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Roadmap for incorporating risk as a basis of performance objectives in building regulation

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ABSTRACT

It has been suggested that future generations of building regulation can become more risk-informed and performance based, and that this can be best facilitated through viewing the building regulatory system as a socio-technical system (STS). A central component of the STS approach to building regulation is that government (regulators) and the market understand and agree the risk measure(s) that have and will be used to define the tolerable level of risks that are addressed through building regulation, the specific risk criteria that will be used in the evaluation of the risks for regulation and design, and the analysis and design approaches that will be used to demonstrate that building design solutions can be verified as meeting the risk criteria and measures. To support these efforts, a risk characterization roadmap is presented as guidance for building regulators embarking on efforts to use risk as a basis for building performance requirements. While the roadmap has been designed to address all health and safety hazards considered within building regulations, characterization of fire risk is used as an example throughout.

1. Introduction

Starting in the late 1980 s, the structure of building regulations in several countries began to be transitioned from prescriptive-based (i.e., providing large numbers of specifications that must be complied with) to functional- or performance-based (i.e., providing target outcomes or expectations, without detailed requirements) (NKB, 1978; SFPE, 1996; CIB, 1997; IRCC, 1998; Hadjisophocleous et al., 1998; Meacham, 1998a; Scholten, 2001; Meijer et al., 2002; Coglianese et al., 2003; Sheridan et al., 2003; Tubbs, 2004; Meacham et al., 2005; Pilzer, 2005; Duncan, 2005; Ang et al., 2007; Meacham, 2009). During the early days, most building regulatory entities adopted the ‘NKB level system’, also referred to as the ‘NKB hierarchy’, which suggested a structure that includes the following levels or tiers (NKB, 1978):

- Level 1a “the overall statement of the properties of a building that must be regarded as important from the point of view of society and its individual members” (i.e., societal goal).
- Level 1b, “the main properties specified as overall goal level classified in functional areas and principles laid down for the realization of the specified intentions” (i.e., functional statements).
- Level 1c, “operative requirements in order that principles laid down under Level 1b within the various functional areas may be applied in the design and construction of buildings” (i.e., performance requirements)
- Level 2, “instructions or guidelines laid down for verification of compliance with the requirements” (i.e., methods of verification)
- Level 3, “supplement to the regulations with examples of acceptable solutions, deemed to satisfy the regulations” (i.e., compliance documents, approved documents)

At this time, many functional- or performance-based building regulations did not include quantitative criteria within the regulations, reflecting rather a qualitative approach to describing required functional and operative (performance) requirements. However, it was recognized that to facilitate design and verification of design against the regulations, quantitative criteria would be necessary somewhere within the building regulatory system, and that clear linkages to documents which included those criteria would be needed. Several papers on these and related topics developed from concepts discussed within working and task groups of the International Council for Research and Innovation in Building and Construction (CIB) and the Inter-jurisdictional

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Regulatory Collaboration Committee (IRCC), which held a series of joint meetings in the late 1990 s and early 2000 s to collaborate on exploration and development of concepts, structures and guidance for development of performance-based building regulations (e.g., see Beller et al, 2002; Bukowski, 2002; Meacham et al., 2002).

One of the concepts that emerged from these discussions was the 'IRCC Hierarchy', illustrated in Fig. 1, which expanded on the NKB model with the inclusion of risk or performance groups and levels and risk or performance criteria (quantitative measures) (Meacham, 2004a). The aims of the IRCC hierarchy were to help reinforce the need that quantitative criteria exist somewhere within the building regulatory system, clearly linked to functional and operative (performance) requirements, and to illustrate how risk could be used as a basis for setting or describing performance expectations. During the period of 1999 – 2009, various building regulatory development entities explored means to quantify performance, use risk as a basis of performance, and link the concepts where appropriate (Meacham, 2010). For some, the desire for better quantification and consideration of risk as a basis of performance came as a result of regulatory system failures (e.g., May 2003; Mumford, 2010), whereas for others the motivation was related to examples where performance was already quantified, such as for structural design (e.g., Eurocodes, 2021). A significant external push came from engineering disciplines, which were developing and promoting performance-based design approaches, in particular earthquake engineering and fire safety engineering (e.g., SEAOC, 1995; Ghobarah, 2001; Meacham, 1998b), but also design for energy performance (e.g., Deru and Torcellini, 2004; EMSD, 2007) and indoor air quality (e.g., Persily, 2015).

Over the past ten years, there has been renewed interest in quantification of performance and use of risk concepts in building regulation, in particular regarding whether, and if so how, risk could be used as a common baseline for establishing health and safety performance requirements within building regulations. To explore this, research has been conducted with the following aims:

1. Investigate shortcomings in a sample of performance-based building regulatory systems: what they are, what impacts they have resulted in, and what is needed to overcome them,
2. Explore the potential for establishing 'tolerable' levels of risk (individual and societal) as the basis of establishing expected levels of safety and performance in building regulation,

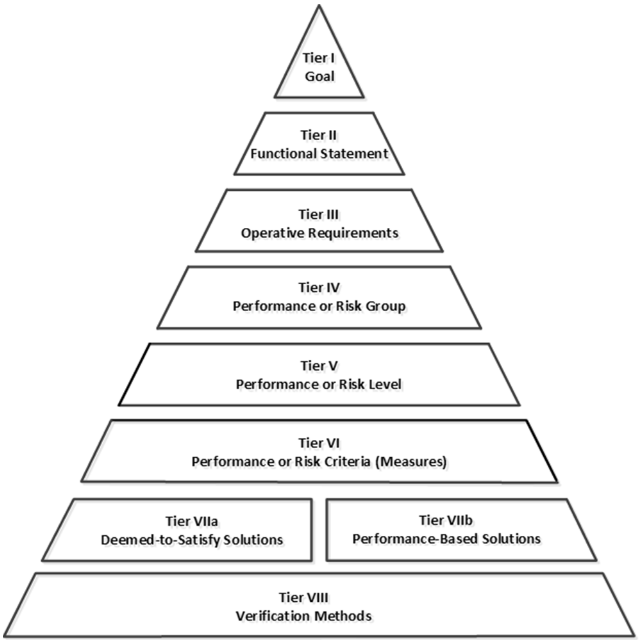


Fig. 1. IRCC Hierarchy (Meacham, 2010).

3. Develop a foundation for a risk-informed performance-based building regulatory system framework that addresses existing gaps and anticipates and adapts to emerging needs,
4. Develop guidance for building regulatory development entities to assist in the development of risk-informed performance objectives (including revision of existing objectives to this approach as well as for new objectives such as sustainability, circular economy and resiliency), and
5. Test the framework, or components of the framework, in countries which would like to move to a risk-informed and performance-based building regulatory system.

The focus of the work described in this paper is on aims (4) and (5).

2. Methods and materials

The roadmap presented below reflects the outcomes of qualitative research efforts, grounded in state-of-the-art reviews and case studies, supported by interviews with building regulatory developers, engineers and other stakeholders over the period 2016–2019. It also reflects collaboration between the authors, taking advantage or their expertise and experience in the areas of risk assessment, building regulation and building engineering. The roadmap reflects one piece of a broader set of work, which when combined provides a robust picture of the current situation and future opportunities for risk-informed performance-based building regulation. The overall research included an assessment of the state of performance-based building regulation, of the use of risk as a basis for establishing quantified performance metrics in building regulation, development of a framework within which risk could be used as a basis for establishing quantified performance metrics, development of frameworks for assessing building regulatory systems, and development of a roadmap for building regulatory developers to assist with incorporating risk as a basis of performance objectives.

With a focus on performance-based building regulation and regulatory systems, a primary resource for information was the IRCC (www.ircc.info), in particular those members which had defined programs exploring the quantification of performance objectives and the use of risk concepts in building regulation. It was determined that such direct interaction was the most appropriate way to gain the most current knowledge regarding practical developments in these areas. Discussion with IRCC members was complemented by a limited review of literature regarding the situation with performance-based building regulatory systems in representative European countries (e.g., Meijer et al., 2002; Ang et al., 2007; Meijer and Visscher, 2017; Osácar et al., 2021; Pedro et al., 2009; Meacham and Stromgren, 2019).

Given the aim of using risk as a basis for establishing performance objectives in building regulation, a major area of exploration was the attributes of a building regulatory system that help to inform a decision as to whether risk as a basis of performance might be feasible. It was found that approaches to regulation (e.g., O'Riordan, 1985), the form of law (e.g., Ale, 2005; OECD, 2010), trust and credibility in those involved in setting regulation, especially so in democratic decision-making systems (e.g., Slovic, 1993) and those involving risk in the decision (Kunreuther and Slovic, 1996; Stern and Fineberg, 1996; Poortinga and Pidgeon, 2003; Lachapelle et al., 2014), and accountability of actors in the system (e.g., May 2007; Mumford, 2010; van der Heijden and de Jong, 2013) are critically important. Development of frameworks and guidance to assist building regulatory developers in addressing these issues, within the context of their legal environment, would therefore be helpful.

With respect to the use of risk as a basis for regulation, it was found that risk has been playing an important role for some decades now, including environmental protection (e.g., NRC, 2009), occupational health and safety (e.g., HSE, 2009), nuclear power (e.g., IAEA, 2005), transportation (e.g., EMSA, 2014), structural performance of buildings and physical infrastructure (e.g., Vrijling, 2001; JCCS, 2001;

Ellingwood, 2015; May and Koski, 2013), hazardous facility planning (e.g., HSE, 1989; AIChE, 1989, 2007; 2009; NSW, 2011), and finance (Ojo, 2010). Various publications exist which provide issues to consider and approaches that might be considered regarding managing risk through regulation (e.g., Stern and Fineberg, 1996; Hutter, 2005; OECD, 2010; UN, 2012; van der Heijden, 2020), but not specifically within building regulation.

Importantly, emerging threats, such as climate change impacts, disaster reduction, terrorism mitigation, and rapid urban expansion (Kunreuther et al., 2004; Smolka, 2006; Thompson and Bank, 2007; IPCC, 2012; UN, 2012; World Bank, 2015; Hurlbert and Gupta, 2016; Clavin et al., 2020; Filkov et al., 2020) have accelerated interest in how more explicit consideration of risk in building regulation might lead to more sustainable and resilient built environment. At the core, effective approaches to developing more resilient built environments require an understanding of the hazard scenarios and associated risks, effective risk reduction measures, and implementation of those measures. While building regulations generally address natural hazards (e.g., earthquake, wind and flooding) and technological hazards (e.g., fire), unfortunately, resilience as a specific policy-level goal of building regulation is absent in many countries (Meacham, 2016). There are many reasons for this, including the fact that there are no universally accepted definitions for the concepts of sustainability and resiliency, and that they can be viewed as being a single concept (most often sustainability) or as separate ones (Marchese et al., 2018). Also, 'hazard mitigation' is already generally addressed in building regulation. However, as resiliency of the built environment become an increasingly important societal goal, building regulations will need to more explicitly address this, and doing so through a risk-informed approach is arguably the most appropriate approach to balance this with the other risks currently managed by building regulation.

There are many definitions and representations of risk and risk management. In the context of using risk as a basis for establishing performance objectives in building regulation, risk is viewed narrowly as a function of hazards which may impact buildings and their occupants, the potential consequences of the event occurrences, and the likelihood of unacceptable or intolerable consequences (outcomes) occurring (Meacham and van Straalen, 2017). This does not mean that managing the risk associated with design and regulatory approval (e.g., May 2003, Imrie, 2007; Imrie and Street, 2009; 2011; Greenwood, 2007), with reputational risk (e.g., Davies, 2002), with risk in the construction process (e.g., Schieg, 2006; Almeida et al., 2010; 2015), or with investment risk (e.g., Dziadosz et al, 2015), liability risk, and the many other sources of risk are not important: they are just not the focus of this research. Rather, the focus is exploring *what hazard-related risks are addressed by building regulation, are there means to determine whether acceptable or tolerable risk levels can be established and used for this purpose, and how might regulatory developers go about this*.

There is also considerable intermixing of the terms 'acceptable' risk and 'tolerable' risk in the literature. In the roadmap presented in Section 4 of this paper, the term 'tolerable' is used instead of 'acceptable' because the term 'acceptable' implies that the people at risk understand all of the factors associated with the risk – including whether or not they have any control over the risk – and make a conscious decision to accept the risk. This is typically not the case in regulation. Rather, people are generally not aware of all the factors influencing the risk – and that they may have little control over the risk – and therefore tolerate the imposed level of risk (e.g., see Fischhoff et al., 1981; Kasperson and Kasperson, 1982). Ultimately, establishing tolerable risk levels in regulation is a decision problem, in which different solutions to a risk problem provide different benefits, and tolerability is a function of the options available and the option(s) selected (e.g., see Tversky and Kahneman 1974, 1981; Fischhoff et al., 1981; May 2001; 2003; Poortinga and Pidgeon, 2003).

