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Towards Sustainable and Resilient High Density Cities through Better Integration of Infrastructure Networks

Abstract

Many developed high density cities around the world are facing unprecedented challenges as their infrastructure facilities are aging while citizen demands are ever surging. The concerted efforts of different infrastructure stakeholders are indispensable to elevate the quality, reliability, and capacity of infrastructure systems to make high-density cities more sustainable and resilient against increasing climate change and manmade threats. To address these challenges, this paper proposes an integrated framework for multisector infrastructure asset management. For deriving the framework, case studies are conducted first on the best infrastructure asset management (IAM) practices of different countries in such diverse aspects as core process integration, contingency management, climate change response and adaptation, program coordination and orchestration, social value creation and sharing, risk management, resilience and sustainability. By using the criteria and a list of questions obtained from the case studies, interviews with different stakeholders in selected infrastructure sectors in Hong Kong are subsequently carried out to identify the barriers and possible solutions to enhancing the integrated management of multisector infrastructure assets in high-density cities. To facilitate such municipalities in managing their infrastructure assets effectively and efficiently, the proposed multisector integrated IAM framework is established from the holistic perspectives of information integration, process integration, collective decision, and harmonization between interdependent infrastructure systems.

Keywords: High density cities; sustainability; resilience; infrastructure system; asset management

1 Introduction

Infrastructure systems are widely acknowledged to be a lifeline in the community and play a pivotal role in sustaining economic prosperity and urban resilience and sustainability. However, urban infrastructures in high-density cities are encountering increasing challenges of decay and deterioration, as many of their current infrastructure systems were built over 40 years ago and are approaching the end of their service lives. Insufficient maintenance and renewal budgets are exacerbating the problem, causing a continuously growing backlog; and many municipalities believe that it is more cost-effective to conduct renewal work only when a particular infrastructure component fails than have preventive and proactive maintenance and resilience management. Additional extrinsic pressures placed on infrastructure systems arise from increasing demand levels, more strict regulations, environmental issues, social inequality, climate change, natural hazards, and even human-induced incidents.

The IAM practices of many municipalities are still at an early stage to tackle these challenges; they are implementing premature infrastructure asset management (IAM) frameworks and inadequate resilient and sustainable practices (Khan *et al*., 2017). Despite the few IAM trial studies that are have begun to pilot process and data integration, the industry is calling for more innovative solutions, especially for such integrated management of cross-sector municipal infrastructure assets as roads, water supplies and drainage. A consistent integrated asset management framework across agencies is even more urgently needed to fill the gap.

Moreover, an integrated IAM information system / platform is also required, as traditional software tools generally concentrate on the separate functionalities of IAM (Ossai, 2017). These tools provide few data exchange and data interoperability functions; and without a unified data regime, they are incapable of processing and analyzing the volume of static and dynamic infrastructure asset data for informed decision-making.

Infrastructure interdependencies and the cascading effects of infrastructure failures have gradually received the attention of IAM practitioners and researchers. The life of a component of an infrastructure system is not only influenced by other facilities in its vicinity, its breakdown and disruption can also induce a knock-on effect to the entire infrastructure network, sometimes with catastrophic consequences. Maintaining a stand-alone asset management system for an individual infrastructure is a myopic endeavor, as it fails to acknowledge the interrelationships and interdependencies in the entire infrastructure network, *viz.* tracking and tracing interconnected assets, detecting inter-network failures and managing incidents. Thus, consolidating up-to-date data from various infrastructure system owners and operators for joint decision support at the strategic, tactical, and operational levels can radically streamline the decision-making processes and improve the accuracy, timeliness, effectiveness, and efficiency of IAM decisions.

Failing to consider infrastructure interdependencies in such high-density cities as Hong Kong can be much more of a nuisance to utility agencies compared with other cities, as the infrastructures (e.g. pipelines and facilities) are usually constructed within a very limited space (Li *et al*., 2017) and managed by diverse operators. For example, in Hong Kong, the underground space of one-mile of roadway usually has more than 30-miles of utility lines – 3.5, 24 and 85 times that of Singapore, the United Kingdom and United States respectively (Wong, 2006). Engineers often have to endure inaccurate record plans to perform maintenance and rehabilitation works, and sometimes even leading to the accidental damage of lines. Moreover, from a maintenance and renewal perspective, it is common to find sections of road being re-excavated within few years of resurfacing due to a disregard of the interdependencies involved. Although executing such corridor upgrade works across organizations proactively could save costs and reduce disruptions to the neighborhood, utility departments currently lack the incentive to coordinate these practices.

The fragmented, inconsistent, and incompatible asset management information and processes involved, together with insufficient and ineffective coordination and communication across organizations, restrict the ability of municipalities to evolve IAM to an advanced level or cope with external challenges in the near future. In response, this paper proposes an integrated framework to facilitate IAM in high-density cities. Initially, the current IAM practices in Hong Kong, as a representative international high-density city, are reviewed and compared with idiosyncratic best practices adopted in pioneer countries worldwide. The conceptual resilient and sustainable multisector integrated IAM (RSM-IIAM) framework is then presented aimed at providing an advanced, sustainable, and resilient IAM through information integration, process harmonization, and use of interdependencies spanning multiple infrastructure assets.

Some recommendations for enhancing the IAM in high-density cities are then given, for example, strengthening stakeholder awareness; standardizing processes; improving coordination and end-user engagement; developing an inter-network platform; and contemplating sustainability and resilience requirements. Concluding remarks further identify the potential of using the RSM-IIAM framework to seek IAM improvement opportunities.

2 Background

2.1 The IAM concept, frameworks and supporting tools

The IAM concept has two generally acknowledged definitions, with one from ISO 55000 and the other from the International Infrastructure Management Manual (IIMM). ISO 55000 defines IAM as the coordinated activity of an organization to realize the value of its assets. IIMM concludes that IAM involves the systematic and coordinated activities and practices of an organization to deliver its objectives optimally and sustainably through the cost-effective lifecycle management of assets. Furthermore, IIMM identifies five key elements of IAM practice as defined level of service and monitoring performance; management of demand change; lifecycle approach; risk management and optimized long-term financial planning (IPWEA, 2015). There has been much research and industry work pertinent to sector-specific IAM regardless of different terms (e.g. facility management, public works management and utility management) being used interchangeably in the AEC literature (Uddin *et al.*, 2013). For example, Arif and Bayraktar (2012) proposed a theoretical framework for transportation IAM based on a thorough overview of asset management best practices in the transportation sector; while Grussing (2013) firstly applied asset management principles to building management and proposed a framework to improve facility information storage for actionable decision support. Myriad investigations have also been made from a lifecycle perspective, such as the framework devised by EI-Diraby and Rasic (2004) to evaluate and reduce the life cycle cost and emissions of infrastructure systems and Yuan *et al*.'s (2017) proposed linkage mechanism to integrate design, construction, operation and maintenance activities.

In addition, an easy-to-use information management system is the spine of effective asset management programs. Institutions worldwide are struggling to collect data from different sources and integrating existing databases within organizations. Mooney *et al*. (2005) described a web-based infrastructure management system with embedded structural, geotechnical data and analytics modules for planning project-level activities. A construction information database framework (CIDF) was developed to coordinate the processes of capital investment, schedule planning and performance measurement (Cho *et al*., 2012), and a national-level knowledge portal WATERiD was built in the U.S. to facilitate experience sharing in water IAM (Jung *et al*., 2013). As for enabling tools, information and communication technologies (ICT) have a promising potential to store, process and analyze gigantic volumes of heterogeneous IAM data. There are still a limited number of successful big data applications in the AEC industry however (Alavi and Gandomi, 2017). Pioneering work includes exploiting the potential of using big data and internet of things (IoTs) in automated infrastructure data collection (Martínez-Rojas *et al*, 2015), ontology-based representation of IAM knowledge (Shih *et al*., 2009), data management and storage techniques for IAM information (Ng *et al*., 2017), and BIM-GIS integration for visualization and IAM decision making (Halfawy *et al*., 2008; Karan *et al*., 2015).

2.2 Interdependency in infrastructure systems

The scope of an infrastructure system can also indicate whether interactions exist between different systems. Some asset management activities can be integrated within one specified infrastructure management system. As for municipal scope, processes can be formulated to collate various data and functions into one management environment in order to obtain efficient and cost-effective operations and maintenance. Because of being defined within one specified system (e.g. water, drainage, or roads), such interactions can be regarded as intra-dependent. However, as Pederson *et al*. (2006) comment, failing to understand the impact of one infrastructure system on another leads to the disarrangement of resources, ineffective responses and inadequate coordination between decision makers and agencies. Inter-connection between infrastructure systems is acknowledged as inter-dependence (Vespignani, 2010). Rinaldi *et al*. (2001) define infrastructure interdependency as "a bi-directional relationship between two infrastructures, through which the state of each infrastructure influences, or is correlated to, the state of the other”. He and his colleagues also classified interdependency as either physical, cyber, geographical or logical. Two infrastructure systems are physically interdependent if the state of each is dependent on the material outputs of the other, while an infrastructure has a *cyber-interdependency* if its state depends on information transmitted through the information infrastructure. Moreover, due to their intimate interactions with human needs, infrastructures formulate a system of systems incorporating human-cyber-physical interdependencies. Although interdependencies receive limited consideration in the municipal sector (IPWEA, 2015), Halfawy (2008) and Nafi and Kleiner (2010) suggest that benefits can be derived from coordinating renewal plans co-located in a particular area, thus reducing duplication work and disturbance to nearby communities. Such interdependencies upon which municipal works could be coordinated are represented as geographic interdependencies (Rinaldi *et al*., 2001), while the physical and cyber interdependencies of industry technical infrastructure systems generally act as basic nexus between systems (Duenas-Osorio *et al*., 2007; Johansson and Hassel, 2010; Eusgeld *et al*., 2011).

