Engineering Asset Management at Times of Major, Large-Scale Instabilities and Disruptions

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Abstract. Contemporary organizations function in a complex business and operational environment composed of closely interdependent systems. They are also complex by their internal structure, management and deployed modern technologies. This complexity is not always well understood, and cannot be efficiently controlled. As the complexity and interdependencies increase, man-made systems become more unstable creating conditions for cascading, system-level failures causing serious threats to both themselves and society in general. Such breakdowns may consist of a) serious physical damages and destruction of their physical assets (caused by natural disasters, extreme weather phenomena and climate change, malicious human actions, etc.), and/or b) large functional disruptions with no physical damages of assets (caused by major organization’s internal disturbances, market crashes, pandemics, disruptions of supply chains, etc.). Those sources of risks are basically external to organizations. They are unable to control them, but are deeply affected by those risks.

The latest case of the COVID-19 pandemic demonstrates the above. It is affecting both all sectors of life and businesses worldwide. It convincingly shows that we need to think, plan and act globally in order to deal with such situations that will also take place in the future. Thus, organizations have to find ways of coping with this reality to remain economically viable. We are of opinion that the concepts of structured Asset Management (AM) and resilience put together may provide an efficient framework in this regard.

Two case studies in a major North American electrical utility demonstrate the applicability of this approach: i) during an exceptional ice storm with significant damages of its physical assets, and ii) coping with challenges of COVID-19 with no destruction of its physical assets.

Keywords: Complexity · Major disruptions · Asset management · Resilience · Pandemic

1 Introduction

In the modern and deeply connected world, various man-made systems have created highly interdependent networks that are not fully understood, and cannot be adequately
controlled [12, 24, 39, 42]. The type of connections between networks and entities may be physical, informational, energy, material, geospatial, policy/procedural/logistic, societal, financial/monetary, etc. [20, 24, 33]. Such a context particularly applies to critical infrastructures: transportation systems, power, energy and communication grids, as well as water and gas distribution systems [56]. Meanwhile, other man-made systems such as finance, health care, education, supply chains, cyber and social networks, etc. also grow in complexity and interconnectedness. They are closely linked to above mentioned critical infrastructures [20, 33].

Consequently, contemporary organizations operate in an increasingly complex operating and business environment that is characterized by deep intrinsic uncertainties related to the often rapid evolution of markets/customer expectations, changing regulatory framework, new technologies including the advent of the Industry 4.0 concept, rapidly changing natural environment, change in the political environment, malicious human actions, climate change, changes in demand, advent of new competitors, pandemics, etc.

Such a complex world offers extraordinary opportunities for advances and prosperity in all spheres of life and activities. However, this complex world has become highly fragile and vulnerable to failure at all scales, posing serious threats to society, even when external shocks/disruptions are absent [12]. With the growing complexity as well as density and strength of interactions, man-made systems can become unstable, creating potentially uncontrollable situations, and cascading failures even when decision-makers are highly competent, possess data and technological means at their disposal, and do their best.

The challenges related to the complexity, cascading and system-level breakdowns of contemporary man-made systems led to research works aiming at better understanding and managing them that resulted in numerous publications. Certain research works discuss the global impact of the complexity on overall human activities including growing importance of extreme events as well as emergent and systemic risks [12, 33, 35, 39, 41, 42, 46, 54]. Some other authors analyze the impact of complexity to technological and engineered systems highlighting the need to further study them in order to enable a more efficient management [20, 21, 23, 24, 33, 38, 56]. Complex technical and non-technical mechanisms that trigger the causal relationships of catastrophic system-level failures are still not fully understood and can create new types of emerging risks through unexpected behaviors and combinations of various influence factors (technological, natural, human). Those new, previously unknown or not considered risks could pose utmost challenges to resilience, safety and business continuity of modern organizations, and the society as a whole. This topic has already been discussed in research works [5–7, 17, 18, 26, 39, 47]. However, it should be emphasized that certain risks may be positive (opportunities), and should be managed as such [17, 18, 49].

Systemic failures within organizations profoundly affect their operational and business environment. The may consist of a) serious physical damages and destruction of their physical assets (caused by natural disasters, extreme weather phenomena and climate change, malicious human actions, etc.), and/or b) large functional failures/disruptions with no physical damages of assets (caused by major organization’s internal disturbances for various reasons, market crashes, pandemics, political instabilities, significant
disruptions of supply chains, etc.). Majority of above mentioned sources of risks are basically external to organizations which do not control them, but are deeply exposed to and affected by those risks (Fig. 1).