Determination of a tolerable risk level is a complex decision problem that requires experts, quality data, broad stakeholder involvement, and an appropriate deliberative process. As May (2003) notes, "On the one hand, determining levels of acceptable risk is fundamentally a value judgment that presumably requires some form of collective decision making. On the other hand, knowledge of relevant risk considerations, technical details, and costs and benefits are important for establishing meaningful standards. The first consideration argues for public processes for establishing safety goals. The second argues for deference to technical experts. Finding the appropriate middle ground is a serious challenge." With respect to technical experts, having them critically involved in regulatory decisions is important. As Burgess and Thomson (2015) note, there is a risk in the "overzealous use of secondary reference standards, where adoption commits the industry to mandatory conformance against those standards. Where drafted outside the administrative processes applied to the Building Code, referenced standards may not be subject to appropriate levels of stakeholder consultation, public review and regulatory impact analysis." Observation such as these point to the need to carefully address the trust and accountability issues noted above and finding a framework within which to address them. The analytical-deliberative process for risk decisions outlined by Stern and Fineberg (1996) provides a useful construct, which fits well within a socio-technical systems (STS) approach to building regulation development.

Socio-technical systems (STS) are defined by the interaction of actors, institutions, and technology in effective system operation (Emory, 1993). Trist (1993) identifies three levels of STS: primary work systems, whole organization systems, and macrosocial systems, which include systems in communities and industrial sectors, and institutions operating at the overall level of society, the latter of which include the infrastructure of the built environment. With respect to critical infrastructure and the built environment, STS theories and applications emerged around such areas as accident analysis and risk management (e.g., Rasmussen, 1997; Rasmussen & Svedung, 2000; Leveson, 2004; 2017), building-hazard-regulation interactions (Petak, 2002; Meacham and van Straalen, 2017), innovation in construction (e.g., Rohracher, 2001; Harty, 2005; Schweber and Harty, 2010), and critical infrastructure interdependencies and vulnerabilities (e.g., Edwards, 2003; Hansman et al., 2006; Kroes et al., 2006; Ottens et al., 2006; Jönsson et al., 2008).

Building from the STS literature, Meacham and van Straalen (2017) have suggested that building regulatory systems are STS due to the necessary interaction of actors (stakeholders / human aspects), institutions (organizational aspects) and innovation (technology / technical aspects) required to establish regulatory and market mechanisms to achieve acceptably performing buildings. They argue that since acceptable building performance, particularly for health and safety concerns, is connected to acceptable or tolerable safety / risk, adequately characterizing and reflecting tolerable risk is core to a successful building regulatory system. As such, their formulation of building regulations as STS necessarily reflects a structure in which characterizing risk for informing regulatory decisions regarding buildings (technology) is a central theme, illustrating relationships with institutional and actor subsystems in the policy decision-making process. To best reflect this, they suggest the conceptualization introduced by Petak (2002) is most appropriate to represent the socio-technical building regulatory system (STBRS).

The STBRS framework is characterized by two operational environments, 'legal and regulatory' (blue) and 'market' (green), within which policy decisions are made in an 'interactions' environment (red). The interactions environment consists of six subsystems associated with three key components: *technology* (Built Environment Subsystem (BESS), Hazard Subsystem (HSS) and Design, Construction and Evaluation Subsystem (DCESS) (blue boxes)); *policy / decision making* (Political, Economic and Societal Subsystem (PESSS) and Policy Formulation, Implementation and Adoption Subsystem (PFIASS) (red boxes)); and the *market actors* (Organizational Implementation Decision-Making Subsystem (OIDMSS) (green boxes)). The high-level interactions between sub-systems are illustrated in Fig. 2. Note that as discussed here, the Fire

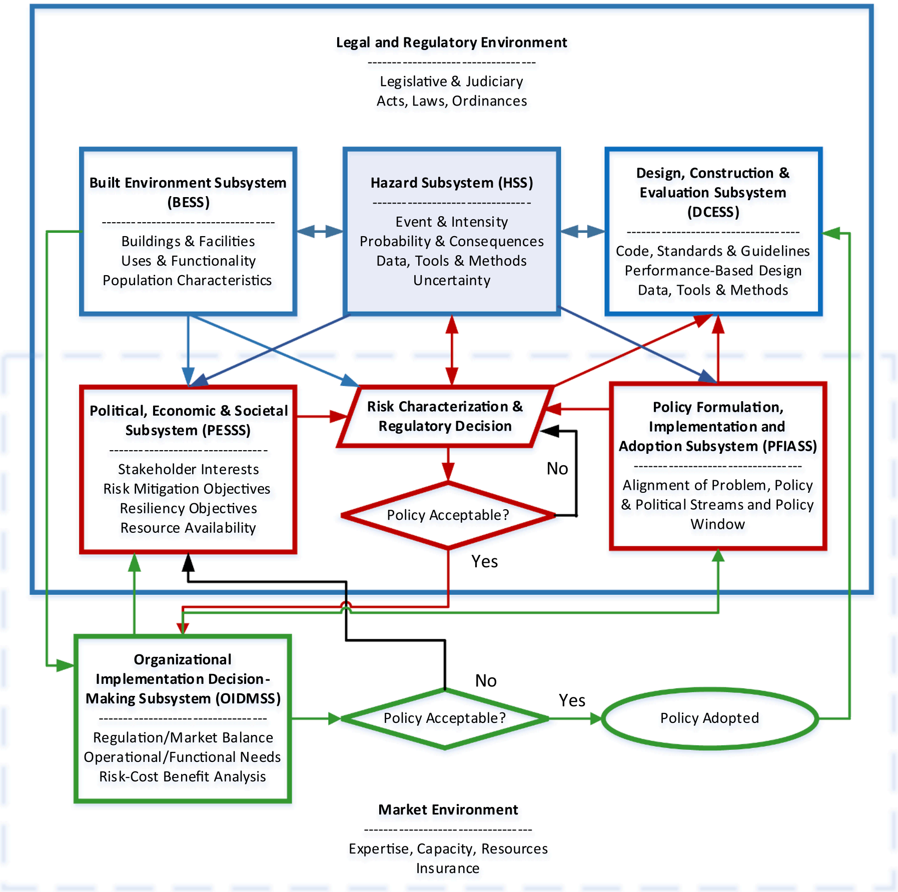


Fig. 2. Building regulatory system as a socio-technical system ().
Adapted from Meacham and van Straalen, 2017

Hazard Subsystem (FHSS) in the original formulation (Meacham and van Straalen, 2017) has been replaced with the more generic Hazard Subsystem (HSS). The BESS, HSS and DCESS interact with each other to describe/define the hazards, assessment approaches and mitigation options. The selection of regulated levels of performance, and tools and methods of analysis recognized for compliance with the regulations, are developed and agreed in the PESSS, PFIASS, and Risk Characterization and Regulatory Decision environment. The policy suggestions are vetted and balanced with market options in the OIDMSS. Arrows reflect influences.

It is worth noting the individual subsystems are also socio-technical systems, each with their own interactions that need to be considered. For example, the HSS needs to consider the range of safety and hazard events considered by the building regulation. The HSS will typically consider fire, earthquake, flood, wind and other hazards of importance. Each hazard will have different hazard characterization approaches depending on accepted practice in the associated disciplines (e.g., earthquake versus fire), which in turn has impacts on the overall risk characterization approach.

It is also important to note that even though reference standards and guidelines are shown as part of the DCESS, they may or may not become part of the regulatory environment depending on the legal and regulatory system since they may be used on a mandatory (regulatory) or voluntary basis (market driven). However, their placement reflects the typical role they play within the building regulatory system. In addition, there may be other regulations impacting and / or being developed within the DCESS, in particular where separate building regulations and fire (prevention) regulations are promulgated, related environmental regulation (e.g., energy performance / resource use) and so forth.

The risk tolerability decisions, which are central to the STBRS approach, can be explicit (e.g., risk-based or risk-informed decision making, including explicit consideration of probability and consequence) or implicit (e.g., prescribed solutions based largely on likelihood of event occurrence, without consideration of consequence, or on consequence / consequence avoidance). Arguably, most current building regulations take an implicit approach to risk tolerability decisions. For example, in case of fire safety it is deemed that a tolerable level of risk will be achieved if specific fire protection measures, regardless of the actual fire that might occur in a building, are in place, such as a regulated fire resistance rating for structural members, or minimum egress capacity. This concept has worked its way into the framing of fire safety engineering for fire, for example, with ISO 23932-1 (2018) stating that all fire safety engineering analyses are risk analyses which require comparison between estimated risk and tolerable risk, where the tolerable risk can be either explicitly stated (i.e., absolute or implicitly derived) or is implicitly defined by the regulatory provisions.

However, simply assuming that all building regulations adequately reflect societally tolerable risk levels may be incomplete. In some cases, a long-term 'regulation by disaster' approach to regulation may have added numerous provisions over time, without being subjected to a holistic assessment, to the point where there may be overlapping provisions, competing provisions, and perhaps 'over regulation' in some areas and gaps in others (e.g., Field and Rivkin, 1975). Concerns such as this helped facilitate the transition to functional- or performance-based regulation. However, these types of regulation may also have gaps in adequately managing risks, as can be observed with the 'leaky building' issue in New Zealand (e.g., May 2003; Mumford, 2010) and the Grenfell Tower fire in London and the English building regulatory system (e.g., DHCLG, 2017; 2018). Also, if a holistic review of the building regulatory system is not undertaken, there can be mitigation cost burdens imposed without the benefits that are anticipated (e.g., Greenwood, 2007; Ashe et al., 2009; van der Heijden and de Jong, 2013). It has been shown through a case study on the building regulatory system failure in England associated with the Grenfell Tower fire that application of a STS approach for assessing building regulatory systems can be helpful in identifying such gaps (Meacham and Stromgren, 2019; Meacham et al., 2020).

Instead of assuming that the building regulatory system adequately addresses a society's tolerable risk level for different events, and waiting for a regulatory failure to determine if the assumed level of risk imposed by the building regulatory system is in fact tolerable, a more proactive and transparent approach would be to implement a risk-based or risk-informed approach to building regulation and regulatory system development. In concept, risk-based implies that sufficient data are available to adequately estimate a tolerable risk level and design to that. A risk-informed approach, by comparison, considers that the risk data may be incomplete, or at a minimum, is not widely accepted or agreed, and that factors other than an objective calculation of the risk are needed to deem the risk tolerable (see for example the US Nuclear Regulatory Commission (USNRC, 2021) approach to risk-informed performance-based approaches). In either approach, however, quantifying the risk is an important step in the process.

While this may seem simple in concept, as overviewed above, there are a number of complicated factors that affect the identification, implementation and certainty of quantified risk criteria for use in regulation and the application of risk-informed and risk-based design, respectively. Meacham and van Straalen (2017) describe challenges and present a set of eight steps that can facilitate incorporation and acceptance of risk criteria and methods in a broadly universal manner within the context of the STBRS approach. The steps are illustrated in Fig. 3.

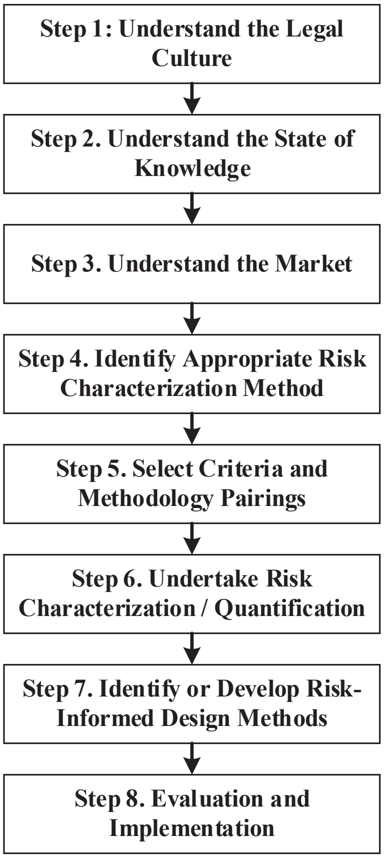


Fig. 3. Steps to Facilitate Incorporation and Acceptance of Risk Criteria and Methods in Performance-Based Building Regulation.

A brief description of the eight steps is provided below. Each step notes in parentheses where it links to the STBRS framework subsystems presented in Fig. 2:

Step 1. Understand the Legal Culture (Legal and Regulatory Environment): The legal culture (form of law, liabilities structures, etc.) and associated factors that can influence the characterization of risk, use of quantified measures and associated methods of assessment, and enforcement of risk-informed design within a jurisdiction (e.g., see Seiler, 2002).

Step 2. Understand the State of Knowledge (BESS, HSS, DCESS): Significant knowledge about the hazards/risks of concern, to whom or what, and under what conditions or situations, needs to be obtained. While characterizing the risk comes in the interaction phase, this step is needed to benchmark the state of knowledge.