2.3 Sustainability and resilience of infrastructure systems

Although studies deal mostly with individual parts of sustainability assessment, operationalization of the sustainability concept in IAM gradually converges to the multi-criteria decision-making paradigm with the dimensions of the triple bottom line (*viz.* economic, environmental, and social) being balanced. A spectrum of metrics and aggregated sustainability assessment index are developed to facilitate strategic IAM planning and project selection (López & Monzón, 2010; Ariaratnam *et al*., 2013; Sierra *et al*., 2017). Apart from transportation, virtually no work on other infrastructure sectors exists, and practical sustainability assessment methods leveraged in reality are largely based on yes/no questions and textual descriptions of possible categories rather than quantitative evaluation.

As for resilience in infrastructure sector, current studies addressing engineering systems relate to defining and quantifying resilience (Hosseini *et al*., 2016). Approaches adopted in the specified domain are comparable with those in community resilience analysis. These include the resilience index (Cimellaro *et al*., 2016), multi-dimension and multi-stage resilience assessment framework (Ouyang *et al*., 2012; Matthews *et al*., 2015), dynamic inoperability input-output model (DIIM) (Baroud *et al*., 2014) and probabilistic modeling approach (Ouyang *et al*., 2014; Franchin and Cavalieri, 2015). Owing to the complexity of infrastructure networks, complex network theory is also harnessed for resilience analysis in road transportation, water and gas distribution, electricity transmission and telecommunication systems (Zhang and Wang, 2016; Levenberg *et al*., 2017; Krishnamurthy *et al*., 2016). Interdependencies between interlaced infrastructure systems can induce cascading effects that lead to a sharp decrease in the urban resilience level. Although a resilience index considering interdependency is proposed to evaluate regional physical infrastructure systems disturbed by disasters (Cimellaro *et al*., 2014), research is further needed to reveal the relationship between the interdependency and resilience level of infrastructure systems (Feng *et al*., 2017). Noticeably, Bocchini *et al*. (2014) and Lounis and McAllister (2016) first suggested that infrastructure resilience and sustainability are complementary and should be considered in a holistic manner, in which sustainability analysis accounts for normal operation conditions, whereas resilience analysis focuses on exceptional events.

3 Research methodology

Owing to the exploratory and interpretive nature of this research, qualitative approaches are adopted to investigate the current practice of IAM adopted in Hong Kong and highlight the best IAM practices in pioneer countries worldwide. This involves twelve semi-structured interviews with asset management experts and industry practitioners in Hong Kong to obtain fundamental information to identify the issues to be addressed by the IIAM framework. For carrying out the interviews, a critical decision has to be made to define an appropriate unit of analysis (Hallowell, 2012). Since the objective of the study is to formulate an IIAM framework, it is necessary to identify current IAM practices throughout the various infrastructure sectors involved. Thus, the scope of the investigation is not simply limited to a single project. Both the maturity and merits of the current practices of each sector are examined to obtain an impartial account. The proposed integrated IAM framework in this research is developed through the overall research procedures illustrated in **Figure 1**. According to the work by Maclaren (1996), six types of methods can be leveraged when developing the framework, namely domain-based, goal-based, sectoral, issue-based, causal-effect and combination methods. Since the combination method can consolidate the advantages of several individual frameworks, we choose the combination of goal-based and issue-based approaches to develop our framework (Pan et al., 2018). The goal-based and issue-based frameworks are more suitable for dealing with the distinction between global and local IAM issues; they reduce the number of problems that have to be considered in a generic context to only those relating to specified IAM goals and issues. Moreover, the overall research conforms to grounded theory, which is a "code-concept-category-theory" based, hierarchical, and inductive research method; and the process can be claimed to add to the validity and reliability of the study (Glaser & Strauss, 2006).

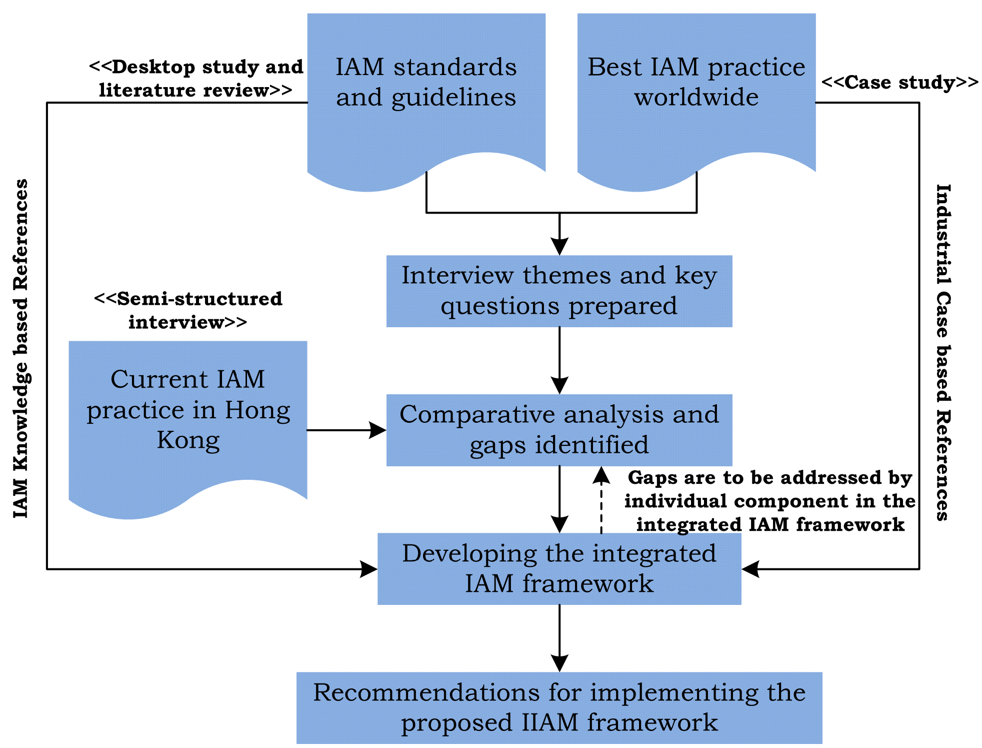

Fig.1. The overall research procedure to develop the integrated IAM framework

Several standards and specifications relating to IAM were consulted to prepare the interviews. The standards include the ISO 55000 family and several sector-specific IAM guidelines and reports issued by professional agencies and associations worldwide as listed in **Table 1** in the Appendix. The essential features in these documents are generally clustered into six themes on which the interview focuses, including policies, strategies and objectives; human resources; an information system/database; condition monitoring and performance assessment; risk analysis and criticality identification; operation, maintenance, capital investment plans. Since the case study method focuses on understanding the full scope of targeting research problems (Creswell, 2014), the best practices of the pioneer regions are complementarily scrutinized based on the cases provided by the guidelines and reports listed in **Table 1**. In this research, the United States, Canada, United Kingdom, and Australasia are acknowledged as pioneers, as they all have their own IAM guidelines and many municipalities in these countries are actively piloting principles and approaches of asset management to enhance their infrastructure system management capabilities. The objective of the case studies is to identify the idiosyncratic features of the asset management culture of each region; and the anticipated items consist of *Core process integration and contingency management* (United States), *Program coordination and climate change response* (Canada), *Broader social value and future-proofing* (United Kingdom), *Risk control and sustainable concerns* (Australasia). Moreover, the guidelines, reports, and best practices identified in these pioneer countries could be partially positioned as the benchmark for comparing prevailing IAM practices worldwide with that of Hong Kong, as well as providing implications for proposing the integrated IAM framework. Therefore, the key points in guidelines and merits identified through the case study of worldwide best practices are collectively referenced when formulating the interview questions, as stated in **Table 2** shown in Appendix.

The extent to which the interview results are representative and generalizable is directly determined by the infrastructure sector selected. The selection consideration relates to the scale, nature, and relative maturity of the asset management practices, authority of the asset management agency, ease of obtaining information, etc. Interviews scheduled in all these sectors arguably provide a sufficient degree of comprehensiveness and diversity. The electricity, water-related, road and railway sectors are chosen because they are predominately governed by municipalities and because some organizations in these sectors are market leaders in Hong Kong. Moreover, the electricity and railway sectors are more automatic and intelligent, characterized by complex control and information systems, and by which practitioners can acquire accurate supervisory and real-time data (Johansson and Hassel, 2010). As is customary, the interviewees for each sector were selected by convenience and snowball sampling (Lai *et al*., 2011; Creswell, 2014; Zhang *et al*., 2016; Yang and Chua, 2016). Of the 12 interviewees involved, 6 are from government departments, 4 from public organizations or non-government service providers and the remaining 2 are from consultancy companies (**Table 3**). All are working in infrastructure system operation and maintenance and quite experienced in asset management, which is demonstrated by 8 interviewees obtaining work experience over 5 years and 3 interviewees over 10 years. Two are from a power-related field and the same number of interviews was conducted in the railway sector. Each of three interviews was conducted in water related and road sectors. Over 90% of the interviewees are mid-level managers such as senior engineers and some even occupy such upper-management position as assistant directors or chief engineers. Each interview was conducted face-to-face for about an hour. For interview result analysis, descriptive coding and values coding are leveraged as main approaches (Saldana, 2016; Guo et al., 2017). Particularly, interview transcripts are coded by using the six themes above, which is a process of descriptive coding. Comparatively, value coding is implemented by the proposed three-stage categorization method elaborated in section 5.2.

Table 3. Particulars of Interviewees

Code	***Infrastructure Sector***	***Institution***	***Position***	***Experience (work years)***
1	Water-related	Government department	Assistant director	>10
2	Water-related	Government department	Senior engineer	>5
3	Water-related	Government department	Senior engineer	>5
4	Road	Government department	Chief engineer	>10
5	Road	Government department	Senior O&M engineer	>5
6	Road	Government department	Senior O&M engineer	>5
7	Electricity	Service provider	Senior operation engineer	>5
8	Electricity	Service provider	Senior operation manager	>5
9	Railway	Service provider	Senior electrical and mechanical engineer	>5
10	Railway	Service provider	Senior electrical and mechanical engineer	>5
11	Utilities	Consultancy	Senior engineer	>10
12	Utilities	Consultancy	Engineer	>3

4 Case studies of IAM best practices worldwide

Advanced asset management practice is demonstrated in pioneer programs as consolidating condition assessment, system performance evaluation, and risk analysis to facilitate maintenance, rehabilitation, and replacement optimization. Best IAM practices in this paper refer to those systematically implementing the advanced IAM functions with forward-looking considerations. The following section summarizes the best IAM practices in the United States, Canada, United Kingdom, and Australasia to highlight the prevailing trends in different sectors. This not only enables the various emphases on asset management prevailing in each region to be compared, but will also benefit other municipalities sharing similar conditions.