![Fig. 1. Types of operating and business environment regarding an organization](image1.png)

To make these systems convenient, fundamental changes are required in ways they are studied, modeled, exploited and managed. Shifting the attention from a component-oriented view to an interaction-oriented, holistic view will allow better understanding of complex man-made systems, and the emergent phenomena characterizing them. This paradigm shift will enable new solutions to both long-standing and emergent problems.

The latest case of the COVID-19 pandemic demonstrates the above. It has affected life, businesses and growth in virtually every sector around the world although there was no destruction of physical assets. New research on this topic is emerging, but one still does not understand its true scale [3, 26, 28, 30, 31, 40, 43, 44, 51, 55] (Fig. 2).

![Fig. 2. Projections of COVID-19 impact on the world GDP](image2.png)

Supply chains are also profoundly affected or disrupted worsening an already serious worldwide situation [10, 27, 52]. Moreover, both the confinement and high, sudden unemployment create additional tensions within and between societies/countries that further amplify both negative impacts of the pandemic as well as existing conflicts and tensions potentially creating new ones. Mankind finds itself in an uncharted territory.
It is worth highlighting that since 2007 the World Economic Forum (WEF) has never identified the pandemic risks as a serious threat in its *Global Risk Report* showing the limits of predictions under complexity and deep uncertainties [54].

Meanwhile, global shocks and large-scale disruptions cannot be excluded in the future. The COVID-19 case convincingly demonstrates that we need to think, plan and act globally in order to deal with similar situations, even under extreme uncertainties embedded in our lack of complete understanding of the epidemiologic, biological and mutational aspects of this menace.

In such a context, organizations face significant challenges in designing an adequate asset management system (AMS). The paper aims at proposing a novel resilience-based engineering asset management (AM) relevant at times of major, large-scale disruptions and instabilities.

The remaining of the paper includes the proposed resilience-based methodology related to engineering asset management. It is followed by two case studies that demonstrate interrelations between AM and resilience in a major North American electrical utility: i) during an exceptional ice storm with significant damages of its physical assets (consequence of type a) above), and ii) coping with the challenges of COVID-19 where no destruction of physical assets happened. The paper ends with a discussion regarding needs for future research and anticipated benefits of the proposed methodology.

# Methodology

This Section presents the proposed resilience-based approach in engineering asset management (AM) at times of major, large-scale disruptions and instabilities. Organizations have to find ways of coping with the new reality (“new normal”) to remain economically viable and assure their sustainable development. It seems that the concept of resilience has gained popularity and application among contemporary organizations in the context of ever-growing complexity of operational and business environment exposed to deep uncertainties as well as new emerging and systemic risks. It is still a field of research under strong development, but there are several publications which already provide significant insights [1, 4, 5, 8–11, 16, 27, 29, 32, 34, 37, 40, 47, 48]. There are numerous definitions of resilience across the literature, but the ISO definition is retained in this paper. It defines the resilience as an adaptive capacity of an organization in a complex and changing environment [19].

The resilience has four properties: 1. robustness, 2. redundancy, 3. resourcefulness, 4. rapidity, and four interrelated dimensions: 1. technical, 2. organizational, 3. social and 4. economic [4, 5, 53, 56]. It covers four phases regarding the occurrence of a disruptive (adverse) event: 1. planning (preparation, anticipation) – before an adverse event; 2. absorption – loss of performance while an event occurs; 3. recovery – recover the performance after event; 4. adaptation – lessons learnt and continuous improvement after an adverse event (Fig. 3).

As presented in Fig. 3, the resilience also includes the robustness that is defined as the ability of a system to withstand damage (ability to absorb a shock) and continue operating [1]. The level of loss of the performance following an adverse event will be lesser if a system design is more robust (absorption phase). The ability and time to
recover from damages is a function of both the magnitude and nature of the performance loss, overall preparedness and available resources. The recovery time is longer if fewer resources are available and/or the level of performance loss is greater. Thus, there are various possible recovery patterns (Fig. 3). The achieved level of performance after recovery may also differ. Systems and organizations that successfully adapt and learn from internal and external return of experience may achieve better levels of performance through adaptation and continuous improvement. The resilience is a constant process that itself must be adaptive and improving.