Step 3. Understand the Market (Market Environment / OIDMSS): It is unlikely to have a successful risk-informed regulatory system if the market does not accept the concepts. Factors include whether the market is open to using risk-informed tools, if sufficient data exist to apply the tools with confidence, whether the education, competency assessment and professional qualifications systems in place, if the lines between what is regulated and what is market driven are well characterized and agreed, and whether supporting market instruments are in place, such as liability cover for engineers and loss protection for consumers.

Step 4. Identify Appropriate Risk Characterization Method (PFIASS, PESSS, Risk Characterization): Ultimately, to gain acceptance on tolerable risk levels, it will be necessary to have an interplay between experts and the public (or those representing the public) so as to come to an agreement about who is at risk, from what, how to quantify, what data are acceptable, what methods of assessment or estimation are acceptable, what level of uncertainty is acceptable, and how the resulting risk estimates are to be used. Factors such as historical risk / risk tolerability data, perceptions of risk, social equity, vulnerable populations, reliability of technology and related issues are likely to play a role in the process.

Step 5. Select Criteria and Methodology Pairings (HSS, BESS, PESSS, Risk Characterization): The likelihood that a regulatory risk criterion will be accepted depends on confidence by those bearing the risk that the development and selection of the criterion is based on sound data and methods, appropriately treats uncertainty and variability, is adequately valued, and can be readily and consistently applied. How well the criteria and methods reflect/incorporate public perceptions, values, input and expectations is critical.

Step 6. Undertake Risk Characterization / Quantification (Risk Characterization): In order to develop an integrally linked hierarchical construct such as envisioned in the IRCC Hierarchy (Fig. 1), which links concepts of tolerable risk to tolerable levels of building performance, a well-defined and transparent risk characterization process, reflecting the above, is needed.

Step 7. Identify or Develop Risk-Informed Design Methods (HSS, Risk Characterization, DCESS): If there currently building regulatory systems lacks appropriate risk-informed design approaches, then new standards and guidelines may need to be developed to support design and evaluation. Where such methods exist, it is likely they will need to be modified to accommodate regulatory changes related to such factors as the risk metrics, how the risk is to be assessed and how risk mitigation designs should be undertaken and evaluated.

Step 8. Evaluation and Implementation: As would be expected in any building regulatory system, it will be required to ensure that an appropriate balance has been achieved between regulatory and market objectives, that the market is able and willing to implement the policy, and that the right enforcement mechanisms are in place (regulatory, market or both). As part of any such evaluation, consideration of economic impact will be important, including cost–benefit assessments by policy makers and ultimately by the market on the benefits gained through the regulatory approach.

These steps are reflective of good policy development (Kingdon, 1995; Weimer et al., 2010; Coglianese, 2012; van der Heijden, 2020), risk governance (e.g., Aven and Renn, 2010; OECD, 2010; van der Heijden, 2019) and risk management principles (e.g., Stern and Fineberg, 1996; ISO 31000, 2018).

The roadmap presented below focuses on Steps 4–7, which reflects the activities of identifying, characterizing, quantifying, and developing assessment tools for the hazard-related risks of concern within performance-based building regulation. The specific components of the STBRS framework that is addressed is illustrated in Fig. 4. While there is some discussion on these concepts in the literature, in particular for individual building systems and components, such as structural design (e.g., Ellingwood, 2015) and fire safety (e.g., van Coile et al., 2019), and more broadly on incorporating risk into building regulation (e.g., Meacham, 2010), there is no comprehensive roadmap to guide policy and regulatory decisions on these issues. The following presents such a roadmap and associated rationale, building from Stern and Fineberg (1996), Meacham (2004; 2010); Meacham and van Straalen, 2018; van Coile et al. (2019); Meacham et al. (2020) and related works.

3. Roadmap for incorporating risk into building regulation

The principal aim of the risk characterization roadmap (roadmap) is to guide building regulators, as well as practitioners, in the process of incorporating risk as the basis of performance objectives in building regulation. This is a foundational component within a socio-technical building regulatory systems (STBRS) approach (Meacham and van Straalen, 2017; 2018), which argues that risk should be characterized within a framework for building regulatory policy decisions that utilizes available data, available tools, and the values and perceptions of those impacted by the risk, as this is critical to gaining agreement on risk measures, risk criteria, risk quantification means, and risk-based design verification means. To this end, the roadmap addresses:

- The need to identify and gain agreement on a risk measure (or set of risk measures) for the hazards of concern in the building regulation.
- The need to identify and gain agreement on risk criteria, which reflect the risk measures, that will be used for verifying compliance of designs against the established risk measures.
- The need to select tolerable risk thresholds and how this can be accomplished through 'aggregated' or 'non-aggregated' representations of individual and societal risk.
- Some important benefits and challenges of 'complex' and 'simplified' approaches for risk-based and risk-informed design approaches to demonstrate compliance with regulated risk measures.
- The need to appropriately couple risk criteria, analysis approaches, and design methods based on the selected risk measure(s).

As part of the roadmap process, hazard-specific approaches for characterizing risk and developing risk acceptance criteria, such as the approach outlined recently by van Coile et al. (2019) for probabilistic risk assessments for fire, are considered. However, approaches such as these largely focus on development of risk acceptance criteria from a designer's perspective; that is, there is an assumption that the engineer needs to make the risk acceptability decision as there are no regulated risk criteria to use. In this roadmap, a fundamental premise is that characterizing risk for use as a basis for performance objectives in building regulation, and selection of risk measures and risk criteria for use in those regulations, should be facilitated by government and key stakeholders as appropriate to the legal and regulatory environment. Leaving the decision to solely the market can result in multiple interpretations of risk acceptability / tolerability limits, which can result in uneven levels of building performance and safety. This reality has been identified by many in the fire area (e.g., Lundin, 2005; Alvarez et al., 2013, 2014; Bjelland et al., 2012, 2015) and beyond (e.g., May 2003; Mumford, 2010).

As a means to more transparently consider and select risk measures, the concept of 'aggregated' risk measures is introduced. In brief, an aggregated risk measure is a single representation of risk that can serve as a benchmark for setting tolerable risk criteria for use in regulation and design. There can be aggregated individual risk value and aggregated societal risk values. Section 4 introduces one approach to developing aggregated risk values for building regulation, which can serve as a basis for reflecting and balancing all health and safety objectives addressed by the building regulation.

With respect to 'aggregated' risk measures, this roadmap does not explicitly consider largely economic, willingness to pay, or benefit-cost approaches to quantifying risk, such as the life quality index (LQI) approach (Nathwani, Lind and Pandey, 1997). This is not to say that such approaches are not valuable; rather, that a different process / roadmap would be needed if a regulator were to adopt such methods, and that literature exists on how to do so. This includes discussion on

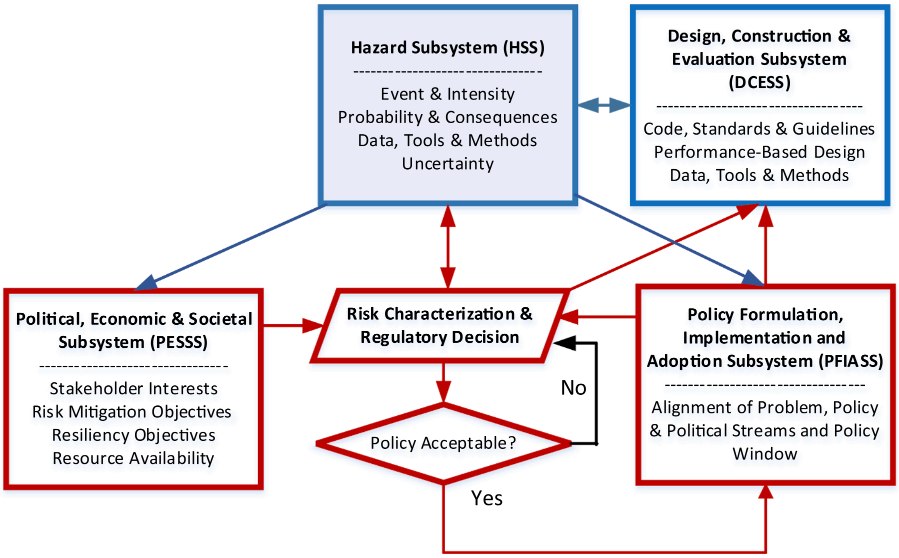


Fig. 4. Core Components of STBRS Framework Addressed by Risk Incorporation Roadmap.

how LQI can be used as a tool for the assessment of risk reduction initiatives that would support the public interest and enhance safety (Pandey and Nathwani, 2003), the application of the LQI approach to various safety domains, including fire safety (e.g., Hasofer and Thomas, 2008; De Sanctis et al., 2011; Fischer, 2014), structural safety (e.g., Lind, 2002, 2004), and natural hazards risk reduction (e.g., Sanchez-Silva and Rackwitz, 2004), and guidance for use in regulatory development (Fischer et al., 2011; 2013).

Also, benefit-cost analysis (BCA) (or cost-benefit analysis (CBA)) approaches are not specifically addressed, since these would be expected in step 8 (Evaluation and Implementation), which is not discussed in this paper. As with LQI approaches, the literature on BCA is extensive (e.g., Sunstein, 2002; Fischhoff, 2015), including concerns as a regulatory-setting tool (e.g., Ackerman and Heinzerling, 2004), especially for societal risks (e.g., Hopkins, 2015), and is not included in the roadmap.

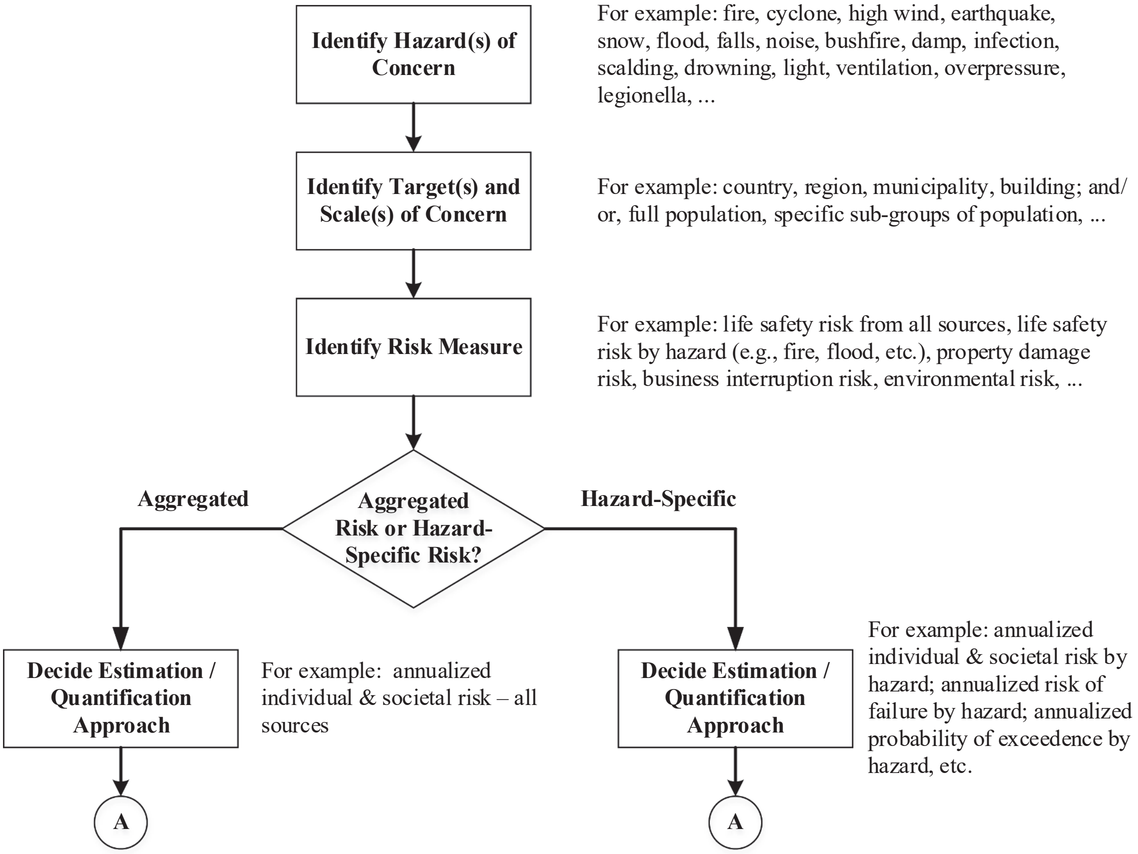
Finally, consideration is given to the supporting infrastructure within the building regulatory system as well, including the management of construction risk and the associated linkages as described by Almeida et al., (2010, 2015) in their Risk-Managed Performance-Based Building (RM-PBB) approach, which consolidates principles of quality management, conformity assessment, performance-based building and risk management. In particular, the RM-PBB approach provides useful insight into linkages to consensus standards as one set of tools for managing risk. Similarly, the STBRSAM approach (Meacham et al., 2020), which likewise illustrates the importance of linkages to consensus standards, but also to industry guidelines, data, information sources and communications pathways, in this case building from the models of Rasmussen (1997) and Leveson (2004) as applied to the building regulatory system as a whole, is considered. However, because these approaches are not focused on the development and vetting of risk criteria for use in building regulation specifically, they are not central to the roadmap process.