4.1 United States – core process integration and contingency management

Asset management in the transportation sector was developed ahead of that in other infrastructure systems in the U.S., after which other infrastructure domains (e.g. bridges and underground utilities) followed suit (Uddin *et al*., 2013). Research and development works continue to refine Pavement Management Systems (PMS), which include condition-based maintenance strategies founded on a sound understanding of the deterioration patterns, lifecycle cost analysis, criticality identification, and capital arrangements. For the bridge management domain, municipalities usually have a system that houses condition assessment data, with a separate bridge preservation program. However, the current trend converts from developing individual and exclusive functionality to integrating core and advanced asset management functions within one infrastructure asset system. In 2016, 55.2% of U.S. cities had such programs in development. Henderson in Nevada, Portland in Oregon and Saco in Maine, for example, are pilot cities aiming to implement a city-wide asset management and maintenance program with GIS-based asset inventories for the roadways, water and wastewater sectors, through both top-down and bottom-up approach (U.S. EPA and FHWA, 2015). Nearly 20% of these pilot cities reported having already established relatively well-integrated systems (Underground Construction, 2016). Enabled by such systems, condition assessment, involving rehabilitation and replacement schedules, occurs at regular intervals, taking into account deterioration rates and useful life expectancy. Moreover, the cities are targeting ongoing work through lifecycle and replacement cost analysis. Other useful approaches, such as criticality analysis, are also leveraged to drive maintenance policies and the optimization of operations and maintenance investment. City municipalities now realize the importance of having a strategic plan that pulls everything together in terms of resource allocation to provide a suitable framework for decision making (Younis and Knight, 2014; IPWEA, 2015).

The concept of critical infrastructure systems after the 911 New York terrorist attacks has been promoted to an unprecedented level. Since the interaction between types of infrastructure systems often create complex relationships, dependencies and interdependencies across infrastructure boundaries, disruption occurring in one infrastructure system often causes a cascading effect on components in other systems. Therefore, close attention has been paid to developing models that accurately simulate critical infrastructure interdependencies and identify vulnerabilities in order to initiate mitigation procedures (Pederson *et al*., 2006). Power, transportation, communication and water utilities are frequently analyzed first, due to their more obvious physical and cyber interdependencies and greater insight provided in terms of economy and community safety (Duenas-Osorio *et al*., 2007; Johansson and Hassel, 2010; Chou and Tseng, 2010; Eusgeld *et al*., 2011).

4.2 Canada – program coordination and climate change response

Evidence reveals that IAM practices are stepping into a detailed and elegant development stage. Pilot cities such as Calgary in Alberta and Hamilton in Ontario are endeavoring to develop a corporate asset management plan based on asset inventories. A risk assessment process is also being detailed into the individual level from the asset class level, to allow business units to identify the asset areas with the greatest risk exposure ratings for assisting projections of future investment (Gay and Sinha, 2014). Although some rough estimates are made of infrastructure asset conditions and remaining life according to industry averages and the experience of operators, municipalities prefer to develop models of their physical condition and level of service.

Canada’s InfraGuide (2003a) emphasizes the consideration of multi-disciplines (i.e. water, roadways and sewage) in municipal renewal work, since a coordinated approach to renewal planning (i.e. one upgrade for all of the surface and underground systems) helps maintain a high level of service while minimizing life cycle costs, impact on the environment and disruption to the community. Simultaneously upgrading all infrastructure elements on a specific street or in a geographic area, also known as “corridor upgrading”, serves as best practice for coordinated management (Shahata and Zayed, 2010). However, different assets have different service life expectancies and it is important to ensure that the economic life lost through early replacement does not exceed the economic benefits resulting from improved coordination. Organization arrangements are overarching for well-coordinated asset management. An asset management committee can be established, with representation from a variety of service areas, which is exclusively responsible for coordinating work with the help of a regular meeting schedule. The committee also acts as a fair and transparent platform from which both the internal utilities of government and external private agencies can lead with a rotating chair, thus enhancing participation and commitment to coordinate and communicate with each other (InfraGuide, 2003b; IPWEA, 2015).

Federal, provincial, and municipal government initiatives across Canada aim to incorporate climate change and greenhouse gas-reduction considerations into the design of new government buildings and facilities. Therefore, stringent design standards and regulations urge infrastructure utilities to engage in creating adaptation plans. The Public Infrastructure Engineering Vulnerability Committee has recently developed an innovative engineering protocol for conducting an “infrastructure vulnerability assessment” that broadly and systematically examines the vulnerability of Canada’s infrastructure systems to the impact of climate change from an engineering perspective. This now underlies proactive and preventive IAM work in some municipalities, with one section of Toronto, for example, changing all its storm water pipes to a larger diameter in order to alleviate anticipated pressures from extensive storm weather caused by climate change (Kessler, 2011).

4.3 United Kingdom – broader social value and future-proofing

With the formal publication of the ISO 55000 family of standards for asset management, the UK asset management philosophy has gradually converted from a least-cost to best-value orientation. The main drive of asset management also emphasizes performance and risk management instead of solely cost considerations. Compared with simply minimizing maintenance expenditure, maximizing performance and minimizing risk while satisfying budgetary constraints (rather than just meeting minimum performance requirements) is endorsed by a value-based philosophy (CSIC, 2015). Many utility departments have recently formulated their own sector-specific asset management guidelines built on the principles involved (UK Roads Liaison Group, 2016b). Pilot authorities also seek opportunities to embrace broader values when developing their asset management framework. For example, after identifying stakeholder expectancies by survey, London's Islington highway authority correspondingly set social objectives in highway assessment management in addition to its engineering ones. Typical crime statistics are also entered into the asset management system, which allows highway assets to be appropriately valued and the identification of major prostitution, car crime, drug abuse and assault locations for further monitoring (Hooper *et al.*, 2009) – social benefits therefore being obtained through an integrated asset management framework.

Future proofing is suggested as a principle in formulating asset management objectives to address ageing issues, extreme weather events and demand changes (ICE, 2013). In doing this, the planning and design stage of infrastructure systems has the potential to create greatest value. The design of London's Heathrow airport baggage-handling facilities, for instance, incorporates sufficient flexibility and redundancy by anticipating changes in technology and the quantity of passengers to allow the screening machines to be easily upgraded in future. Moreover, in anticipation of more stringent environmental policies and projected increases in temperature and precipitation in future, the airport has also established a carbon dioxide reduction target as well as new asset design standards for buildings and drainage (Masood *et al.*, 2016; Lai *et al.*, 2017). Similarly, in addition to satisfying the current requirements, it also serves as an opportunity to consider the future when devising rehabilitation programs.

4.4 Australasia – risk control and sustainability concerns

Owing to government statutory requirements for adopting asset management principles to manage infrastructure systems at both national levels, the New Zealand National Asset Management Steering Group (NAMS) in collaboration with the Institute of Public Works Engineering of Australia (IPWEA) have developed the International Infrastructure Management Manual (IIMM) that provides practitioners with guidance in applying the principles espoused in ISO standards. Pilot programs have developed a quantitative risk-based decision-making method that incorporates the combined assessment of the probability and consequence of failure for each significant asset in the inventory (IWR, 2013). For example, considering their geographical profile, many coastal cities recognize the importance of planning for a major natural hazard event such as a tsunami. Supported by GIS, information mapping of critical assets can be laid over potential tsunami inundation areas, which enables plans to be formulated targeting the known vulnerability (IPWEA, 2015). In New Zealand, a national "Engineering lifeline" process has been developed to enhance the integration and planning of coordinated action. The process highlights that the interdependency of the networks serves as key factor in responding to and recovering from an emergent event. Utility providers can work together to plan for minimizing the overall risk exposure of the community.

The triple bottom lines of sustainability are also council concerns, since focusing solely on financial matters would be detrimental to other aspects of sustainability. From an environmental protection perspective, pioneer cities consider reducing their carbon footprint by operating the water network better and avoiding future water main bursts, for example. In addition, IAM regulations mitigating the impact of climate change are embryonic in Australasia but likely to grow in future, particularly for the development of coastal communities.

4.5 Summary

The asset management systems established in these countries typically support the functional operation and maintenance management (e.g. condition assessment, deterioration, life cycle cost analysis and risk/criticality analysis) of different types of municipal assets (e.g. road, water and drainage networks), rarely accounting for the interdependency of the risks and vulnerability between the systems. The lack of coordination of multi-disciplinary asset management activities has created significant inefficiencies in coordinating renewal and asset planning. From the InfraGuide's view, optimal renewal plans for assets in a particular geographic location should be coordinated to span multiple infrastructure assets as much as possible and thus help minimize the disruption, costs and risks associated with maintenance operations to nearby communities. Inevitably, such coordinated maintenance work extends over several infrastructure sectors. However, emergency management would be more complicated since not only transparent and detailed infrastructure networks need to be clarified but also the key interdependencies and propagation mechanisms involved. **Figure 2** summarizes the best IAM practices worldwide. The codes in the angle brackets correspond to the interview questions in **Table. 2**. This also reflects the considerable referencing to best practices worldwide when devising the interview protocol, which facilitates the comparison between current practices in Hong Kong and the best worldwide. It is noteworthy that in **Figure 2**, Q12 (target level of service), Q31 (data collection requirements), Q61 (decision-making techniques) and Q63 (balance between planned and unplanned work) are rarely addressed by these best practices. These key points are explained in related guidelines and potential difficulties in real IAM practices. Thus, they are included in the interview protocol to investigate these special aspects in the operationalization of IAM in Hong Kong.

