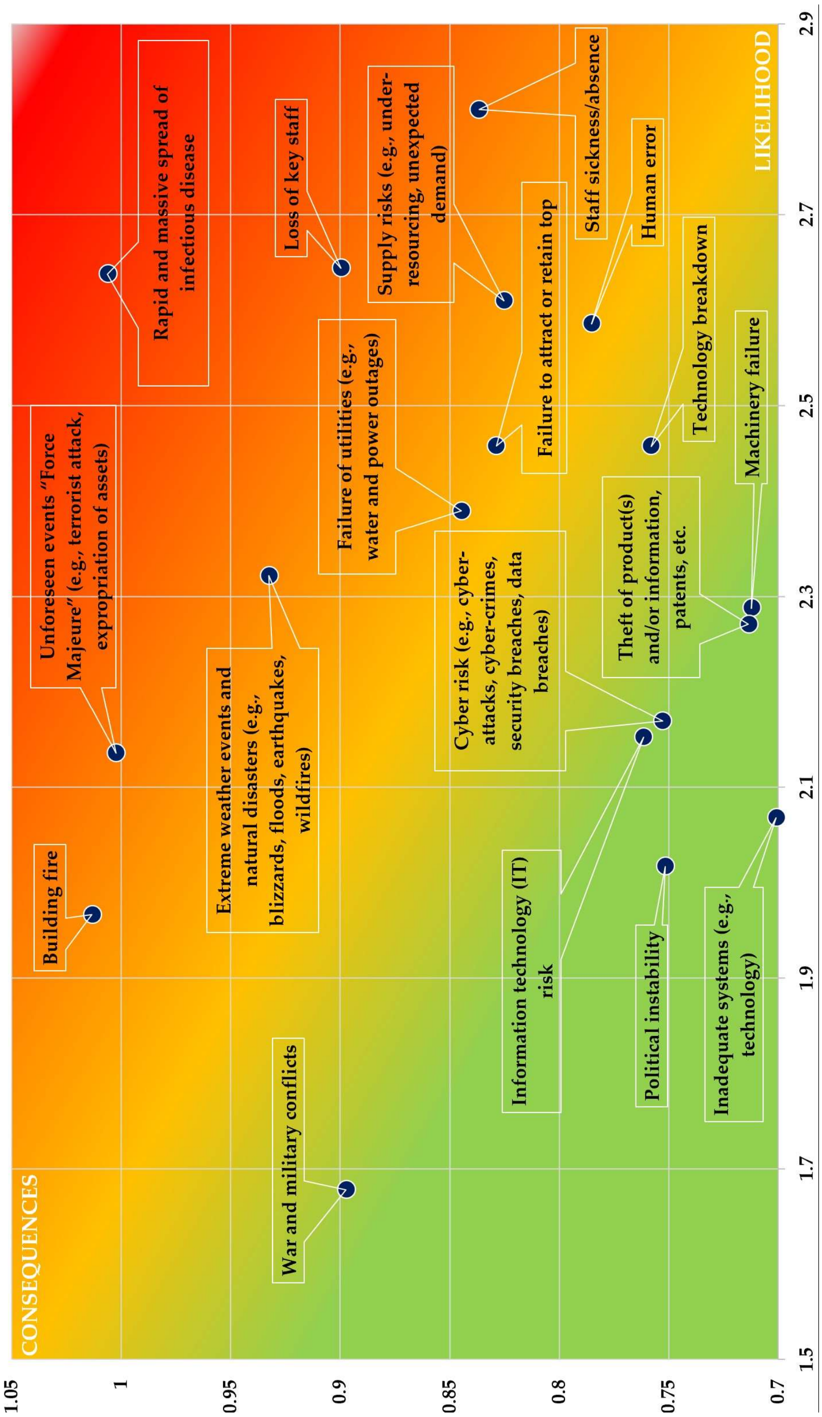

Figure 3. The developed risk matrix with the resilience component.

Our analysis of risk matrices demonstrated that when factoring in resilience, all 23 risk events shifted in the risk matrix. For instance, the "technology breakdown" transitioned from a medium likelihood and medium consequence to medium likelihood and low consequence. However, looking at the "staff sickness/absence", the consideration of resilience moves this risk factor from medium consequence to high consequence. These observations compellingly underscore the significance of resilience as a factor that should be integrated into the construction of risk matrices. Also, as shown in the above figures, other differences can be observed between the two risk matrices. The top-5 risky events in the risk matrix without the consideration of resilience are the following: (1) loss of key staff,

(2) staff sickness/absence, (3) rapid and massive spread of infectious disease, (4) supply risks such as under-resourcing, and (5) human error. On the other hand, the top-5 risky events in the risk matrix with the consideration of resilience are: (1) rapid and massive spread of infectious disease, (2) loss of key staff, (3) staff sickness/absence, (4) extreme weather events and natural disasters such as floods and wildfires, and (5) supply risks such as under-resourcing. Comparing the remaining risk events in the two cases would show further differences; hence, the incorporation of resilience in risk matrices could mean considerable differences in terms of allocating scarce resources when it comes to risk mitigation and management.