4. Identify and agree risk Measures, tolerability levels and criteria

The first part of the roadmap is focused on identifying and agreeing the scope or extent to which risk will be used as a basis for establishing regulatory provisions. This involves identifying the hazard(s) of concern (e.g., people, property), the scale of concern, and the measure(s) of risk to be used. Hazards are important to consider as a particular regulatory process may be driven by some or all hazards impacting on a building. Scale is important as one needs to differentiate large-scale impacts, such as seismic or hurricane impact, from local impacts, such as building fire. The decisions on hazard(s) and scale then impact selection of the risk measure, which can be individual and/or societal, and hazard-specific or aggregated (e.g., overall risk to life). These steps are illustrated in Fig. 5.

4.1. *Identify Hazard(s) of concern*

Since the focus is on the built environment, the hazards of concern reflect health- and safety-related risks in buildings. These might include: fire, cyclones/hurricane, tornado, high wind, earthquake, snow, flood, falls, noise, bushfire, damp, infection, scalding, drowning, light, ventilation, overpressure, legionella. To fit within the risk characterization steps which follow, it is important to consider what qualities of the hazard might affect judgments about the risk, such as whether it is localized or global, of low concern or catastrophic potential, and so forth. The hazard experience will be critical to inform the analysis. Historical data on hazard events (e.g., earthquake, flood, high wind, fire), knowledge of hazard development and transmission (e.g., legionella), and the ability to estimate or predict the hazards will be crucial. It will also be important to understand how hazards might overlap, or conversely, the hazard or risk mitigations overlap in mitigating the hazard (e.g., structural stability in the case of earthquake, flood, high



For example: fire, cyclone, high wind, earthquake, snow, flood, falls, noise, bushfire, damp, infection, scalding, drowning, light, ventilation, overpressure, legionella, ...

For example: country, region, municipality, building; and/or, full population, specific sub-groups of population, ...

For example: life safety risk from all sources, life safety risk by hazard (e.g., fire, flood, etc.), property damage risk, business interruption risk, environmental risk, ...

For example: annualized individual & societal risk – all sources

For example: annualized individual & societal risk by hazard; annualized risk of failure by hazard; annualized probability of exceedence by hazard, etc.

Fig. 5. Roadmap for Incorporating Risk into Regulation – Identify and Agree Scope.

wind, fire, etc.). This is particularly important since ultimately a balancing of risk will be needed, and single risk mitigation measures may help address multiple hazards.

4.2. Identify targets and Scale(s) of concern

It is important to clearly define who or what is at risk (targets). For building regulation, the focus is most often people. Even so, additional focus may be needed, i.e., the whole population or some subset of the population (e.g., vulnerable group). Property protection is sometimes considered in building regulation, most often related to minimizing risk to life and preventing damage to neighboring property in case of an event, but also for facilities deemed essential to operate during hazard events. Here again, additional detail is needed. Is the focus a compartment in a building, an entire building or a community? Although interruption of business or operations is largely addressed in the private sectors, aspects can sometimes be embedded into building regulation, especially as related to essential facilities.

Given that this process is applicable both to integration of risk metrics into building regulation, and for assessing the level of residual risk remaining following implementation of risk mitigation measures in a specific building or part of a building, identifying the scale is important. For societal life safety risk mitigation, community-wide consideration may be needed (e.g., earthquake, flooding, cyclone). For individual life safety risk, the scale may be focused on a single building level, or smaller, such as a compartment (e.g., fire, trips and falls).

4.3. Establish risk Measure(s)

Every way of characterizing risk requires value judgments. Ultimately, risk decisions are significantly policy decisions – whether in government or private-sector entity – that are informed by analytical data and stakeholder deliberation regarding the hazards of concern and the values of the society or entity. Some value decisions are difficult and controversial, such as value of a human life, which is one reason for concern with benefit-cost analysis (Ackerman and Heinzerling, 2004). As noted above, for building regulation, a primary concern is risk to life (or, providing safety to life) with respect to various health and safety hazards and hazard events. For purpose of discussion and examples, risk to life will be the primary focus in this article.

When dealing with safety to people, risk of injury or death are common risk measures. To gain acceptance, as discussed by Stern and Fineberg (1996), it will be necessary to have an interplay between experts and the public to gain agreement on who is at risk, from what, how to quantify risk, what data are acceptable, what methods of assessment or estimation are acceptable, and how the resulting risk estimates are to be used. Historical data, perceptions of risk, social equity, vulnerable populations and reliability of technology are likely to play a role in the process.

In general, there are two types of risk measure: individual and societal. Individual risk relates to the frequency or probability of an individual or an individual of a unique population group (e.g., children, women, elderly) being harmed given a specific hazard, sometimes assessed with respect to a specific location or as associated with a specific activity. Typical individual risks of concern include general health risks (e.g., cancer, respiratory disease, heart disease), safety risks (e.g., burns, asphyxiation, acute or chronic toxicity) associated with localized technological hazards (e.g., localized fire, explosion, chemical release), risks associated with accidents / unintended incidents (e.g., slips, falls, cuts from glazing). Individual risk can also be of concern as related to natural hazards and large technological hazards. The term ‘societal risk’ is often used when discussing risk associated with hazards or events that impact large geographical areas and therefore large numbers of people (e.g., natural hazards, such as earthquake and cyclone, or large technological hazard, such as open air chemical release). This concept also applies to hazards or hazard events that impact large numbers of people within a single building (e.g., fire in a high-rise building, large shopping center, arena, etc.).

4.4. Decide risk representation approach

Once the hazards, scale and risk measure are identified, the next steps involve determining how to represent the risk for use in regulation, establishing tolerable risk limits, and quantifying risk criteria. As with any approach to risk quantification, a potential concern is the availability and reliability of data, as well as how data are used in analyses. Once decided, risk can be incorporated as a basis of regulation. These steps are reflected in Fig. 6, which is a continuation of the roadmap given by Fig. 5.

As part of the risk decisions, it is important to determine whether to aggregate risks across the population or regulated area of concern for all risk/hazard contributors, or to consider each risk/hazard contribution individually. Either way, it is likely that individual and societal risk measures will be included in case of risk to life. The following outlines a process for identifying and agreeing individual and societal risk measures and acceptability thresholds for both hazard-specific and aggregated risk approaches. It is then discussed how the risk values could be incorporated into the building regulatory system as the basis for establishing performance objectives.

4.4.1. Hazard-Based risk approach

Hazard-based (non-aggregated) approaches are categorized as being based on a hazard-specific or facility-specific concerns, such as fire risk, earthquake risk, etc. Advantages to using this approach include the ability to establish risk-informed performance levels for building use groups (such as critical facilities, public assembly, domestic dwelling) based on hazard type, or to assess vulnerabilities to specific hazard types. A disadvantage is that such approaches do not inherently consider the whole of the risk profile impacting the target (person), which could lead to differences in tolerable risk level by hazard-specific, non-optimized solutions.

4.4.1.1. Individual risk criteria. As noted above, the focus in this discussion is on risk to life (fatality risk). Risk of injury can also be consider using this approach but is not considered in this discussion. Characterization of individual risk to life can be accomplished in several ways, and generally will depend on the way in which the risk information is intended to be used. For example, it can be characterized using annual mortality and population figures (number of deaths across the population divided by the total population). A time basis average can be used (same calculus, over say a 10-year period). It can also be considered based on age (and gender) across all events (intentional, unintentional and health). In some cases, only specific target populations are considered (typically those considered vulnerable populations). A limit-state approach can also be used, wherein the risk is assessed in terms of the relationship between the probable exposure (load) and the resistance to that exposure (e.g., probability of an earthquake of sufficient intensity resulting in structural failure leading to loss of life).

While challenges exist in identifying populations of concern, hazards to which they are exposed, means to reflect the risk, data for analysis (historical) and data for prediction, guidance is readily available (e.g., see discussion in Stern and Fineberg, 1996). In addition, there exist numerous resources which discuss quantification of individual risk (e.g., AIChE, 2009; Jonkman et al., 2003; Duijm, 2009; EMSA, 2015; van Coile et al., 2019; BSI, 2019), and which benchmark levels of individual risk reflected in various legislation (e.g., AIChE, 2009; HSE, 2001; Duijm, 2009; EMSA, 2015). Table 1 presents some of the types and formulations of individual risk criteria. To provide a consistent benchmark, the values in Table 1 reflect risk presented by hazardous facilities (e.g., chemical) for determining ‘safe’ distances for different population groups.

It is worth noting that as reflected in Table 1, there can be a range of

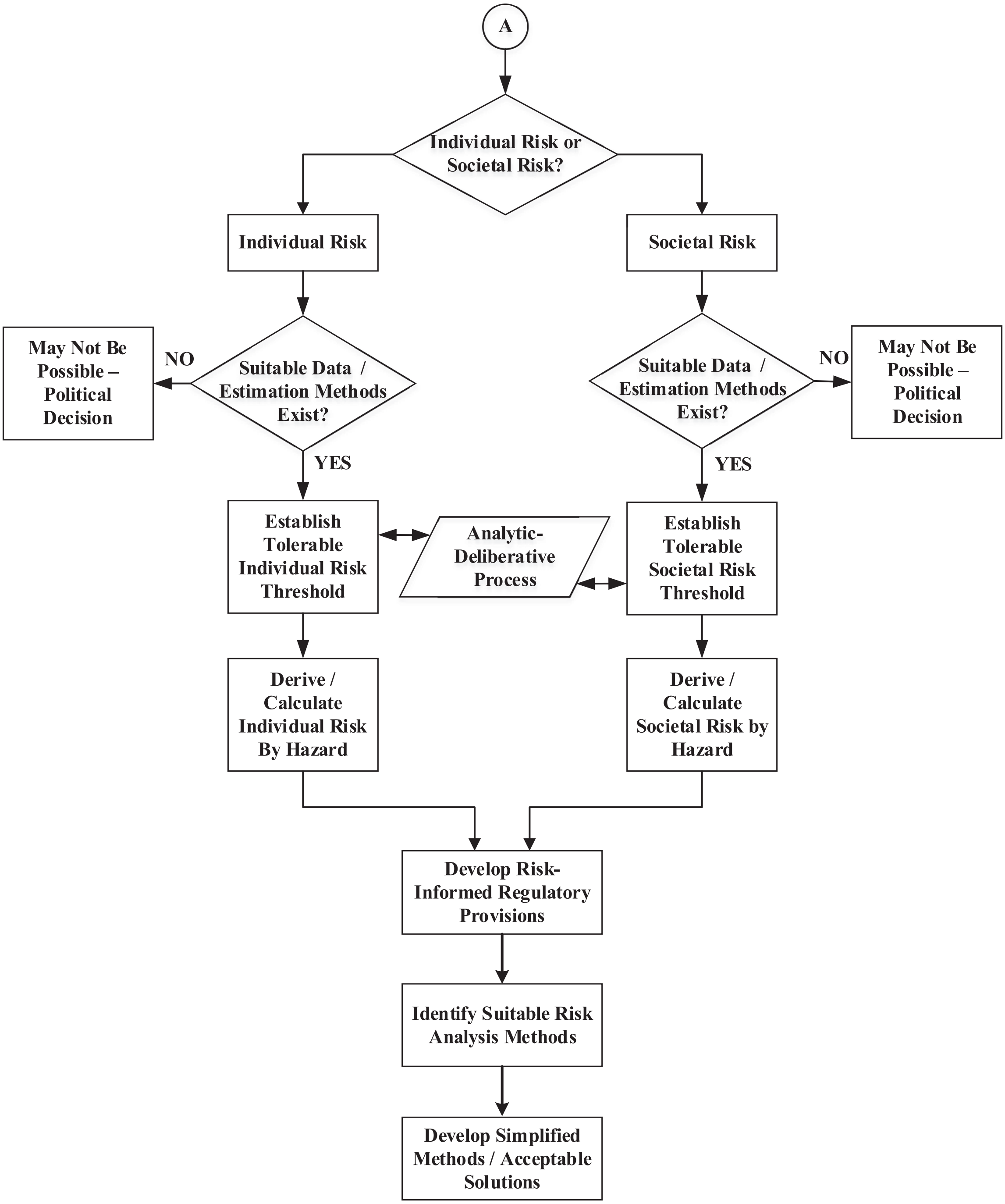


Fig. 6. Roadmap for Incorporating Risk into Regulation – Quantification and Incorporation.

risk acceptance / tolerability criteria, in part a function of the type of event and its consequence potential and the jurisdiction (culture / society) in which the criteria are set, but also reflective of the variability in the population, with some members of society more at risk than others (vulnerable populations).