As depicted in Fig. 1, there are elements in the overall business and operational environment belonging to the external environment of an enterprise (e.g. natural, business, legal, regulatory and political environment, market factors, pandemics, etc.). This environment cannot be accurately predicted, controlled, nor strongly influenced. Its complexity is high. Deep uncertainties and opacity are prevailing here. Nevertheless, it usually exercises a major impact on the performance of an organization and is prone to emerging and extreme risks. Resilience management is a recommended approach in managing risks and uncertainties of this environment. The concept of the Complex System Governance (CSG) may also be quite useful in this regard [6, 21, 38].

Effective and efficient organizations use a structured approach to their AM in order to balance competing priorities, manage various influence factors (external and internal), and ensure an equilibrium between long-term benefits and immediate needs [15]. An Asset Management System based on the ISO 55000 family of standards helps an organization to establish a coherent approach and coordinated allocation of appropriate resources and activities [14]. An efficient AM is also able to take into account the risks of extreme and rare events in the overall strategy and asset management decision-making, and there are already discussions and research on how AM may help in dealing with COVID-19 [2, 14, 15, 24, 28, 40, 45, 49].

Figure 4 shows the proposed, high-level holistic resilience-based asset management approach that integrates relevant functions and activities of an organization, and relates them to the main four phases of the resilience concept.

The proposed approach integrates and harmonizes the following functions and activities of an organization [22] (Fig. 4):
1. **Operation management; maintenance, monitoring and inspection management, asset management:** An adequate performance in those enterprise’s functions brings an adequate operating environment supporting a sustainable development even in cases of major disruptions. They positively contribute to all four resilience phases (plan, absorb, recover, adapt).

2. **General (overall) management, risk and emergency management, return of experience and lessons learnt** are essential in the overall resilience management of an organization. The excellence in those functions increases the overall resilience in all four phases. As far as risk assessment and management are concerned, it is recommended to follow general prescriptions of the Standard ISO 31000 [17], but other approaches such as business continuity management and emerging risks management may also complement it [16, 18, 48]. The excellence in those functions and activities brings an overall improved performance of an enterprise even in the case of major disruptions because of its ability to control and manage its main functions and processes. In this regard, attention should be paid to achieve and improve human and organizational performance since it may also be a major contributor to accidents and disasters, but also positively contribute in cases of an organization’s hardship.

3. **Establishing an adequate equipment and system design criteria; R&D and innovation:** given complexity of operating and business environment, deep uncertainties related to occurrence, magnitude and nature of disruptive events or large-scale instabilities, it is crucial to foresee future operating conditions as accurately as possible and integrate them into design criteria for events that may threat physical integrity of assets. Disruptive events with no physical damages of assets (e.g. pandemics, market...
crashes, political instabilities, significant disruptions of supply chains, etc.) require the knowledge of nature of such events as well as vulnerabilities of an organization exposed to them. It seems that traditional methods of analyzing them are not always good enough [5, 12, 24, 33, 43, 45, 48, 56], and new ones should be elaborated. Since uncertainties regarding future operating conditions of an organization are deep, sufficient margins should be provided, but also optimized in order to assure its economic viability and sustainable development. For that purpose, R&D and innovation are vital factors in both improving and gathering knowledge and develop new methodologies that can contribute to a better understanding and modeling of less known phenomena. Those new approaches would provide new insights, support a sound decision making at all management levels and enable assessing both the efficiency of asset management system and the adequacy of preventive and mitigating measures with regard to the overall performance and resilience of the organization.

4. **The fourth element relates to the legal and regulatory framework** which is not under the control of an organization. However, an adequate legal and regulatory framework is of a key importance for safe and sustainable operation acting through laws, regulatory directives, prescriptions and requirements.

The relationships between these four functions and activities are multiple and of different types such as physical, spatial, informational, financial, resource exchanges etc. Consequently, changes in their nature or characteristics may cause unexpected impacts that are often non-linear due to the complexity of their connections.