While the survey data is based on a relatively small number of businesses, its findings illustrate the difference that resilience integration could make in risk analysis and its important role in modern risk assessment/management practices. More specifically, the inclusion of resilience in risk matrix offers a more comprehensive and accurate evaluation as shown in our empirical analysis. Resilience measures a system's ability to anticipate, prepare for, respond to, and recover from disruptions or adverse events. Including this factor allows for a deeper understanding of how well a system can withstand and rebound from risks, beyond merely identifying the likelihood and consequences of those risks. It offers insight into the system's adaptive capacity, preparedness, and ability to manage unexpected challenges effectively, thereby enhancing the accuracy of risk evaluation by considering both potential impact and the system's ability to cope with it.

5. Conclusions

The increasing and evolving nature of disaster risks on a global, national, and local scale, driven by socio-political, environmental, and technological changes, has highlighted the critical importance of risk assessment for international agencies and governments at various levels. Risk assessment involves evaluating uncertain future situations by considering the potential consequences of an event and the likelihood of its occurrence. The original risk matrix was introduced in 1995 as a means to facilitate risk assessment. Risk matrix has gained wide acceptance as a simple yet effective tool for risk analysis and decision-making. Its popularity can be attributed to its utilization of basic risk components (consequence and likelihood) and its user-friendly nature.

Variations and extensions of the risk matrix have been developed to enhance its effectiveness or accuracy. A number of these extensions indirectly address some aspects of resilience, such as those considering detectability, recoverability, vulnerability, coping capacity, and changing risk. However, none explicitly include resilience in the risk matrix formulation. This paper aimed to explore the risk matrix and its extensions, discuss the significance of incorporating resilience into risk assessment, and apply a resilience-based risk matrix to empirical data.

Various metrics have been proposed to assess resilience in different domains. In the existing literature, relevant concepts/measures like robustness, redundancy, resourcefulness, recovery speed, scenario-based performance, failure duration, recovery duration, residual performance have been used to quantify resilience is different settings [48, 55, 57]. We employed an empirical method to quantify resilience and subsequently constructs a risk matrix. To achieve this, we administered a survey to participants representing small and medium-sized businesses, who provided their assessments of resilience through answering specific questions.

The main components of our survey were general questions about the business (e.g., its type, size, and location), hazard assessment of risk events, consequence assessment of risk events, resilience evaluation corresponding to risk events, and factors contributing to business resilience. Based on the collected data, descriptive analyses were provided. Within the hazard component, events such as the loss of essential staff, rapid and extensive transmission of infectious diseases, staff sickness or absence, and failure to deliver goods or services appeared to be more probable. In terms of perceived consequences, the primary categories included supply-related risks, human error, loss of key staff, rapid and massive spread of infectious diseases, and non-delivery of goods or services. Also, participants consistently identified inadequate training, human error, and machinery failure as the risk events with the highest average resilience. Factors contributing the most to business resilience, based on mean and median measures, were supportive business culture, shared information and knowledge, shared vision and clarity of purpose, and effective and empowered leadership across all levels of the organization.

We also developed risk matrices with and without the resilience consideration, i.e., one based on the Likelihood multiplied by Consequences, and another where we multiply Likelihood by "Consequences divided by Resilience". Our analysis of risk matrices demonstrated that when factoring in resilience, all risk events shifted in the risk matrix. We observed notable distinctions between the two risk matrices. In the risk matrix that does not incorporate resilience, the top five risky events were identified as (1) loss of key staff, (2) staff sickness/absence, (3) rapid and massive spread of infectious disease, (4) supply risks like under-resourcing, and (5) human error. Conversely, in the risk matrix that considers resilience, the top five risky events were (1) rapid and massive spread of infectious disease, (2) loss of key staff, (3) staff sickness/absence, (4) extreme weather events and natural disasters such as floods and wildfires, and (5) supply risks such as under-resourcing.

Resilience is an important aspect of risk assessment, and hence its consideration in the development of risk matrix can enhance the accuracy and effectiveness of this tool. In this paper, we discussed the original risk matrix, its applications, its extensions, and proposed a simple approach to account for resilience in constructing risk matrices, which illustrated using examples from our survey results. Integrating resilience into risk matrices could lead to significant variations in how limited resources are allocated for risk mitigation and management. Incorporating resilience into risk evaluations provides a broader perspective on how well a system can adapt, prepare, and handle unforeseen challenges, ultimately improving risk assessment accuracy by considering both potential impact and the system's capacity to manage it.

Although our empirical data analysis highlights the potential impact of integrating resilience in risk matrices and its significance in contemporary risk assessment and management, it's important to note that our survey sample size was relatively small, constituting one of the limitations of our study. Moreover, perception-based Likert-scale surveys, while useful for subjective estimations, have limitations in reflecting objective realities and may be biased. Podsakoff, MacKenzie, Lee, & Podsakoff (2003) [59] highlight biases distorting reliability, oversimplification of complexities, and limitations in precision, impacting survey insights. Potential avenues for future research could encompass analogous investigations in diverse settings, at larger scales, and with alternative methods for incorporating resilience into risk matrices.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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(Executive Editor: Wen-jun Li)