4.4.1.2. Societal risk criteria. In much of the literature, societal risk is represented by criterion lines on an F-N curve, where generally F is the frequency of a particular hazard, event or type of event, and N is the number of fatalities, given that hazard, event or type of event (see for example, AIChE, 1989; 1999; 2009 VROM, 2005; Jonkman et al., 2003; Ale, 2005; HSE, 2009; EMSA, 2015; van Coile, 2019).

The origins of the F-N curve, or more broadly, probability-consequence diagrams, dates to early days of risk assessment as a more formal application in the nuclear safety area as a means to compare risks from nuclear power to those from natural hazards and transportation (Ale et al., 2015). Work by Farmer (1967), Starr (1969) and Rasmussen (1975) were instrumental at this time. The seminal paper by Starr (1969) laid the foundation for applying the concept of the F-N curve as reflecting society's level of tolerability to a specific hazard. In what some psychologists refer to as a 'revealed preference' approach (Fischhoff et al., 1981), Starr (1969) observed that: the public is willing to accept 'voluntary' risks roughly 1000 time greater than 'involuntary' risks; that the statistical death from disease seems to be a psychological benchmark for comparing acceptability of other risks; that the social acceptance of the risk is proportional to the third power of the benefits;

Table 1
Representative Types and Formulations of Individual Risk Criteria.

Type / Format	Source
Employees at the major risk establishment will be protected on the basis of normal occupational safety requirements. Workplaces at other establishments must not be exposed to a location-based risk of fatality (or equivalent qualitative criteria), greater than approximately 10^{-5} per year.	Duijm (2009)
General residential areas and other areas frequented by the general public, including schools, homes for the elderly, etc., must not be exposed to a location-based (individual) risk of death (or equivalent qualitative criteria) exceeding approximately 10^{-6} per year.	Duijm (2009)
The United Kingdom uses the term, 'consultation distance' (CD), which is comparable to safety distance in practice. These 'consultation distances' around each major hazard establishment are determined by the central authority, the Health and Safety Executive (HSE). Consultation distances are divided into three zones, so that the probabilities for exposure to a dangerous dose are 10^{-5} (inner zone), 10^{-6} (middle zone), and 0.3×10^{-6} (outer zone). These probabilities are approximately equivalent to individual risk or location-based risk.	HSE (1989)
The following risk assessment criteria are suggested for the assessment of the safety of location of a proposed development of a potentially hazardous nature, or for land use planning in the vicinity of existing hazardous installations: (a) Hospitals, schools, child-care facilities and old age housing development should not be exposed to individual fatality risk levels in excess of half in one million per year ($0.5x\ 10^{-6}$) (b) Residential developments and places of continuous occupancy, such as hotels and tourist resorts, should not be exposed to individual fatality risk levels in excess of one in a million per year (1×10^{-6} per year). (c) Commercial developments, including offices, retail centres, warehouses with showrooms, restaurants and entertainment centres, should not be exposed to individual fatality risk levels in excess of five in a million per year (5×10^{-6} per year). (d) Sporting complexes and active open space areas should not be exposed to individual fatality risk levels in excess of ten in a million per year (10×10^{-6}) (e) Individual fatality risk levels for industrial sites at levels of 50 in a million per year (50×10^{-6} per year) should, as a target, be contained within the boundaries of the site where applicable.	(NSW (2011)

and that the social acceptance of the risk is directly influenced by the public awareness of the activity. An example of an F-N curve is provided in Fig. 7, as derived from representative data of large life-loss events in Australia during the period 1875–2017 (Meacham, 2017). In addition to being used to understand risk from historical events, F-N curves can be constructed using quantitative risk assessment (QRA) as a predictive tool as well, across many types of hazards (e.g., see AIChE, 1989; 2009; Ale et al., 2015; BSI, 2019).

Once F-N curves are developed, one then need to establish the acceptability or tolerability criteria for the represented risk. This is most often accomplished by introduction of one or more F-N criterion lines reflect the target level of acceptable or tolerable risk of various hazardous activities or events. F-N criteria lines can be described with the following general formula: $1\text{-}F_N(x) < C \cdot x^n$, where n is the steepness of the limit line and C the constant that determines the position of the limit line (Jonkman et al., 2003). A line with a steepness of $n = 1$ is called risk neutral. If the steepness $n = 2$, the standard is called risk averse (Vrijling and van Gelder, 1997). In this case larger accidents are weighted more heavily and are thus only accepted with a relatively lower probability. Table 2 gives the values of the coefficients for some international standards for hazardous installations, with F-N criterion lines for these data shown in Fig. 8 (adapted from Jonkman et al., 2003).

The determination of a risk tolerability line (criterion line) is a judgment to be made by appropriate decision makers (Evans, 2003; Evans and Verlander, 1997), often reflecting a significant aversion to large life-loss events (i.e., slope of $n = 2$ as discussed above). Therefore, F-N curves derived from data alone should not be used as an indicator of tolerable levels of societal risk; rather, F-N curves derived from data should be used for reflecting the historical (or estimated) relationship between the frequency of events (hazards), which result in one or more fatalities per year, which can then be used to help establish the tolerable risk (reflected as criterion lines).

Also, when using the F-N curve approach for reflecting tolerable risk levels, some applications use at least two criterion lines, an 'intolerable' (unacceptable) limit, where any calculated risk above the line must be reduced, and a 'negligible' (or *de minimis*) limit, where any calculated risk below the line is deemed tolerable. In addition, for the region in between the criterion lines, the ALARA (As Low As Reasonably Achievable) or ALARP (As Low As Reasonably Practicable) concepts may be applied as a means to facilitate the use of mitigation strategies to lower the risk as close as practicable to the *de minimis* level. This is well-

Table 2
Some International F-N Curve Criterion Lines (Standards) (Jonkman et al., 2003).

Country	*n*	C	Application
UK (HSE)	1	10^{-2}	Hazardous installations
Hong Kong (truncated)	1	10^{-3}	Hazardous installations
The Netherlands (VROM)	2	10^{-3}	Hazardous installations
Denmark	2	10^{-2}	Hazardous installations

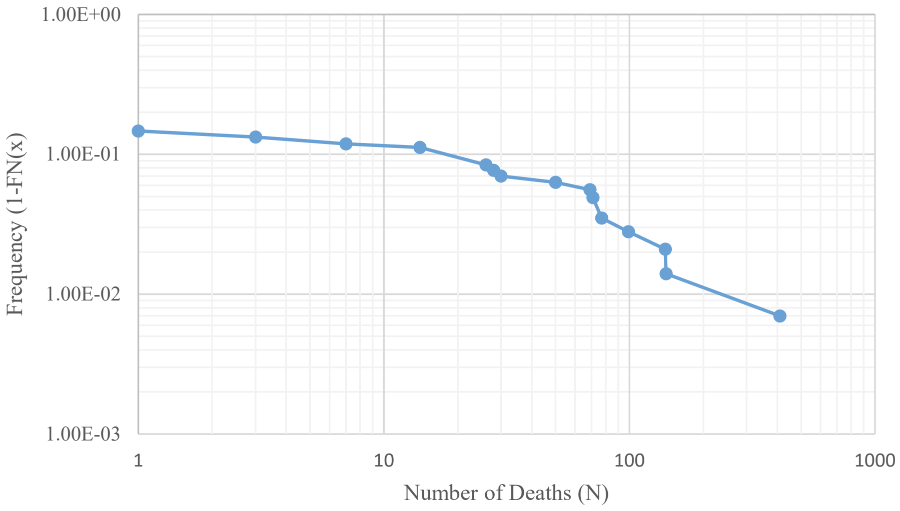


Fig. 7. F-N Curve for Cyclones in Australia (1875–2017).

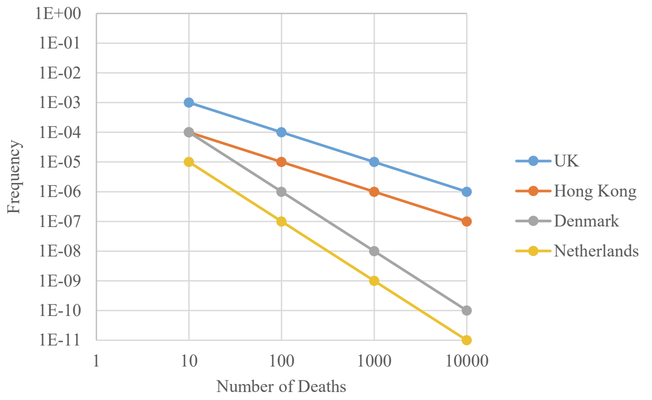


Fig. 8. Some International F-N Curve Criterion Lines (Jonkman et al., 2003).

described in the literature for various hazards (e.g., see Meacham, 2004; Ale, 2005; HSE, 2009; EMSA, 2014; van Coile et al., 2019). An example of F-N criterion lines for intolerable and negligible risk, with an ALARP region in between, for land use safety planning is provided in Fig. 9 (NSW, 2011).

In the examples above, the F-N criterion lines are reflective of single hazards / risks (hazardous installations, land use safety planning). However, as discussed below, a reflection of overall risk from all hazards, and associated criterion lines, can be developed as 'aggregated' risk measures.

4.4.2. *Aggregated risk approach*

As defined here, an aggregated risk approach is one in which risk contributions from various hazards are aggregated into single representation of acceptable or tolerable risk. This is a new approach for building regulation, which typically focuses on hazard-specific risks individually (i.e., risk of failure or fatality due to structural loading or fire individually, but not as components of a single risk measure). The single representation can serve as a regulatory baseline, against which the contribution of each hazard-related risk, as associated with a building or class of buildings, can be identified, tolerability levels set, mitigation measures developed, and efficacy assessed.

4.4.2.1. Aggregated individual risk. An advantage of using the concept of an aggregated risk measure is that it reflects the balanced mortality risk of an individual or social group through its whole life. This allows one to consider the contributions from different sources and make mitigation decisions that are balanced appropriately between various contributors (e.g., hazards), societal costs, and related factors. An exemplar aggregated individual risk metric is risk of death from all sources addressed within the regulatory regime. In this case, risk of death from building related safety and health hazards. One could construct the aggregated individual risk value from a summation of individually derived hazard-specific risks, as discussed above (bottom-up approach). However, one could arguably develop a better substantiated metric by starting with a characterization of total risk from all sources and apportioning the risk within the regulated area based on the data (top-down approach). Both approaches can be used in the process, providing a form of verification.

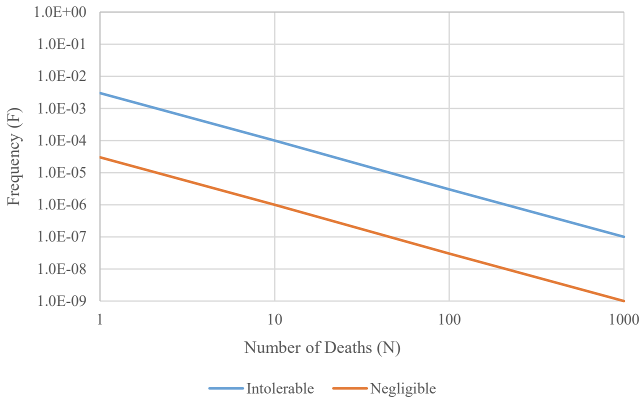


Fig. 9. F-N Criterion Lines – Intolerable, Negligible and ALARP (NSW, 2011).

In the 'top down' approach, nearly every country reports mortality and morbidity statistics. These data are either reported or estimated for most countries, regardless of economic classification of the country. The data are based on the International Statistical Classification of Diseases and Related Health Problems, 10th revision (ICD-10), as developed by the World Health Organization WHO. There are hundreds of ICD-10 codes, which cover illness, disease, accidental and other sources of fatalities and injuries. There are numerous ICD-10 codes that could be associated with risks in buildings, such as trips, falls, impact from falling debris, fire, scalding and more. There are several ICD-10 codes for burn-related deaths and injuries alone, including as caused by electricity; fire, flames; hot gas, liquid or hot object; radiation; steam; and thermal. These can even be reported at a more granular level, for example, deaths classified as by fire / flames can include reporting of such details as source inside or outside of a building, different fuel sources (e.g., bed, sofa), smoke inhalation and more (for example, see US Centers for Disease Control, ICD-10-CM for 'exposure, fire' (CDC, 2020)).

At an individual country level, sources such as the Australian Bureau of Statistics (ABS), Statistics Denmark, the Netherlands Central Bureau for Statistics (CBS), and the U.S. Centers for Disease Control (CDC) publish age-specific mortality rate data across all sources. Likewise, national (or other) databases with population numbers are readily available. The average annualized individual risk of death from all sources (or individual sources) can be estimated given such data. For quantifying individual risk to life (mortality risk), as averaged across the population, the following relationship can be used:

Aggregated individual risk = probability of an individual dying (1 / population of concern) × number of deaths (from any or all causes being considered)

If one considers fatalities from all sources, this can be considered the annualized background individual risk (total individual risk) of death. For example, the risk of death from all sources across the whole of the population in Australia can be estimated as follows, where the total number of fatalities in 2015 as published by the ABS was 159,052 (ABS, 2015), and the total population of Australian in 2015 was 23,940,000 (ABS, 2015a).