Thus, the overall asset management and resilience strategy in cases of major disruptions and instabilities is composed of an array of interacting and interdependent activities and functions within a multilevel structure of an organization, and outside. The cumulative effect of various actions produces a result that is superior to a simple sum of individual effects [24]. It is worth emphasizing that is important to have an overall good performance in all the activities presented in Fig. 4. The excellence or a good performance in just one or two domains cannot usually make up for serious weaknesses in other activities [22]. The proposed methodology favors an overall culture of preventive actions within an organization. However, it should be stressed that organizations ought to consider balancing preventive and mitigation strategies to ensure sufficient safety margins, adequate performance, economic viability and long-term sustainability. It is also worth highlighting that the methodology is technologically neutral and may be easily adapted to any type and size of the organization with its specific management, business and operational environment.

3 **Case Studies**

Two case studies demonstrate interrelations between AM and resilience in Hydro-Quebec (HQ): i) during an exceptional ice storm with significant damages of its physical assets, and ii) coping with the challenges of COVID-19 where no destruction of physical assets happened, but the overall functioning of the organization is deeply affected at all levels [13, 23–25, 50]. Both case studies relate to external operating and business environment that the enterprise does not control, but is exposed to the consequences (Fig. 1).
HQ is a major North-American electrical utility owned by the Government of Quebec [23]. It manages 63 hydroelectric power plants with approximately 38 GW installed generation power, and 353 hydroelectric generators. It operates the most extended and complex transmission line network in North-America, with over 34,000 km high voltage (49 kV to 735/765 kV) lines (more than 11 000 km of 735-kV), and 533 transmission substations. Approximately 85% of concentrated load is located in the south within the larger Montréal (Metropolitan) loop. HQ has 15 strategic inter-connections with neighbour grids for exports/imports (Ontario, New Brunswick, NE USA). Its distribution grid comprises 118,000 + km MT and 107,000 + km LT lines, 680,000 + pole mounted transformers and 3000 + distribution substations (Fig. 5).

3.1 Disruptions Due to an Exceptional Ice Storm 1998

The Occurrence of a Disruptive Event (Fig. 3): Between January 5 and 10, 1998, Québec experienced exceptionally harsh weather as three successive storms left up to 110 mm of ice over the south of the province. The 1998 ice storm was exceptional because of two unusual situations that occurred hundreds of kilometres away from Québec. First, El Niño caused a large mass of warm air to form over the Gulf of Mexico. Due to prevailing winds, this warm air mass moved to Québec followed by another one. Second, the usual pattern of west-to-east prevailing winds stopped for a few days as a result of a major high-pressure system that stationed over Newfoundland and Labrador. The 1998 ice storm consisted of three successive freezing rainfall events within a very brief span of time, covering a space of about 400 000 km², of which 130 000 km² were in Québec.
According to Environment Canada, during these three episodes of freezing rain, the average ice accretion was between 50 and 70 mm.

*The Absorption Phase (Fig. 3):* Storms damaged 24,000 poles, 900 steel towers and 3,000 km of lines and left 1,393,000 customers without power [23, 24]. The ice storm has had an overall cost to the public finances of $1.656 billion with two-thirds or $1.028 billion, was borne by the Québec government, directly or through HQ.

*The Recovery Phase (Fig. 3):* The whole society was mobilized in recovery activities. Every afternoon at 5, the Quebec’s Premier Lucien Bouchard, HQ’s President and CEO, André Caillé, and a representative of the Organisation de la sécurité civile (ORSC) held a press briefing to inform the public about the condition of the grid. The aim was to provide accurate information and keep the public informed at every stage of the response. On January 10, the ORSC set ‘Operation Ice Storm’ into motion, which comprised several work units, each charged with a priority mission to assist disaster victims. Some 750 volunteers from government departments and agencies took care of administration, food, financial assistance, firewood, generators, accommodation and information. Close to 9,000 soldiers were called in to help pick up branches, dispose of broken parts of transmission and distribution lines, transport new components for rebuilding lines and ensuring safety. The media played an important role in the ice storm. From the very outset, HQ set up 30 missions to be deployed in the affected areas. Each mission consisted of some 120 people, including a mission chief, a building supply procurement manager, about 50 soldiers, tree trimmers, line crews and a community relations officer. On February 6th 1998, the power restored to last customer highlighting the end of the recovery phase.