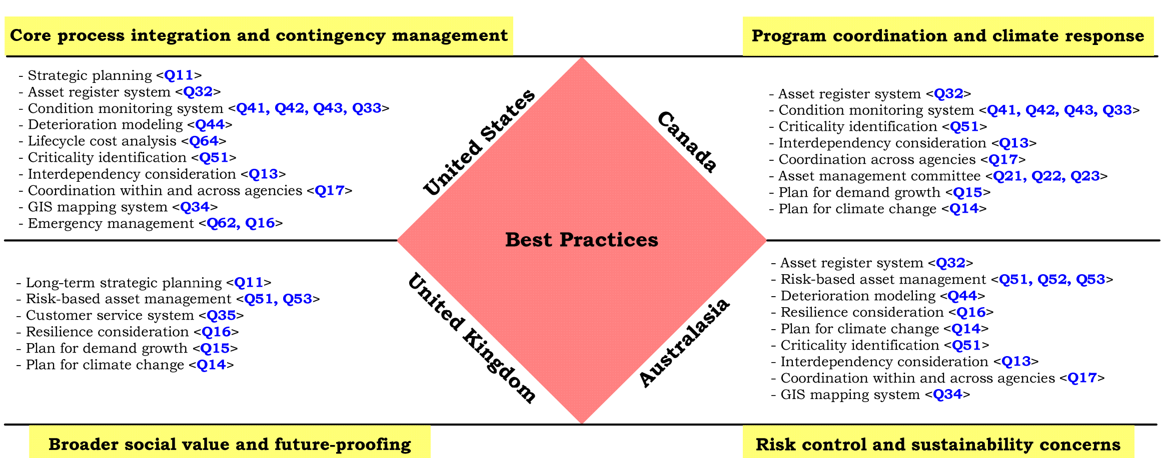

Fig. 2. Summary of best IAM practices worldwide

5 Analysis of current IAM practices for high-density cities

This section investigates the current IAM practices in Hong Kong, as a representative high-density city. Hong Kong is a regional and global economic hub serving as the southern gateway to and from China and world leader in terms of density of high-rise buildings and public housing estates. After decades of community and economic development, it also has a large amount of ageing and tightly coupled city infrastructure systems (water, electricity, transport, etc.). Owing to space limitations, underground utilities are quite close to each other, which can cause problems when an infrastructure component needs to be rehabilitated or renewed. With the current advances in smart technologies, different services are mutually interconnected in an increasing variety of hidden locations, where the failure of one component can cause a serious cascading effect on others in the immediate vicinity. Moreover, the city is exposed to the highest natural disaster risks (e.g. landslides, tropical cyclones, rising sea levels, heavy rain, and intense heat) in Asia (Chan, 2014; ARCADIS, 2015). The city's infrastructure systems are also fragile and vulnerable, as exemplified by a recent contaminated drinking water incident in the city's public housing estates, exposing a low emergency response efficiency and weak resilience capacity of its communities. In the words of Pun, Sun and Yam (2015), "hazard management is usually less emphasized in the community". Thus, there is an urgent need for Hong Kong-like highly dense mega cities to enhance their asset management capacity and the resilience of their built environment.

5.1 Experiences of Hong Kong's IAM practices

As stated in the methodology section, the electricity, water-related, road and railway sectors are chosen because they are predominately governed by municipalities and because some organizations in these sectors are market leaders in Hong Kong. It is presumed that the selection criteria are reasonable and the results obtained are representative and generalizable among other infrastructure sectors, since they can reveal both the merits and shortcomings of the IAM practice in Hong Kong. The details in each infrastructure sector are investigated in the following subsections.

5.1.1 Case pertaining to electricity IAM

A fruitful representative of electricity IAM over the last 15 years is the Power Systems Business Group (PSBG). Due to the management excellence of its physical assets, PSBG became the first Asian electricity utility company to receive the PAS 55 compliance certificate in 2010 (TWPL, 2010). Early in 2002, PSBG formulated its customized strategic asset management model aiming to consolidate the hitherto dispersed asset capital investment decision-making processes. The lifecycle planning concept is adopted in the detailed integrated asset management plan, thus avoiding the myopic focus on short-term cost savings that often contributes to performance problems and resulting longer-term higher operation and maintenance (O&M) costs. A risk-based management framework is also introduced to provide a consistent basis for global investment and resourcing arrangements *(cf:* Ioannou *et al*., 2017). Three-pillar information systems enable PSBG to conduct effective asset management work. These comprise: an Enterprise Work Management System (EWMS), which serves as the master asset register (and has evolved to become a rich source of O&M cost and activity data); an Automated Mapping/ Facility Management (AM/FM) system (a geographical information system storing master records of power line assets and with such additional functions as network analysis, trench work management and outage displays); and a Trouble Call and Outage Management system (TCOM) (developed not only to track customer trouble calls and dispatch emergency crews but also to record outage durations and affected customers).

5.1.2 Cases pertaining to road and railway IAM

The Hong Kong Highway Department's excavation-permit administration system illustrates the effectiveness of coordinating municipal work. Under this scheme, utility providers have to apply for permits through the Excavation Permit Management System (XPMS) when road excavation work is unavoidable (Hong Kong HyD, 2004). Moreover, a 'no-cut' rule or moratorium on excavation specifies that, except for emergencies, no excavation work is allowed for a certain number of months after pavement overlay. Excavation requests must be registered through the XPMS and if there is a small time-gap or conflict between two planned works, applicants have to collaborate with each other to produce a coordinated arrangement for submission. This initiative aims to be both cost-effective and limit disruption to the community through work coordination.

Hong Kong's MTR is representative of railway asset management excellence certificated by BSI ISO 55001 in 2014. As a member of the Community of Metros (CoMET), the MTR is also continuously ranked highly compared with its counterparts in the CoMET group in performance in terms of various evaluation elements comprising operational reliability, service quality and safety, the effectiveness of its processes and efficiency of resource inputs (MTR Corporation, 2015). The asset management strategy is clearly derived from the corporate strategic plan. Meeting the basic Standard Performance Requirement (SPR) stipulated by its Operating Agreement (OA), the MTR has further established its own Customer Service Pledge (CSP), which is more stringent in respect of the MTR's train frequencies and station facilities, including train service delivery, on-time journeys, escalator reliability, etc. Comprehensive asset replacement plans have been made for the future renewal of assets based on condition and performance. Nonetheless, continuous improvement is still needed to enhance the existing systems or to bring forward the roll out of the asset management system. The level of detail and scope to which condition assessment is conducted is also in need of further refinement. The basis of the intervention is formed by bridging performance appraisal with risk assessment and applying asset criticality down to all key sub-assemblies or components. Moreover, the MTR aims to enhance the asset information system, adopt state-of-art sensor technology, big data, and cloud computing to collect real-time operational data for comparison against pre-set alarm thresholds using sophisticated analytics and artificial intelligence to increase the efficiency of precautionary decision making.

5.1.3 Case pertaining to water-related IAM

Municipal sectors are seemly lagging behind well-acknowledged electricity asset management practice, particularly in handling underground assets (Halfawy *et al*., 2008). Owing to progressive development in many relatively mature districts over several decades, it is common to find organizations owning and managing extensive networks unable to report what infrastructure they have, its location, condition, value or performance and level of service being provided (Martin *et al*., 2013). When conducting repair or renewal work, because of the complicated public and private ownership of underground municipal infrastructure systems, the proponent (e.g. the Highway Department) needs to communicate with other stakeholders (e.g. the Water Supplies Department and the Drainage Services Department) who are responsible for the management of geographically co-located infrastructure systems and soliciting the spatial layout of their components. Such common practice in Hong Kong lacks accuracy and efficiency in handling municipal work due to inconsistencies and even contradictions between different data resources. The Water Supplies Department (WSD), for example, has been using a System Control and Data Acquisition (SCADA) system to monitor the supply and distribution of fresh and flushing water. Hundreds of District Metering Areas (DMAs) and Pressure Management Areas (PMAs) have been progressively established since 2000 and network monitoring data (i.e. flow, pressure, etc.) collected from the DMAs are been processed with discrete systems. Thus, in pursuing an integrated, holistic, and effective single-platform for performance analysis, the WSD is now working on establishing an Intelligent Network Management System (INMS) (Hong Kong WSD, 2016). Similarly, realizing the possible potential benefits from implementing systematic asset management, the Drainage Services Department (DSD) commissioned AECOM Asia Co. Ltd. in 2012 to provide consultancy support for implementing a Total Asset Management (TAM) scheme. This strengthened its developing lifecycle asset management policy and strategy, defining an appropriate service level and formulating a performance and risk management framework (Martin *et al*., 2013).

5.2 Challenges and barriers to continuous improvement

Since the vast majority of existing asset management systems still focus on operational management aspects (e.g. work orders, service request), with little or no functionality to support long-term renewal planning decisions (e.g. deterioration modeling, risk assessment, lifecycle cost analysis, renewal prioritization), there lacks a rational reference for funding allocation. Therefore, the annual budget is merely based on historical records. Departments are quite accustomed to making *ad hoc* decisions based on practical experience and operational resources are allocated to the emergency rehabilitation of failed infrastructure components to a large extent instead of preventative initiatives due to adequate funding to date. Though pilot utility departments have initiated risk analysis underpinned by monitoring data in current asset management practice, such condition-based inspection sheds limited light on the consequence of possible component failure (Ugarelli *et al*., 2010).

Moreover, data quality issues arising from data 'silos' - in terms of data inconsistency, inaccuracy, incompleteness and irrelevance - have been the major obstacles that influence the efficiency and effectiveness of IAM. Fragmented decision-making processes hinder both the large-scale adoption of integrated IAM across multiple organizations and sectors and coordination between asset management stakeholders, thus destroying the potential for integrated decision making. Apart from modeling for short-term operational purposes, such long-term considerations as interdependency, sustainability and resilience need to be encapsulated in the integrated IAM framework as new requirements within the context of growing complexity and uncertainty in infrastructure systems (Saidi *et al*., 2018).