Average annualized individual risk (background individual risk) = (1/23,940,000 people) × (159,052 deaths/year) = 6.64×10^{-3}

Taking risk of death from all sources as a background individual risk benchmark, it follows that one can then evaluate the contribution from specific sources, such as building-related risks and hazards (i.e., component risk sources). It is suggested one can then reflect the risk contribution from component sources on a percentage basis. These would be benchmark individual component risk values. Such benchmark individual risk can be derived from deaths associated with building-related hazards.

4.4.2.2. Aggregated societal risk. As discussed above, F-N curves are often used to reflect societal risk, as they provide a means to represent the risk to large populations, typical from large events. In an aggregated risk approach, the starting point is assessing the historic risk to life across all large-life loss events. This analysis would be undertaken using data from the country or jurisdiction of concern.

For example, data on large life loss events for Australia can be used to create a historical F-N curve (Australia, 2017). Such a curve is illustrated in Fig. 9. It is derived in the same way as Fig. 3 above, which was for cyclones, but in this case, is for all large life-loss events, including natural hazards, technological hazards (e.g., fire and explosion), and

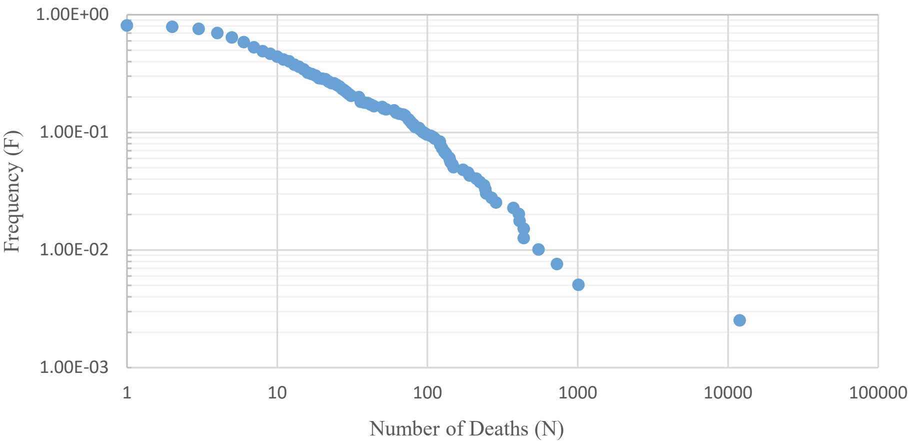


Fig. 10. F-N Curve – Modern Era Large Life-Loss Events in Australia (1804 – 2018).

health-related (e.g., 1918 pandemic). In Fig. 10, data for all multi-fatality events in Australia between 1804 and 2018 have been tabularized, cumulative frequencies have been calculated (e.g., number of 2-person life loss events, number of 3-person life loss events, etc. over the period), and the frequency (F) of events that resulted in the different number (N) of fatalities has been plotted.

While the numbers may seem high, one must consider the time span and the events considered (e.g., 1918 influenza pandemic, bushfires, cyclones, etc.). Also, while the above F-N curve reflects *historical* loss expectations for large-scale events, it does not specifically address fatality risk in buildings as associated with such events. In deriving and agreeing such a background aggregated societal risk value, factors such as time horizon, events considered, and of course representativeness and goodness of the data are important.

Consider life loss associated with fire and explosion hazards. At the time of the industrial revolution and soon after, there were many large life-loss events associated with exploding boilers, the high concentrations of workers in high-production mills with inadequate exits, and similar. As fire and life safety technologies were implemented in regulation, such as safety requirements on high pressure vessels (boilers), installation of automatic fire sprinklers, requirements for adequate means of escape, and so forth, such large life-loss diminished in frequency and number of deaths per event, and the overall risk to life from such events lowered. On a purely numerical basis, the risk of death due to fire and explosion is much lower today than it was 100 years ago. However, over the same period, risk tolerability changed as well. Today, a fire with as few as three fatalities may be considered catastrophic.[1]

In summary, one can adopt a 'bottom up' approach that focuses on hazard-specific risks, for individual and societal risks, and use those values as a basis for regulation. However, one can also adopts a 'top down' approach of developing singular aggregated individual and societal risk values as the basis for regulation. In many instances, aspects of both will be applied, both for setting specific risk criteria by hazard in the regulation, and as part of a 'check and balances' assessment of reasonableness of the metrics.

4.5. Developing tolerable risk thresholds for buildings

Regardless of the quantification approach adopted, to use risk as a basis of regulation, a decision is required regarding the tolerable risk threshold(s) (criteria) to be used, as this will become the benchmark against which designs will be compared. As noted in Section 2, the term 'tolerable' is used instead of 'acceptable' because the term 'acceptable' implies that the people at risk understand all of the factors associated with the risk – including whether or not they have any control over the risk – and make a conscious decision to accept the risk, which is typically not the case in regulation. Rather, people are generally not aware of all the factors influencing the risk and therefore tolerate the imposed level of risk (e.g., see Fischhoff et al., 1981; Kasperson and Kasperson, 1982).

It is suggested that for use in building regulation, one can establish tolerable risk threshold as a function of the contribution of risk imposed by those features of new and/or existing buildings, which fall under the bounds of building regulation (benchmark individual and societal risk), as adjusted to reflect societal preferences, uncertainty, and related factors. While arguably this should be the result of an analytic-deliberative process between government and stakeholders (e.g., Stern and Fineberg, 1996; Meacham, 2004), as a starting point, it is proposed that one can use the historically tolerable risk benchmark. This use of a 'revealed preference' approach for building regulation is not new, with suggested approaches suggested by Litai (1980), Rasbash (1984) and Wolski et al. (2000), for example.

Approaches of Litai (1980) and Wolski et al. (2000) provide suggested means for adjusting tolerable risk thresholds based on expressed preference attributes. This can be a helpful way to integrate societal perceptions of risk, as derived from surveys and analysis. However, this can be a time-consuming process, and care must be taken not to bias results based on the form of survey questioning. As an initial step, it is therefore suggested to start with a much simpler approach of establishing tolerable risk thresholds as a percentage of exposure to all sources of risk and adjust from there as appropriate. Other approaches are feasible as well, including how risk is considered for new and/or existing buildings.

For application of this concept in Australia, it was suggested that:

- The tolerable level of annualized individual risk of death from all relevant hazards that impact a new building (building to be constructed under the legislated risk threshold) shall not exceed 1% of the age-specific risk of death that people face from all sources (background individual risk).
- The tolerable levels of annualized individual risk of death from all relevant hazards that impact an existing building shall not exceed 10% of the age-specific risk of death that people face from all sources (background individual risk).
- The tolerable level of annualized societal risk of death from all relevant hazards that impact a new building shall be characterized by a criterion line applied to an F-N curve that reflects a tenfold decrease in the likelihood of a multiple fatality event for each tenfold

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[1] In the classification system used by the NFPA in the USA, catastrophic multiple-death fires are defined as a fire in a home that kills five or more people, or a fire in a non-home structure or non-structural property (vehicle and wildfires are included) that kills three or more people (Badger, 2020).

increase in potential fatalities, as anchored against the benchmark level of individual risk from regulated hazards for new buildings.

- The tolerable level of annualized societal risk of death from all relevant hazards that impact an existing building shall be characterized by a criterion line applied to an F-N curve that reflects a tenfold decrease in the likelihood of a multiple fatality event for each tenfold increase in potential fatalities, as anchored against the benchmark level of individual risk from regulated hazards for existing buildings.

The 1% and 10% of background individual risk targets as suggested for Australia were inspired by a Dutch approach to tolerable risk targets for populations around the potential site of a new hazardous facility. In 1988, a law was passed in which the tolerability limit for individual risk due to process industry hazards was set at 10^{-6} per year. The Netherlands Ministry for Housing, Land Use Planning and Environment (VROM) took the approach that since life expectancy in the Netherlands is highest for 14-year-old children, at a minimum death rate of 10^{-4} per year, exposure to a hazardous activity should be limited to only 1% of the already existing probability to die that year (10^{-6}) (Pasman and Vrijling, 2003). It was further determined that the risk to those around an existing facility should be limited to 10% of the already existing probability to die that year (10^{-5}).

Unlike this Dutch approach, however, it was suggested that the 1% and 10% targets for Australia be considered relative to the age of the population, since age is a key indicator of vulnerability. Again, it is well understood that there are a variety of factors which define vulnerable populations, diminished physical or mental abilities, but as a first approximation age seems to be a reasonable starting point. It also helps that there are clear regions where age and fatality rate is closely linked. Review of national statistical data allows for the individual risk from all sources to be looked at for specific ages. When this is done, one generally finds higher risks (mortality rates) for the very young and the very old. This is illustrated in Figs. 11, showing exemplar data from Australia and the USA.

The data reflect death rates per 1,000 of population by age group. Although the age groupings differ based on reporting by respective country, note that the shape of the curve is similar for each. This reflects the situation in most developed countries where the very young are at high risk (infant mortality), which lowers during the early childhood and teen years, increases slightly from about age 20 to age 30, and increases more significantly thereafter, as originally observed in the 1800 s (Gompertz, 1825). In this case, as reflected in Fig. 10, the average annual risk in both USA and Australia around 30 years of age is about 10^{-3}; however, risks for the very young and the very old are much higher. For a 10-year-old, the risk is about 10^{-4}: an order of magnitude lower. By contrast, for an 80-year old, the risk of death is about 10^{-1}: two orders of magnitude higher. The risk approaches 1.0 as one nears 100 years of age.

Differences may exist for specific age ranges, as well as for the slope of the curves, from country to country, and for different economic status. A very low risk of death from fire has been observed for the very young in Sweden, for example, which has partly been associated with the social systems that are in place (Jonsson et al., 2017). There can be hazard-related differences as well. However, in taking the approach of regulating for a target additional contribution of 1% above the background age-related risk, such variability can be taken into account, and the outcome is a more equitable distribution (1% for all).

For example, if a tolerable risk criterion of 1% above the background age-related risk is adopted for new buildings, and a single average value is taken across the population, the benchmark annual risk of death from all sources would be about 10^{-3}, and therefore the annual risk of death from building related hazards is about 10^{-5}. For existing buildings, the value would be about 10^{-4}. If the suitability of safety measures are judged on their ability to achieve that level for the entirety of the population, that would mean the risk of death from a building-related hazard for an 80-year-old person would have to be reduced to a level that is 4 orders of magnitude below the risk of death by all other means. The cost to reduce the risk of death for this population group, solely through building features resulting from provisions in a building code, would be significantly and restrictively high, and far from optimized from a net-social benefit perspective. It is simply not practical to reduce the risk of death to this population group so much just through building-related measures. This is why in practice we rely on human intervention as well, such as caregivers. The same can be said for the other at-risk group, infants. Building regulations, and the safety measures in buildings which result, are not currently aimed at protecting to a high level infants or the elderly; rather, it is expected that care givers will be helping these populations, and the risk mitigation levels are targeted at them.

By taking an approach where the target risk contribution from a building is no more than 1% of the background risk of the target population, a more achievable outcome is reached. For persons older than 80, the risk contributed by the building would not be expected to be more than 10^{-3}, whereas for those in the 30–45 age bracket, the building-related risk would about 10^{-5}, and for infants 10^{-4}, and for young children 10^{-6}. While some might say 10^{-3} for elderly is too high (too much risk), it should be understood that the ability of the person to respond (to alarms, to odors, to another person), to move (without slipping or falling), and to withstand the hazard, is already much lower than for say a 30-year-old, so the options become more limited and more costly. A

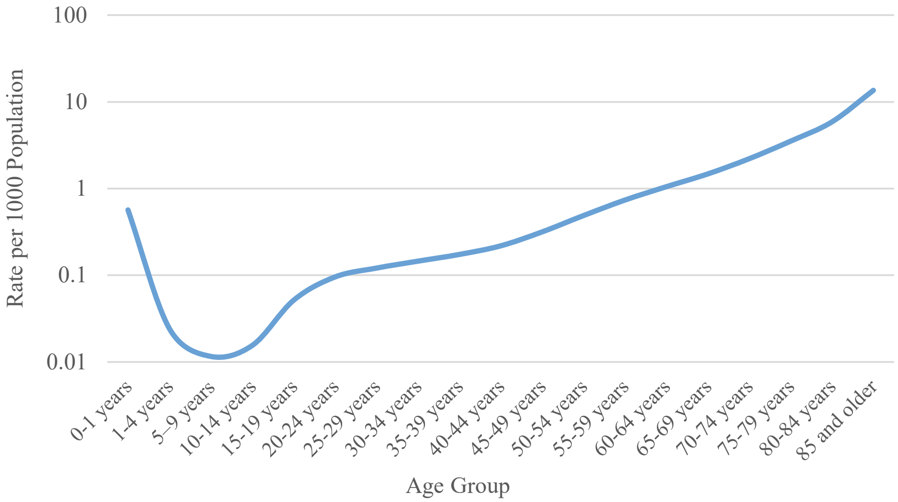

Fig. 11a. Age Specific Death Rates in the USA (derived from US CDC data (Heron, 2019)).