*The adaption/improvement phase (Fig. 3) and the general resilience-based AM approach (Fig. 4):* Following the 1998 ice storm, HQ has undertaken a comprehensive programme to reinforce its grid. This activity includes R&D efforts to better understand icing events and mitigation measures to strengthen facilities and assets. Test lines were built at HQ’s research institute, IREQ, in order to replicate icing conditions, and to test and validate specific designs and parameters. New maps were produced for extreme winds, ice accumulation, frosts and their combinations. Results were incorporated into construction standards and methods, while various research projects (IREQ, universities) helped to make the power system more robust. Innovations include the new generation of insulators to better protect facilities and interphase spacers that curb the effects of galloping and high-amplitude oscillations along overhead conductors. There are also works to develop and integrate new technologies or improve existing ones which would help increase efficiency of preventive and mitigating measures (e.g. smart grid features). Several projects to secure power supply to customers were implemented such as diversifying generation sources (e.g. interconnections) and supply corridors (e.g. Montreal loop). More than 900 km of lines were rehabilitated to more robust design criteria (greater than the CSA Standard) and with the installation of anti-cascading pylons. New posts and 295 km of new lines were added while existing 552 km of lines were also reinforced. A new 1,250 MW interconnection to Ontario (Outaouais substation) was built. Other preventive and mitigation measures include: i) Vegetation control to prevent
power failures by maintaining clearance around power lines; ii) Sygivre, a real-time ice storm management system that detects ice storms, tracks their development and keeps potential users informed; iii) De-Icing means: Remotely Operated De-Icing All Weather Vehicle, Lévis Substation De-Icing, De-Icer actuated by Cartridge, On-Load Network De-Icer, and Joule Effect De-Icing; iv) Towers in reserve at the Lines’ Emergency Bank; v) Emergency measures plan updated [23].

HQ transmission grid conception and exploitation philosophy have also been revised and improved at the system level during years 2000s [50]. Four basic principles and successive defence barriers have been reviewed: Principle No. 1: Service continuity must be assured following events most likely to occur on the power system. Principle No. 2: Hydro-Québec’s power system must include ways of avoiding system-wide power failures under extreme contingencies. Principle No. 3: Strategic equipment must not sustain any damage in the event of a general outage to ensure that system restoration is always an option. Principle No. 4: Hydro-Québec’s transmission system must be designed so as to allow the system to be restored within a reasonable period after a catastrophic event (Fig. 6).

Structured Asset Management programs have been elaborated and introduced helping an adequate fitness for service of HQ critical assets. It also supports building the overall resilience of both the physical asset systems and organization. They are continuously improved based on the return of field experience and R&D efforts.

It is worth emphasizing that the Province of Quebec has been exposed to several important ice storms since mid-2000s, but there were no important service interruptions due to the augmented resilience of the whole system.
3.2 Management of COVID-19 Impacts at Hydro-Quebec

Although there is no destruction of physical assets, the ongoing COVID-19 pandemic and crisis brings another set of challenges and issues. They are related to the organization’s ability to carry out normal operation, business and maintenance activities in a context where all the sectors of life and business are severely hit [3, 13, 28, 30, 40]. The organizational and economic resilience of the organization are rather tested in this context. The magnitude of the ongoing crisis is still unknown since it is still unfolding and continuously brings new surprises and unexpected scenarios worldwide. The current situation is a mix of the absorption and recovery phases, with some elements of adaptation (Fig. 3). It seems that existing models are of a limited use [43]. There are already some initial publications on how AM may help organizations in handling the COVID-19 crisis [28, 40], but the discussions and research continue.