Table 4. IAM features based on interview results from infrastructure sectors in Hong Kong

Themes	***Electricity IAM***	***Road and railway IAM***	***Water-related IAM***
Q1. Policies, strategies and objectives	-Strategic planning -Target level of service	-Corporate strategic plan -Target level of service -Coordination within and across agencies	-Strategic planning -Target level of service -Coordination with and across agencies
Q2. Human resources	-Asset management committee -Regular training	-Asset management committee -Regular training	-Asset management committee -Regular training
Q3. Information system/database	-Asset register system -GIS mapping system -Customer service system	-Asset inventory -Condition monitoring system -Customer service system	-Consolidating asset register system -Customer service system
Q4. Condition monitoring and performance assessment	-Condition monitoring techniques	-Condition monitoring techniques -Condition indices and grading	-Condition monitoring techniques
Q5. Risk analysis and criticality identification	-Risk-based asset management	-Risk-based criticality identification	-Risk event identification
Q6. Operation, maintenance, capital investment plans	-Lifecycle cost planning -Emergency management	-Lifecycle cost planning	-Lifecycle cost planning

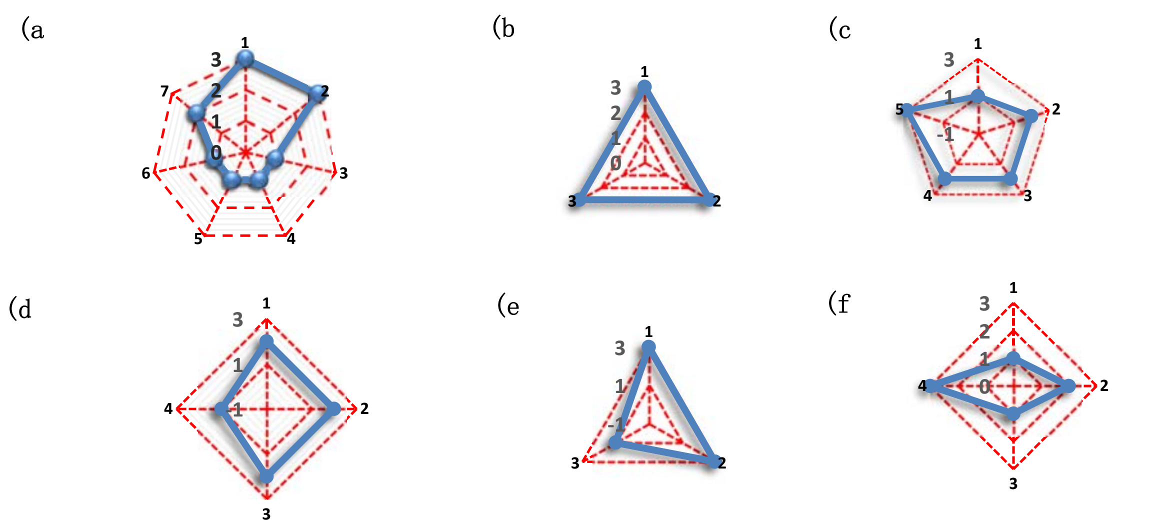

Fig. 3. Current IAM practice with regard to each theme in Hong Kong, with (a) Policies, strategies and objectives, (b) Human resources, (c) Information system/database, (d) Condition monitoring and performance assessment, (e) Risk analysis and criticality identification, (f) Operation, maintenance, capital investment plans

Table 4 presents the interview findings pertaining to current IAM practice in Hong Kong. The interviewees' remarks from the above three sectors are reorganized corresponding to the six themes in the far left column originating from guidelines and international standards. The three-stage categorization (Saldana, 2016) method is used to delineate the level of development in individual themes, with stage 1 denoting fledging IAM practice in Hong Kong, stage 2 representing IAM practice in progress in Hong Kong, and stage 3 indicating prevailing IAM practice in Hong Kong. The principles of classifying the IAM practice in each theme state are as follows. If interviewees in all three sectors mention a common feature in a certain theme, we allocate 3 points on this dimension. For example, interviewees all refer to *strategic planning* (Q11) and *target level of service* (Q12) in the first theme, namely policies, strategies, and objectives, so these two dimensions are both given 3 points. Contrarily, if the interviewees seldom emphasize certain dimension in one theme, we assign 1 point. In the first theme, dimensions of *interdependency consideration* (Q13), *plan for climate change* (Q14), *plan for demand growth* (Q15), and *resilience consideration* (Q16) are less addressed so they earn 1 point. If the interviewees acknowledge the value of certain dimension in one theme, while requesting further refinement in practice, the intermediate score of 2 applies. The detailed scores for each theme are shown in the radar graph in **Fig. 3**. Moreover, assuming that the individual dimensions in each theme carry the same weight, we can obtain the aggregated appraisal of IAM practice in Hong Kong with regard to the six themes (see **Fig. 4**).

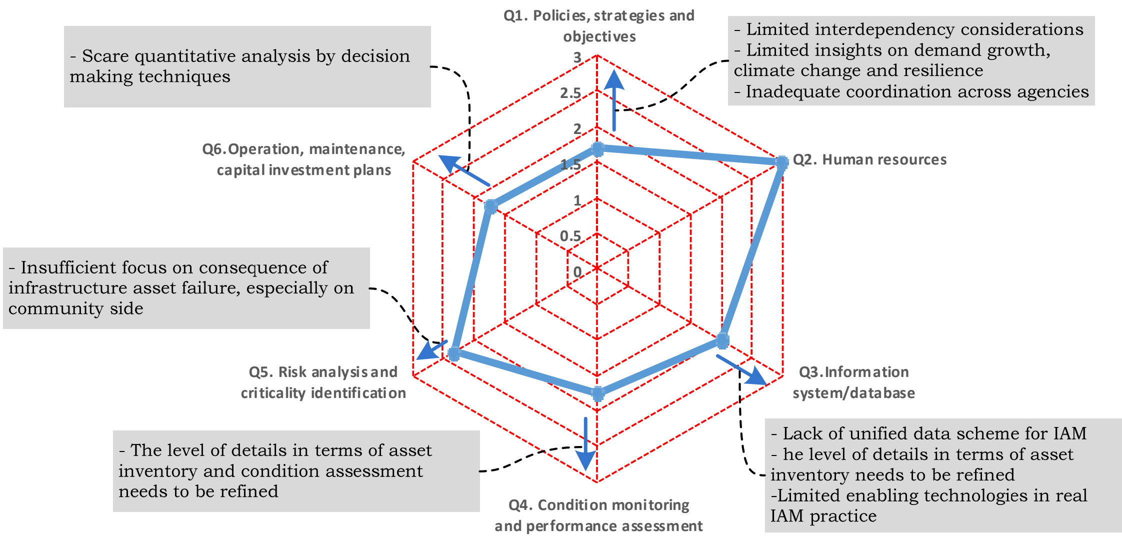

Fig 4. Gaps to fill in term of IAM in Hong Kong

Fig. 5 delineates the current IAM practice in Hong Kong compared with the worldwide best. Although Hong Kong practitioners are proficient in adopting IAM principles in such aspects as human resource training, there is still much room for improvement in other aspects in which several initiatives are carried out by pioneers. The IAM gaps that need to be implemented in Hong Kong - which are expected to be addressed by the proposed integrated IAM framework in the next section - are identified as (see **Figure 4**):

(1) limited consideration of interdependency issues;

(2) limited insights into demand growth, climate change and resilience;

(3) inadequate coordination across agencies;

(4) lack of a unified data scheme for IAM;

(5) the level of detail needs to be refined, in terms of asset inventory and condition assessment;

(6) insufficient focus on the consequences of infrastructure asset failure, especially on the community side;

(7) scarce quantitative analysis by decision-making techniques, e.g. trade-off analysis; and

(8) limited enabling technologies in real IAM practice, e.g. sensors, GIS etc.