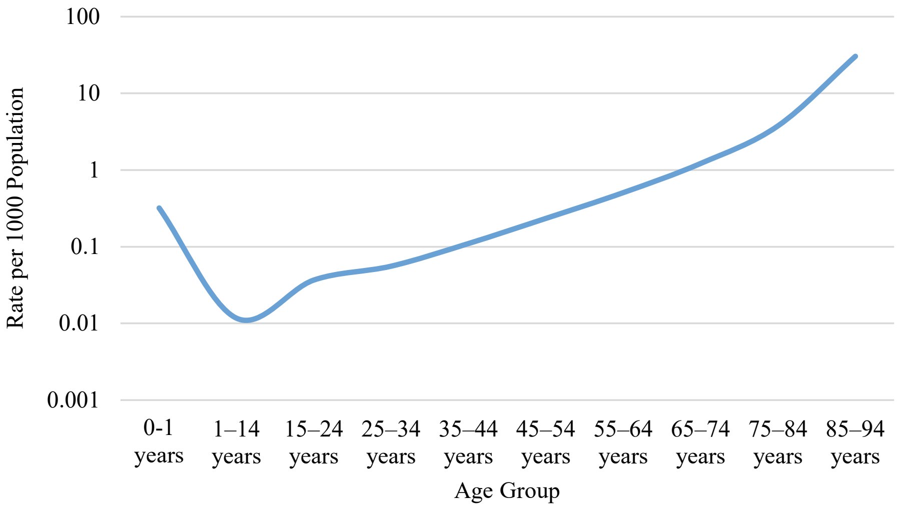

Fig. 11b. Age Specific Death Rates in Australia (derived from ABS, 2015).

society can choose to require measures to lower the risk, taking into account individual characteristics such as a desire to facilitate people living in their own homes longer, but such decisions should be made in balance with available resources and risk reduction measures in other areas. Likewise, concern might be noted relative to infants. However, for infants, the primary means of risk mitigation is the caregiver (parent, guardian, nurse, …). Infants cannot protect themselves from many risks (other than buildup of immunity to sickness and disease). They cannot move themselves. They cannot articulate their needs. There are few features, materials or systems that can be integrated into a building which, without additional intervention of a caregiver, can significantly mitigate risk to a level lower than 10^{-3}.

To assess the viability of the 1% and 10% approach as suggested for Australia to building regulation in another country, benchmarking of the individual and societal risk from all hazards will be required. This should be assessed in aggregate and for individual hazards. Examples of how this can be done are provided below. As noted above, other approaches can be used for establishing tolerable risk thresholds. If selected, they will have to be likewise justified.

4.6. Derive / select risk criteria

4.6.1. Development of component individual risk criteria

As discussed above, mortality data can be used to establish background individual risk. Referring again to Australian data, the total number of fatalities in 2015 was 159,052 (ABS, 2015), and the total population of Australian in 2015 was 23,940,000 (ABS, 2015a). This results in annualized average risk of death (background risk) in Australia from any cause of 6.64x10^{-3}. Going deeper into the data, one can identify fatalities associated with different sources, from health hazards (e.g., cancer, heart disease) to safety-related hazards (e.g., fire). Table 3 reflects analysis of ABS data regarding deaths due to hazards that could be associated with buildings.

Table 3
Average Annualized Benchmark Individual Risk from Safety-Related Regulated Hazards in Australia (Derived from ABS data (ABS, 2015)).

Source	2015
Falls	2.27x10^{-5}
Mechanical Forces	3.17 x10^{-6}
Drowning	3.17 x10^{-6}
Electricity and Temperature	4.59 x10^{-7}
Fire	2.38 x10^{-6}
Hot Surfaces	2.51 x10^{-7}
Forces of Nature	1.38 x10^{-6}
Total	**5.49 x10^{-5}**

The total becomes a benchmark individual risk measure reflecting the annualized risk of death from safety hazards addressed by building regulation of 5.49 x10^{-5}. A similar approach can be applied to building-related health risks (Meacham, 2017). When done for Australia, the total risk of death associated with building related health and safety hazards was estimated at about 5.79x10^{-5}, or about 1% of the background individual risk. Therefore, the 1% of background risk threshold limit would be an appropriate starting point for Australia as a benchmark value for risk to life from building related health and safety hazards. As appropriate, one can refine by age or other factor that is deemed important.

4.6.2. Development of aggregated societal risk criteria

As presented above, aggregated societal risk can be represented by an F-N curve derived from historical data on multi-fatality events across all hazard and hazard event types. Tolerable level(s) of societal risk are reflected by criterion line(s). An example of this based on Australian data is presented in Fig. 8.

The historical data from Australia are represented by the blue dots in Fig. 12. The slope of the data across all hazards is slightly less than -1, but quite close (the orange line, slope -1, is provided for comparison). This suggests that a criterion line aiming to align with the risk associated with historical events would be risk neutral. As discussed earlier in the paper and reflected in Fig. 7, however, a country may choose to set a criterion line that reflects a risk averse position. In such a case, they would apply a risk criterion line with a slope of -2. The level of risk aversion is a policy decision.

As discussed here, it is proposed to benchmark societal risk to the benchmark individual risk value as derived from the data. While 10 deaths is a common starting pointing for number of fatalities when using an F-N curve, the rationale in this case is that it should not be acceptable to have a lower value for risk of a single death than the agreed benchmark individual risk value, and therefore when one applies a criterion line to reflects tolerable societal risk, extrapolating back to a single death should not result in a higher risk than the benchmark individual risk value. However, as with all tolerable risk decisions, this is ultimately a policy decision to be made within the country of application.

If one then deems it reasonable to benchmark societal risk as being anchored to the current benchmark individual risk (6.64x10^{-5}, which is 1% of background risk, as discussed above), with the aim to set a risk neutral tolerable risk benchmark (applying a slope of -1), the resulting societal risk criterion line would be as reflected by the grey line. In this case, the benchmark background tolerable societal risk across all

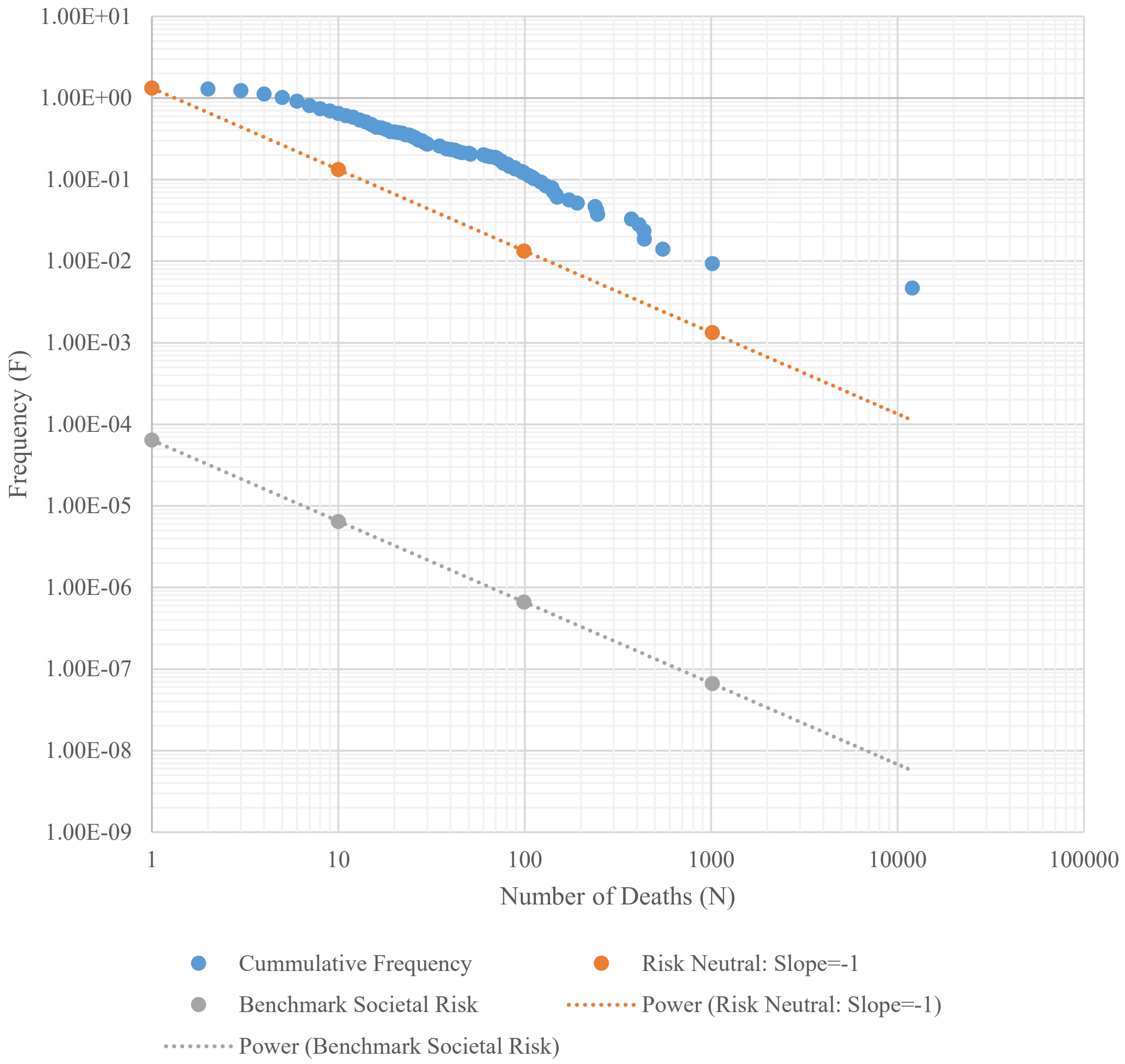

Fig. 12. F-N Curve, Risk Neutral Line and Suggested Tolerable Societal Risk Criterion Line.

hazards. The risk neutral criterion line indicates that each time the number of fatalities increases by a factor of 10, the expected frequency (and therefore risk tolerability level) reduces by a factor of 10. As with the aggregated individual risk, this provides a profile across all events. Such curves can also be generated for specific types of hazard events, such as earthquakes, cyclones, etc., or on a smaller geographic basis, such as state or city, to account for regional variations. As with the discussion of individual risk above, this can be considered the benchmark, or background, societal risk level as associated with natural hazards or other such events included in the dataset.

In summary, an aggregated approach allows for the establishment of singular criteria for tolerable individual and societal risk, upon which building performance requirements (or other regulatory objectives) can be established. As illustrated here, by analyzing past hazard events and associated mortality data, background risk and benchmark risk levels, for the regulated area (in this case buildings), can be established. Exemplar approaches for establishing tolerable risk levels for new buildings (1% of background risk) and existing buildings (10% of background risk) are presented. Representative background and benchmark individual risk values, based on data from Australia, are presented in Table 4.

As noted above, given these benchmark values, it is possible to make further refinements, such as by age, using for example the Gompertz curve representation of changing risk with age. How this might be

Table 4
Exemplar Background and Benchmark Individual Risk by Select Hazards in Buildings.

	Background Individual Risk	Benchmark Individual Risk (1% of Background)
All sources	6.64x10^{-3}	
Regulated hazards (buildings)		6.64 x10^{-5}
Falls		2.27 x10^{-5}
Mechanical forces (impacts)		3.17 x10^{-6}
Fire		2.38 x10^{-6}
Forces of nature (heat, cold)		1.38 x10^{-6}

Table 5
Exemplar Benchmark Age-Related Individual for Fire in Buildings.

	Benchmark Individual Risk
Fire (average across population)	2.38x10^{-6}
Fire (<5 years old)	1.50x10^{-6}
Fire (5 – 20 years old)	2.00x10^{-7}
Fire (20 – 80 years old)	2.00x10^{-6}
Fire (greater than80 years old)	2.00x10-^{5}

reflected is illustrated in Table 5 (estimated from Australian curve) for fire as a hazard.

In practice, specific values for such measures would result from review of country data and consultation with stakeholders in an analytic-deliberative process. While different approaches can be taken to derive these values, it is observed they are in line with values stated in the literature, as derived using other approaches. More research is welcome in this area.

4.7. Developing regulatory provisions

If a decision is taken to use risk as a basis for regulatory provisions, it likely means a changing in thinking regarding the regulation by both the regulatory body as well as stakeholders active within the building sector. The following are needed to clearly establish and validate the approach, engage the regulatory body and stakeholders, and develop useful regulatory analysis and design tools.