As far as Hydro-Quebec is concerned, the magnitude of losses is still unknown. The initial estimates provided by its CEO anticipate up to 1 billion $ reduction in revenues in 2020 only [13]. Hydro–Québec is on the list of essential services established by the Government of Québec. However, the enterprise is adapting to the new context, and has introduced several measures to mitigate the consequences of the crisis [13]: a) workforce: online (remote) work is generally introduced for employees who are able to accomplish their tasks in that way. Other workers (operating and maintenance crews) indispensable to maintain the operation have to respect the new security/safety rules aimed at protecting their health. Daily and short meetings are held to keep in touch and ensure both their wellbeing and the quality of work. There are undergoing discussions upon new ways of performing work (more importance will likely be given to work from home). The foreign business travel is banned. Despite more difficult working and operating conditions, basic maintenance tasks are carried out, and the level of the system performance meets defined requirements; b) customers: a majority of big industrial customers are generally hardly hit due to market instabilities and disruptions. There are discussions with HQ in order to define support measures. Small customers and population in general are provided with support measures regarding modalities of payment including the abandon of the service cut off for nonpayment; c) no visitors are allowed to Hydro-Québec’s offices and installations; d) Supply chain and suppliers (providing goods and services): Even in light of the events related to COVID–19, HQ is planning a number of tender calls to carry out its projects. This message holds for the entire supply chain for projects, including construction activities and the procurement of goods and professional services. The payment delay is also reduced in order to help HQ’s suppliers. This orientation also plays an important role in supporting the economic recovery in Quebec; e) R&D and innovation project as well as the collaboration with the pairs of industry continue since this aspect is important not only in assisting the enterprise in the COVID-19 crisis, but also in preparing and adapting it to other future disruptive events that will likely occur.

3.3 Discussion Regarding Integration of the Resilience-Based AM Approach

Two case studies clearly demonstrate needs for further developing the knowledge and understanding of extreme and disruptive events in order to adequately cope with them and ensure the resilience, economic viability and sustainability of Hydro-Quebec. In this
regard, the development and integration of the resilience-based AM approach (Fig. 4) becomes relevant. On top of the improved operational and management practices as well as R&D and innovation at HQ, further recommendations and initiatives were made in an ongoing process to cope with future extreme risks (weather and/or others [23, 24]), climate change and deep uncertainties: a) Pursue the aim of excellence in general, risk and operation management as well as asset management at all organizational levels through a continuous improvement; b) Continue participating in various pertinent industry working groups to ensure leadership among electrical utilities and define future works; c) Continue participating in relevant standardization bodies in order to influence orientations in the standardization and regulatory framework; d) Continue participating at pertinent conferences and other forums enabling further contacts, feedbacks and balisage among pairs; e) Continue R&D and innovation efforts, collaboration with IREQ, universities, other research institutions. R&D and innovation are important factors in increasing the overall resilience; f) Continue developing and integrating new technologies or improve existing ones which would help increase efficiency of preventive and mitigating measures (e.g. smart grid features, AI); g) Develop new analysis methods and models able to quantify impacts of extreme events in a complex operational and business environment and its deep uncertainties. Those new approaches should provide new insights and enable assessing the adequacy of preventive and mitigating measures with regard to the overall performance and resilience of the organization and support a sound decision making at all management levels. These activities may involve i) understanding short- and long-term impacts of extreme events (weather and others) and climate change on assets and their systems such as required performance, reliability and availability, physical and structural integrity, duration of their useful life; ii) improving or developing new risk analysis and aggregation methods in the context of the complexity and deep uncertainties, including the characterization of systemic and emergent risks, and iii) enhancing multi-criteria decision-making methods in order to better integrate the impact of overall complexity and interdependences to their outcomes [23].

It is worth highlighting that the first case study covers an event occurred more than 20 years ago. The enterprise has had sufficiently time to analyze both the context and relevant factors/lessons in order to prepare and adapt itself to similar situations. The COVID-19 crisis is ongoing. The knowledge is still insufficient for a complete understanding of the phenomenon. Only further analyses and research will enable a better comprehension of this crisis helping the enterprise to improve its resilience to similar future events. The proposed approach may help in this regard.

4 Conclusions

Enterprises worldwide are constantly forced to produce more at lower costs. This way, we created highly dependent and complex economic, financial, technological and cyber systems that offer tremendous opportunities and possibilities to carry on business efficiently. Meanwhile, those man-made systems have shown that they are also fairly fragile at times of major disruptions and instabilities – they are prone to system-level breakdowns and cascading failures. The latest COVID-19 crisis clearly demonstrates this feature. It seems that classical methods of analyze are quite limited in capturing the whole range
of this phenomenon. New ways of thinking and new methods of analyzing complex systems become necessary. The resilience-based approaches are gaining the importance in this context. The paper proposes a resilience-based asset management methodology that has potential of holistically approaching the problem of how to handle extreme and disruptive events in organizations. Two case studies in a major North-American electrical utility (Hydro-Quebec) demonstrate the applicability of the proposed methodology. Suggestions for future research are also provided.

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