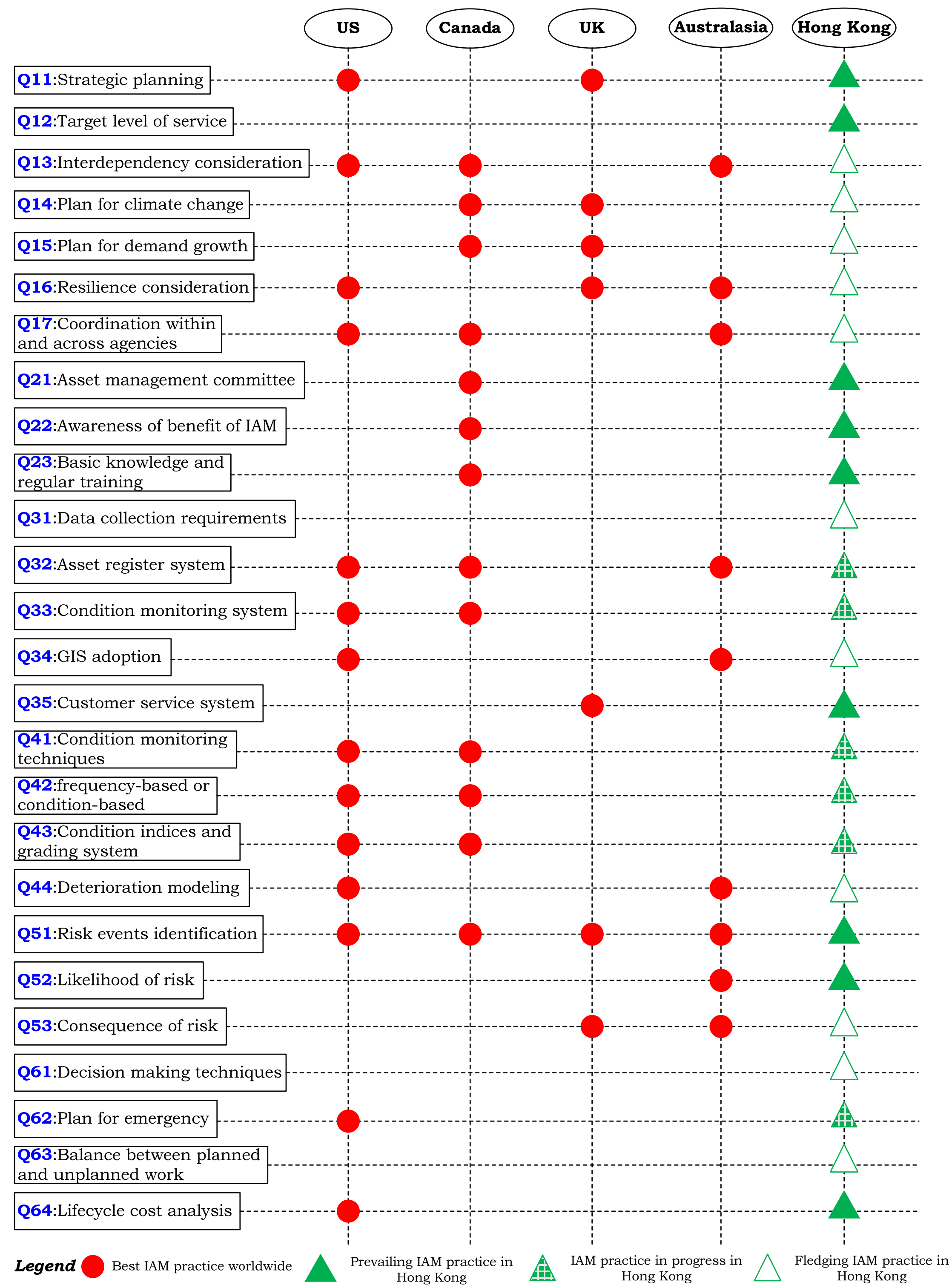

Fig.5. Comparison between current IAM practices in Hong Kong with worldwide best practice

6 The proposed resilient and sustainable multisector integrated IAM framework (RSM-IIAM)

This section proposes the resilient and sustainable multisector integrated IAM framework (RSM-IIAM). The framework comprises the integration of IAM information throughout the lifecycle, integration of IAM processes, integration of IAM by interdependencies, and integration of sustainability and resilience with IAM. Integration of heterogeneous information sources and fragmented processes serves as the premise for integrated decision-making. Integration by interdependency constitutes an effective entry point to link together different infrastructure systems since physical, cyber and geographical interdependencies are all tangible. Sustainability and resilience concepts emerge as new requirements that need to be embraced to develop the new version of IAM. Details are discussed as following subsections.

6.1 Integration of IAM information throughout the lifecycle

Data fragmentation always hinders management process integration because of the sophistication of the lifecycle asset management processes involved. Moreover, data available is often proprietary and the limited acceptance of standardized data format and exchange scheme blocks coordination between different operators (Halfawy, 2008). Data always need to be reinterpreted and reentered into a separate processing system. However, a standardized IAM data schema is key enabler to realize interoperable, consistent, and integrated IAM. Since the data schema accommodates all the related information used for IAM, each disparate data source implements a subset of, and could be mapped to, the standard data model. Since substantial data models have been developed by such reputable associations as the Environmental Systems Research Institute (ESRI), Federal Geographic Data Committee (FGDC), CADD/GIS Technology Center and the OpenGeoSpatial Consortium (OGC), ISO/TC211 Committee, it is economical and practical to harmonize and integrate the available models to identify the gaps and exclusive implementation requirements of IAM (Halfawy, 2010). Considering the geo-reference attribute of infrastructure assets, spatial data standards are preferable for reference, such as the Spatial Data Standard for Facilities, Infrastructure, and Environmental applications (SDSFIE) and the Municipal Infrastructure Data Standard (MIDS).

However, some data models focus less on lifecycle aspects, regardless of physical elements of systems and the implementation specification. There is an increasing trend in the construction industry to use XML as a prominent data encoding and exchanging format; the Geographic Markup Language (GML) is essentially a type of XML encoding for modeling and exchanging spatial and non-spatial attributes of infrastructure assets (Gröger and Plümer, 2012). Available commercial GIS software packages support the GML format for data schema representation. Moreover, BIM tools are acknowledged as a rich information repository for the lifecycle of buildings and facilities and have powerful editing function compared with that of GIS software (Cheng and Deng, 2015). A GIS-BIM integrated pattern is expected to fit the purposes of integrated IAM, in which a BIM module serves as a lifecycle semantic editor, with the GIS component leveraged for visualization and information query and analysis (Kang and Hong, 2015).

As a mature data schema contains a conceptual class hierarchy, geometric data model and semantic data model, the lifecycle semantics of an infrastructure asset should be encapsulated in an asset inventory database and ultimately utilized in IAM processes (Cheng *et al*., 2016). The design stage provides the key attribute information (e.g. geometry, location, and materials data) of an asset. Due to constructability considerations, some design information would need to be rectified. Asset information collected during the construction stage is therefore also indispensable. The operation and maintenance history needs to be recorded promptly in the inventory database since as-built records are essential references for future projects (Yuan *et al*., 2017). Integrating the management of information across the long-term activities of asset management with the short-term of construction for a portfolio of assets should deliver real savings (BSI, 2014a). Moreover, the concept of level of details (LODs) should be inherited from BIM, in which models are organized into different LODs (depending on BIM uses and the project phase), to IAM to improve computational efficiency (Deng *et al*., 2016). Another important consideration for establishing IAM systems is the level of integration and interoperability with other systems already in use. It is much more cost-effective and pragmatic to allow legacy applications to be bridged with the platform via adapters when building the IIAM environment as a modular platform (Halfawy, 2010).

6.2 Integration of the IAM process

Data integration serves as only the first step. Implementing data analysis and decision support modules that would automate some aspects of the decision process serves as a core function of a successful IAM system. Although previously specific software tools targeting a particular function (e.g. work schedule or benefit cost analysis) have largely improved the productivity of IAM, these stand-alone function modules are not incorporated into an integrated process. For example, most commercial asset management systems are essentially work management systems without lifecycle cost analysis and performance assessment functions (Halfawy *et al.*, 2006). ISO 55000 standards designate basic elements that need to be considered in implementing the asset management methodology. Municipalities worldwide have successively developed their own guidelines for specific infrastructure asset sectors. Integrated process models share common requirements and characteristics despite inconsistencies in the various asset-specific detailed guidelines of the management processes.

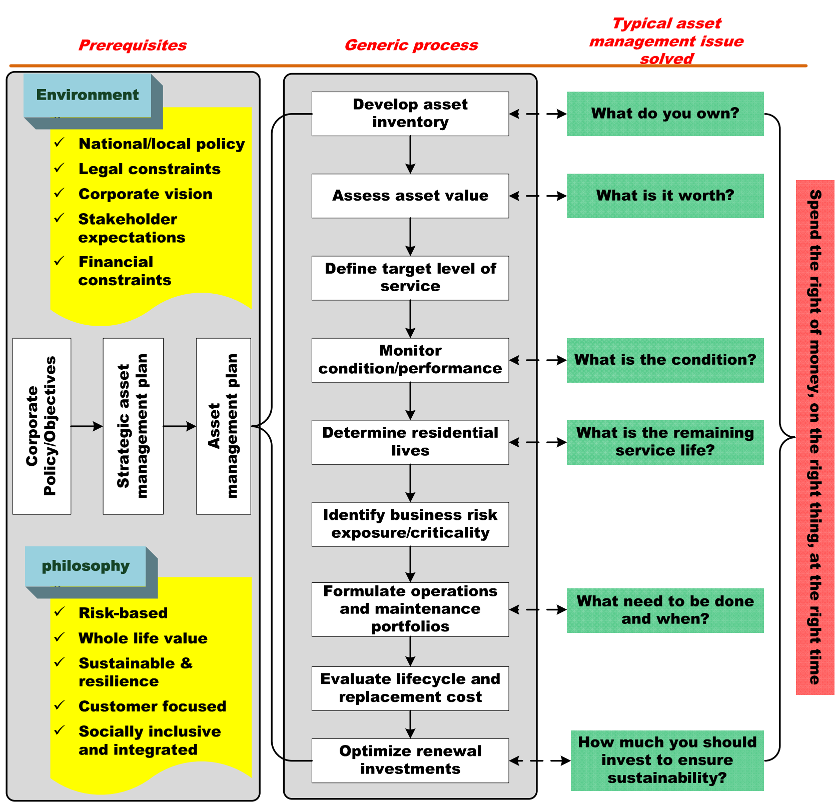

Fig. 6. Prerequisites, integrated asset management processes, and typical asset management issues solved

Figure 6 illustrates the generic IIAM process. When formulating an asset management plan, a utility needs to ensure alignment between asset management objectives and corporate management policy and objectives (Schraven *et al*., 2011; Younis and Knight, 2014). Asset management objectives are included in the strategic asset management plan, considering national or local policy, legal arrangements, corporate vision, stakeholder expectations, and financial constraints, which also serve as a basic decision environment for implementing IAM (UK Roads Liaison Group, 2016a). Various philosophies can direct the generic process, with implications for asset management policies and objectives. Sub-processes in the generic model provide accurate details to typical asset management issues, after which the utility spends its limited funding on doing the right things and at the right time. The process is generally regarded as a stepping-stone to effective asset management and includes:

(1) Development of an asset inventory composed of a list of assets and their principle components (e.g. for a sewerage system, pipelines, manholes, fitting, lift stations and pump stations) requires collecting and sorting both spatial and non-spatial data. This step aims to address the first question "What do you own?"

(2) Assessing the asset value for accounting and auditing purposes, targeting question 2 "What is it worth?" (Lee *et al*., 2015; Park *et al*., 2016)

(3) Defining the target level of services supporting the objectives in the strategic asset management plan, as benchmarks against which performance gaps can be identified and measured. A level of service can include reliability, responsiveness, environmental acceptability, customer values, and cost considerations.