Clear indication of risk as a foundational regulatory metric. If risk is to be used as a basis for quantification of health and safety performance criteria – and as a basis for integrated performance assessment of buildings – this needs to be clearly stated in enabling legislation and regulatory documents and reflected as a foundational principle in the development of supporting documents (e.g., design guidance). Specifically, items such as the following should be stated:

- Risk shall be used as a regulatory benchmark for the establishment of performance requirements (criteria) that will be used for demonstrating compliance with the regulation.
- The approach(es) to characterizing the risk measure shall be _ (to be defined by the country).
- The approach(es) for quantifying risk criteria shall be _ (to be defined by the country).
- The approach for selecting the tolerable individual and societal risk criteria shall be _ (to be defined by the country, e.g., the maximum contribution to risk to life, as related to all regulated building features, be no more than 1% of ‘background’ risk for new construction and no more than 10% of ‘background’ risk for existing buildings).

Detailed assessment and characterization of baseline data. Prior to, or at least concurrent with, implementation of the above change, the required characterization of risk data is required. This is necessary to assess whether adequate data exist to support the intended risk-informed approach.

- For example, if an approach such as illustrated in this paper is to be applied, the age-based mortality rate data and historical F-N data for large-scale events should be completed, so as to provide the evidential justification for use in establishing this regulatory requirement. This will also be needed to serve as a basis for development of guidance documents for risk-informed analysis and design.
- As noted in this paper, this will involve exploring in more detail the age-specific mortality risk baseline and contribution from the built environment, confirming baseline values and describing how 1% and 10% values are calculated (if this particular approach is used), exploring in more detail the F-N curves for societal risks, benchmarking current risk levels, and describing how 1% and 10% values are to be calculated, and establishing the relative contribution of risk, from each regulated area, to the maximum (1% / 10% of background).

New language around assessment methods. When implemented, this approach will require the use of analysis and verification methods which may not be familiar to all stakeholders.

- For aggregated risk approaches, analyses will need to demonstrate that the total contribution of risk from regulated features, materials, components and systems, will in total not exceed a contribution to life risk of more than 1% of the background risk (if this particular approach is used).
- For individual risk (hazard) approaches, analyses will need to demonstrate that the risk associated with specific hazards will not exceed the regulated target.
- It is expected that new methods of analysis will be needed, along with guidance on their use and application. As part of these methods, it should be clear that the design team will have the responsibility for assuring that the materials, components and systems actually used in construction of the building are factored into the risk assessment and ultimate approval of the building.

New assessment methods and additional data. At present, it is recognized that the majority of approaches used to demonstrate compliance with building regulations in many countries are deterministic. While many deterministic methods can still be used in the future, they will need to be risk-informed, and the total contribution to risk, which results from the final building (as approved for occupancy), will need to be assessed.

- While there are risk-based standards currently in use for managing certain risks, such as the Eurocodes for Structure (EN 1990 series (EN, 2002)), this is not the case for all building risk sources and performance needs.
- While there exists guidance for use of some aggregated risk measures as a basis for design, such as the LQI approach (e.g., Fischer et al., 2019), there will need to be new guidelines focused on the aggregated risk approach based on the 1% and 10% targets as discussed above.
- Ultimately, it may be helpful to have an integrated (all hazards) risk verification method, which is able to consider the whole of the final building, and its expected performance, where a whole of building risk measure is used.
- Development of aggregated risk approach guidance may facilitate the need to include expertise not typically considered in building design, so as to take advantage of their knowledge, expertise, data, tools and methods.
    - o This might include: toxicologists, epidemiologists, ergonomists, public health officials, and others in the medical professions; sociologists, psychologists, data scientists and others from the social sciences; risk analysts, material scientists, environmental engineers and others from the scientific and engineering communities, in addition to structural, mechanical, fire, electrical, plumbing and other engineers, structural engineers who may be more typically involved.
    - o These groups would be able to advise on a number of required issues, including: availability, form and format of required data, what is needed to collect appropriate data, and how to treat uncertainty and variability in the data; acceptable methods for analysis, prediction and design given the risk target, the data, the building and the population; identification and treatment of uncertainty and variability in data, populations, analyses and design; development of verification methods for design and review based on the above, and development of application examples, education and training material.

Political, industry and consumer support. Ultimately, for risk to be an effective basis for building regulation, buy-in from stakeholders within the building sector is needed across all levels. This ranges from agreement on the use of risk as a basis for performance at the front end, all the way to integrated assessment tool, and the data upon which it is based, for demonstrating compliance of the constructed building at the time of occupancy.

- Many processes are in place to facilitate these steps already, including various committees (ministerial, regulatory, industry working groups, etc.), a robust regulatory assessment and consultation process, and robust training programs. It might, however, require outreach to new partners, such as the national statistics agency, the medical profession, and others as identified above, so as to facilitate obtaining the necessary support from such groups on the efficacy of the approach, the data used as a basis, the methods of analyses, and so forth.

New / modified educational programs and professional qualifications. Given that this approach will be unfamiliar to many, their will need to be significant emphasis on education – not only for professionals already working in the sector – but perhaps more importantly, to train a new generation of practitioners through the university education system.

- While knowledge, tools, and techniques for much of what will be required is already taught in several disciplines (e.g., reliability / risk-based design in structural engineering, toxicology in medical and environmental sciences, data identification and treatment in many fields), not all disciplines will have core material on needed subjects, which will require the educational programs to shift. This is expected to take some time but will be needed for long-term success.

4.8. *Developing detailed and simplified compliance approaches*

Building on the need for assessment methods, it is recognized that many risk- and reliability-based design approaches can be somewhat complex and require significant amounts of robust data. This can limit their usage in practice. However, it may be possible to develop simplified approaches, which apply under well-bounded conditions, for many types of problems. Some standards already take this approach, such as the Eurocodes for structure (EN 1990 series), which have simplified approaches that are underpinned by rigorous analytical approaches. A process flow chart for how this might work for non-aggregated risk approaches is illustrated in Fig. 13 below.

By working through a process such as this, it can be determined whether complex analytical approaches are needed for each design project, or if simplified methods can be developed to facilitate more widespread use and application of risk-informed approaches.

4.9. *Connecting to implementation and enforcement*

Although Step 8 of the STBRS approach is not addressed in detail here (evaluation and implementation), it is useful to note that concepts outlined by Almeida et al. (2015) in the Risk-Managed Performance-Based Building (RM-PBB) approach are important at this stage. The RM-PBB approach provides a framework for consideration and application of the principles of risk management and performance systematically across all phases of a building project. In the RM-PBB approach, components of the regulatory systems are identified according to three groups: 1) performance-based inputs; 2) standardized management principles, guidelines and standards and; 3) conformity assessment and auditing standards (group 3). The risk roadmap is focused on group 1

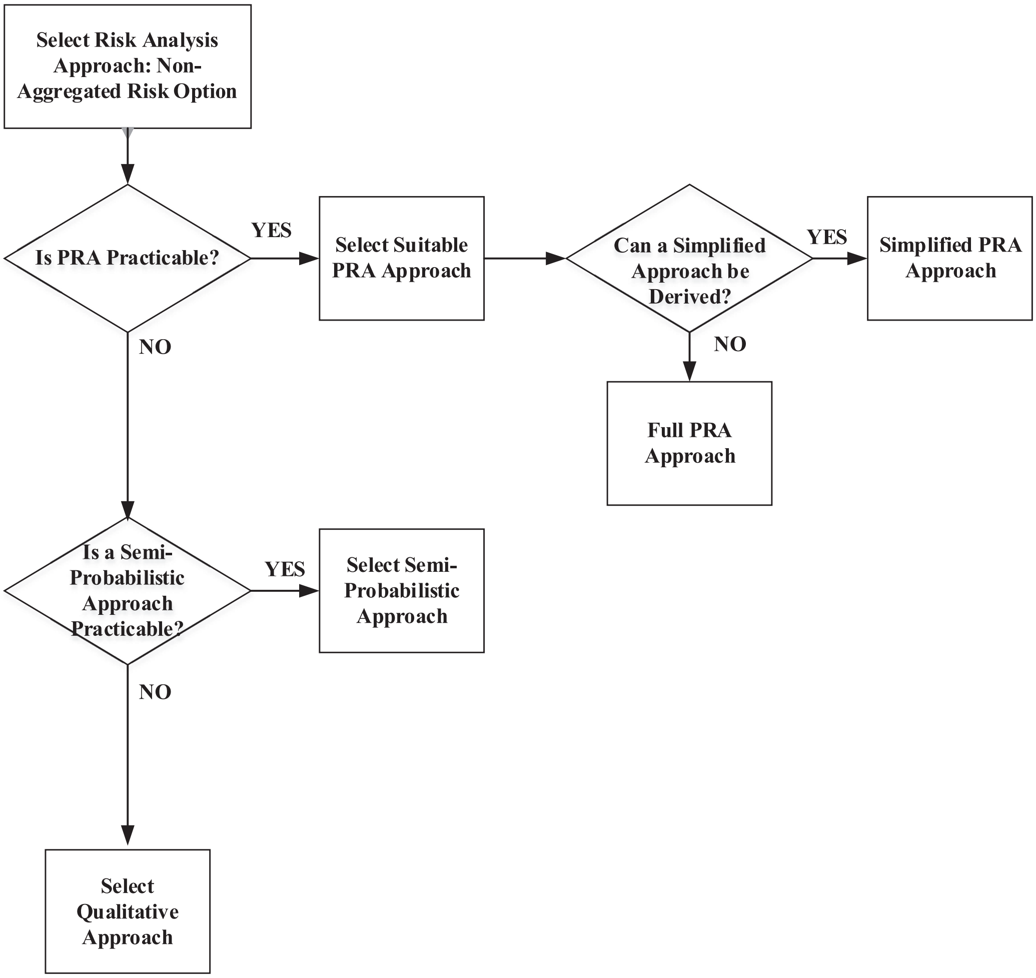

Fig. 13. Process for Assessing Potential for Simplified Methods Development.

related activities – developing risk-informed and performance-based building regulation. However, as Almeida et al. (2015) note, to manage risk across all phases of a building process, one needs to incorporate quality-based and risk-based standardized management principles, guidelines and standards (group 2) into the system, so as to help facilitate appropriate demonstration of conformity with building performance as expressed in terms of engineering performance and risk levels, and to assure the entities providing this demonstration of compliance are controlled through auditing and other measures in a such as way that credibility, confidence and acceptance of the results of the activities performed by those bodies is obtained.

5. Application of the roadmap process – Proof of concept

A critical component in the assessment of any tool is its practical usefulness. In this case, the roadmap was developed in part through work with the Australian Building Codes Board (ABCB) to explore and develop an approach for establishing an individual risk measure and a societal risk measure for use in the National Construction Code (NCC) of Australia. While the reports developed as part of this work are confidential, the following steps were undertaken.

- Use of aggregated risk measures was postulated for use in benchmarking individual and societal risk measures.
- It was postulated and agreed to explore the approach of setting a maximum tolerable risk level for risk contribution from building-related hazards at 1% of background risk for new buildings.
- Background aggregated annual individual and societal risk to life measures were derived from analysis of readily available statistics.
- The contribution of risk from building-related hazards was derived from statistics, resulting in hazard-specific individual risk criteria.
- The hazard-specific individual risk criteria and benchmark tolerable risk levels were compared to verify the appropriateness of each within the system.
- The background aggregated societal risk criteria approach was reviewed and considered appropriate.
- Stakeholders were consulted regarding the overall approach, and generally agreed that setting a maximum tolerable risk level for risk contribution from building-related hazards at 1% of background risk for new buildings was supported by the data, in particular benchmarking hazard-specific risks associated with the built environment.
- Various assessments and case studies were undertaken by stakeholders to apply the concepts, including traditional (hazard-specific) risk assessment approaches, to evaluate whether the market would be in a position to comfortably move forward with a risk-informed approach.
- At present, it is being considered to move forward with the aim to base structural and fire safety provisions on a risk basis, and further explore risk bases for other hazard areas. Individual and societal risk measures are currently being considered.
- It is also been identified that education and training will be required to build up competency in the use and review of risk-informed approaches, and that this is an essential part of moving forward.

Based on the steps undertaken by the ABCB and its stakeholders, it is demonstrated that the roadmap outlined above can be helpful to building regulators in considering a transition to a risk-informed building regulatory system.

6. Conclusions

There is growing interest in using risk as a basis of building regulation. A roadmap is presented to guide building regulators in incorporating risk as the basis of performance objectives in building regulation, and reflecting how the risk criteria can serve as benchmarks for verifying designs for compliance. The roadmap presents a stepwise process that helps regulators define the risks and hazards to be considered and over what scale of concern, options for selecting one or more risk measures to be used, means by which the risk can be estimated and tolerability limit (s) set, and what is needed to transition into a risk-informed regulatory system. The roadmap has been designed to support various means of characterizing risk for use in building regulation, and an approach to benchmarking risk based on historical hazard event data (revealed preference) is illustrated and shown to be a supportable approach.

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