(4) Monitoring asset condition and performance, using both qualitative and quantitative measures consistent with the target level of service. Usually, condition refers to the physical state of the asset, which may or may not affect its performance, while performance dictates the capability of an asset to provide the required level of service. The condition and performance assessment assists in forecasting and scheduling appropriate rehabilitation and reconstruction activities. Each performance measure (i.e. key performance indicator or KPI) should link to a level of service and hence the asset

management strategy corporate vision and strategies (BSI, 2014b; Younis and Knight, 2014). This sub-process helps to answer the question "What is the condition?"

(5) Determining of remaining life of asset components to quantify their deterioration rate and understand the inherent mechanisms involved to assist in predicting their future condition at any given stage of the life cycle. This step can help to answer the question "What is the remaining service life?"

(6) Identifying the critical components of infrastructure assets requiring consideration of both the likelihood and consequences of potential risks (Halfawy *et al*., 2008; Salman and Salem, 2012). Failure mode analysis is also required since the probability of failure is measured in terms of asset performance and is related to the primary failure mode. Expected failure modes may contain condition or structural failure, end of useful life, under-capacity, not meeting the established service level, no longer economic to own and operate, etc. The most frequently used indicator of probability of failure in practice is the remaining asset life when handling asset failure due to aging. Special attention should be given to low probability-devastating impact risks (Komljenovic *et al*., 2016).

(7) Formulating renewal portfolios underpinned by risk assessment serves as an initiating step. Evaluating lifecycle and replacement costs of renewal portfolios facilitates the optimization of capital investment strategies (Shahata and Zayed, 2012, 2013). Thus, final answers to questions "What needs to be done and when" and "How much to invest to ensure sustainability?" are obtained that can be treated as rationales for priority funding.

6.3 Integration of IAM by interdependencies

Although an integrated asset management process could be achieved *within* an infrastructure sector by the intra-dependency presented in **Fig. 7** on the scope of micro level, collating asset management practices *across* sectors involves consideration of the interdependencies between different infrastructure asset systems. Water supply pipelines in a public building need to be connected to municipal water supply mains. Corresponding to Rinaldi *et al*.'s (2001) types of interdependency, the interdependency between the public housing system and municipal water supply system can be identified as a physical attribute; likewise, with municipal gas supply and municipal drainage systems. Therefore, when carrying out renewal work, the relative utility involved needs to take into account demand changes in the public housing system in the near future that may have an unavoidable impact on the municipal water system. Moreover, for maintenance purposes, co-located infrastructure assets (e.g. water mains, sewers and road assets within the same corridor) at a particular site could be optimally upgraded in a bundle, thus minimizing duplicated renewal costs and disturbance to the nearby community (Elsawah *et al.*, 2016; Shahata and Zayed, 2016). Clearly, geographical interdependency also acts as the basis for bundling renewal work in this way (Nafi and Kleiner, 2010; Islam and Moselhi, 2012). Physical and geographical interdependencies are therefore commonly prominent at the local level, while infrastructure inter-networks occur at the meso level.

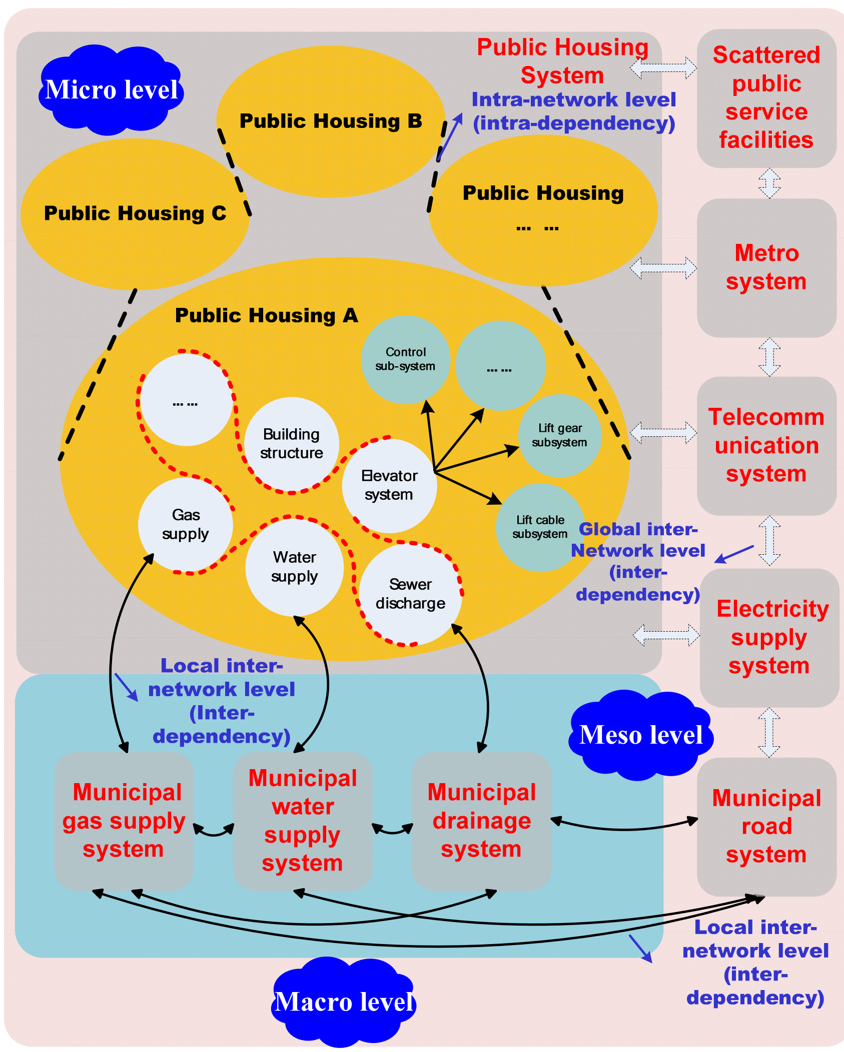

Fig. 7. Levels of integration between infrastructure asset systems

The complex and uncertain interdependencies between infrastructure asset systems necessitates the security of continuously functioning lifeline infrastructure systems to underpin the sustainable development of modern communities faced with increasing natural disasters and man-made threats (Ng and Xu, 2015). To tackle such problems, infrastructure networks need to be handled in a highly integrated manner, with acknowledgement and identification of the critical interdependencies involved. Such an integration of IAM systems emphasizes the need for vulnerability and resilience analyses across systems to support a proactive and adaptive management capacity for disaster and emergencies, which is regarded as at the global inter-network (macro) level in the IAM framework (Johansson and Hassel, 2010; Eusgeld *et al*., 2011; Levenberg *et al*., 2016; Lounis and McAllister, 2016).

6.4 Integration of sustainability and resilience with IAM

Current IAM frameworks mostly focus on performance management and, although sustainability and resilience management are considered to some extent, there is much room to integrate more practical and comprehensive sustainability and resilience improvement methods and tools into mainstream asset management practice (Gay and Sinha, 2014).

While many studies acknowledge that asset management and sustainability are interlinked in several aspects (Marlow *et al*., 2010) and claim a high-level commitment to the principle of sustainability in corporate visions, there is nevertheless a need to better align IAM processes with sustainable practices together with the provision of practical decision support tools. Though sustainability as a broad concept can be interpreted from different perspectives, prevalent practices operationalize sustainable requirements by the concept of the "triple bottom line" (i.e. economic, environment and social) (Jong *et al*., 2015). From an economic perspective, IAM is generally conducted in a long-term cost-effective manner to correspond with the sustainable economic requirements. For environment and social thinking, however, further priorities need to be established when defining the desired level of service of asset management at the strategic planning stage – by setting carbon emission-reduction objectives and promoting social equity for example (Kafle *et al*., 2017). Key sustainability performance indicators for technical, social and cultural aspects need to be formulated to facilitate decision-making and to progress beyond considering sustainability as a “bolt-on issue” to be embedded in “business as usual” IAM practice.

Community resilience is the ability of a community to prepare for anticipated natural or man-made hazards, adapt to changing conditions, withstand, and recover rapidly from any ensuing disruptions (NIST, 2015a, 2015b). Since the social functions of a community determine the functional requirements of its buildings and infrastructure systems, focusing on the resilience of the built environment operationalizes the resilience concept in the form of regional or national resilience strategies (Jabareen, 2013). The objectives of IAM are to sustain a cost-effective system and make future-proofing capital investments and, while resilience is previously perceived as separated from the asset management system, such objectives can be maintained either under normal or disruptive event conditions; if IAM is undertaken during exceptional disrupted conditions, then resilient requirements could emerge. For such high-density cities as Hong Kong, operationalization of the resilience concept by formulating open frameworks, inclusive resilience metrics, integrated decision-support toolkits, interdisciplinary knowledge and easy-to-use management and collaborative systems should be introduced into IIAM to improve the resilience and smartness of its built environment.

7 Recommendations for implementing the framework

The stakeholders are encouraged to implement and operationalize the proposed RSM-IIAM framework according to the following steps: strengthening the awareness of adopting advanced IAM; standardizing asset management processes within and across infrastructure sectors; enhancing coordination between IAM agencies; seeking end-user engagement during IAM practice; and building up an agile inter-network IAM platform by virtue of interdependency, as demonstrated in **Fig. 8**. The detailed interpretation of each step is depicted in the following subsections.

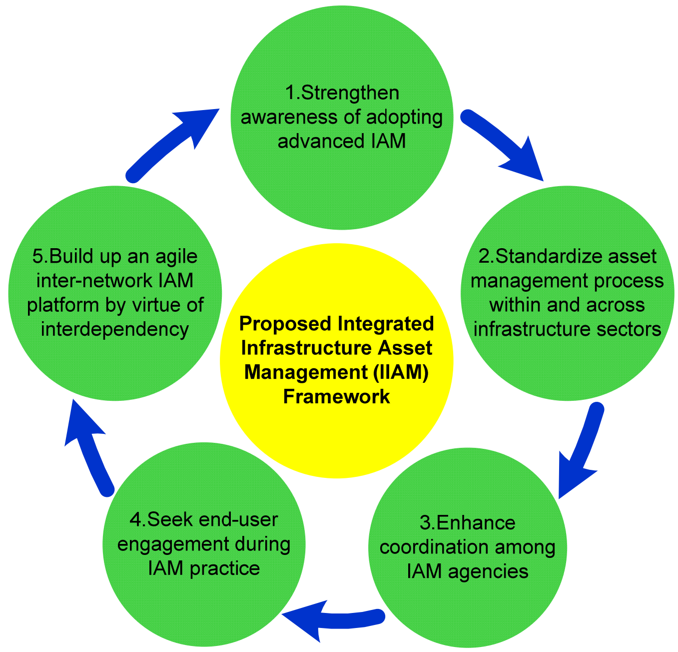

Fig. 8. Recommendations for implementing the proposed IIAM framework

7.1 Strengthen awareness of adopting advanced IAM

It is important that authorities and related organizations realize that AM is necessary for improving the performance and value of infrastructure systems instead of simply treating repair and reinforcement as an unwanted cost. In addition to the technical considerations involved in executing maintenance and rehabilitation work, optimal managerial and economic approaches are needed that minimize the total cost of IAM practice from a lifecycle perspective. Internalizing AM principles in management and aligning corporate policies and strategies with asset management objectives are a prerequisite for alignment with performance assessment and reasonable interventions (i.e. maintenance, rehabilitation, and renewal). Moreover, the level of service reflecting AM objectives would be drilled down to measurable performance indicators, including customer performance and technical performance measures. The way forward would be to adopt practices for translating public and organizational policies into IAM objectives for operationalization into performance measures to monitor and assess asset performance and conditions for prioritizing interventions.

The International Infrastructure Management Manual's (IIMM) maturity index model for IAM creates enough flexibility and compatibility for municipalities to customize their own asset management process consistent with the scale and size of the organization's assets and current management level. As AM practices evolve to advanced levels, strategies become more risk-based with a greater use of predictive methods. The current management practice of infrastructure system owners should therefore continuously emphasize medium- or long-term renewal planning decisions (e.g. deterioration modeling, risk management, life cycle cost analysis and asset prioritization) in addition to such operational management aspects as work orders and service requests.

7.2 Standardize asset management process within and across infrastructure sectors

Where public and private ownership exist within one infrastructure sector, asset management can clearly be developed in different ways. However, although many processes within and across departments and organizations are performed in an unstructured and inconsistent manner, such processes still can share a generic framework as detailed in Section 2 regardless of the size and characteristics of the infrastructure systems involved. For an IIAM framework, the systematization and structuring of processes is essential and standard asset management processes both reduce subjectivity in decision making and serve as benchmark for encapsulating asset management practices within and across departments and organizations into a homogeneous network upon which more efficient resource allocation decisions can be made from a global perspective. Noticeably, considering the inherent nature of different infrastructure systems, the generic process model allows flexibility for selecting suitable assessment and prediction tools to achieve a desired level of functionality.

7.3 Enhance coordination among IAM agencies

Suitable role definitions and organizational designs are fundamental for effective asset management, with an asset management framework to provide information for supporting decision-making in close collaboration with financial, information systems and strategic planning teams. Moreover, asset managers commonly need to coordinate different function teams (e.g. financial planning team, customer service team) within specific asset management organizations and a steering group of cross-organization representatives is beneficial for the integrated management of a utility in capturing opportunities to coordinate across utilities. One approach, adopted by the Hong Kong government, is to establish a formal committee with delegates from a variety of service areas to ensure open lines of communication. This can not only meet basic requirements of avoiding potential work conflicts but reducing repeated work that could cause extra expenditure and neighborhood disruptions. Governments approving budgets on a program level for roads, drainage, water etc. as opposed to an individual project level, also allows significant flexibility to change priorities between individual projects.

7.4 Seek end-user engagement during IAM practice

Since the essence of IAM is to achieve the level of service needed in a cost-effective manner, asset management practitioners should center on end-user expectations and stakeholder interests. Effective asset management then becomes the effective management of stakeholder relationships and interests. Therefore, asset management and the definition of level of service in particular, should start with a clear definition of the interests of end-users, making consultation with end-users inevitable. The associated costs for a particular service level needed should then be articulated to make the level of service provided consistent with the customers' willingness to pay. After sufficient and in-depth consultation with the public, a level of service would be obtained that is neither too high nor low relative to customer expectations, which can serve as benchmark for performance gap analysis. Public engagement also demonstrates good stewardship of public funds and encourages transparency of the asset management decision-making process. This is certainly the case in Hong Kong, where the government has much experience in public engagement.

End-users are encouraged to participate in the asset management processes since they can update and communicate timely service requests; for instance, when confronted with a sudden breakdown of an infrastructure component. Field operations and information monitoring can be witnessed by means of portable devices (e.g. PDA device, mobile phone). The ability of the browser-based wireless Internet to access a centralized terminal platform also enables the AM team to capture and apply these real-time data to support reliable asset inventory and location tracking, condition appraisal, failure detection, emergency responses, maintenance planning and resilience prediction and reaction decisions.

7.5 Build up an agile inter-network IAM platform by virtue of interdependency

While the existing IAM systems well serve idiosyncratic infrastructure assets such as the electricity and gas distribution system in Hong Kong, they fail to address the issue of interoperability between several infrastructure systems, the absence of a universal mechanism to facilitate the exchange of real-time data between different asset management operators and accurately interpret the data for joint decision support. Without knowing the type, location, and condition of waste water pipes near a gas main, for instance, it is difficult to pinpoint the root cause of failure of an infrastructure component and prevent a potential catastrophe. Therefore, an inter-network IAM platform leveraging on emerging technologies would be most valuable in facilitating an integrative, collaborative, and interoperable cross-sector IAM in order to improve incident response capability, productivity, and efficiency.

In Hong Kong and other similar high-density big cities, infrastructure facilities are located in close proximity to each other or housed in common service tunnels. It would be much more beneficial for asset managers to arrange their maintenance and rehabilitation activities jointly for different infrastructure systems located in geographically spatial proximity. This would apply to, for instance, a corridor upgrade assisted by a GIS-based inter-network platform, since it maintains pre-defined links between assets and street addresses. Such links would also facilitate the identification of and serving proper notices to, customers who may be affected by asset failure. By considering interdependencies, renewal plans could be coordinated to span multiple infrastructure assets, thus minimizing the costs, disruptions, and risks to the community.

Managing information across various infrastructure service areas is still very immature, especially with a large volume of incomplete and incompatible data from fragmented data sources and processes. Moreover, the data maintained by infrastructure asset owners are based on unique data collection methods and kept in diverse systems. Therefore, asset managers from different service areas in Hong Kong need to confirm the data required for inter-network IAM decision support at the strategic, tactical, and operational level and to define suitable asset classification standards, generic asset hierarchies, asset attributes, and key performance indicators for collaborative IAM. This could lead to the formulation of a set of universally acceptable asset attributes for asset identification and location, physical condition, maintenance history, failure risk, repair cost, service level and resilience predication to drive the design of the unified data regime. Instead of reinventing existing IAM systems, it is feasible and practical to integrate the strengths of emerging information technologies by capitalizing on the established infrastructure asset classification hierarchies, existing good framework and various software architectures and integration technologies when developing the next generation of agile and interoperable IAM systems.

8 Conclusion

This study formulates an integrated IAM framework by adding resilience and sustainability management to current practices. The framework aims to assist such high-density cities as Hong Kong to improve the management of their complicated and interlaced infrastructure systems against known risks and unpredictable threats and hazards. Semi-structured interviews are conducted within representative infrastructure sectors in Hong Kong to identify the current situation, while best IAM practices of pioneer municipalities worldwide are also investigated for comparison. Based on the findings of interviews and case studies, the RSM-IIAM framework is developed by incorporating aspects of information integration, process integration and making maximum use of the interdependencies between infrastructure systems.

The potential implications of the study for current IAM practice in Hong Kong are an enhanced awareness of advanced IAM, public engagement, strengthened coordination between utility departments and agencies, and the establishment of an agile inter-network platform. The formulated IIAM framework is clearly meaningful and valuable for the infrastructure management of high-density communities. It is also comprehensive and generic enough to be adopted by cities of varying sizes and building density. Additionally, municipalities could hone and customize the generic integrated framework to meet their unique needs as well as align with their own IAM capabilities. For future research, detailed scenarios could be devised to further validate the proposed framework and demonstrate its use in achieving IAM excellence. Further research could also incorporate enhanced resilience and sustainability performance assessment and management practices into the proposed framework to identify continuous improvement opportunities of built environment management towards higher community resilience and sustainability.

Appendix

Table 1. Asset management guidelines and corresponding issuing agencies and associations

Agencies and Associations	*Asset Management Guidelines*
UK Roads Liaison Group UK Department of Transportation	Well-managed Highway Infrastructure: A code of practice (October 2016)
UK Roads Liaison Group UK Department of Transportation Highways Maintenance Efficiency Program (HMEP) Board	Highway Infrastructure Asset Management (Guidance Document) (May 2013)
Institute for Water Resources (IWR) US Army Corps of Engineers	Best Practice in Asset Management (October 2013)
Construction Industry Research and Information Association (CIRIA)	Whole-life Infrastructure Asset Management: Good Practice Guide for Civil Infrastructure (2009)
US Department of Transportation Federal Highway Administration US National Cooperative Highway Research Program (NCHRP)	Transportation Asset Management Guide (Final report) (November 2001)
US Department of Transportation Federal Highway Administration American Association of State Highway and Transportation Officials (AASHTO)	AASHTO Transportation Asset Management Guide – A Focus on Implementation (Executive Summary) (2011)
Transportation Research Board of the National Academics US National Cooperative Highway Research Program (NCHRP)	NCHRP Report 551 Performance Measures and Targets for Transportation Asset Management (2006)
Water Research Foundation	Key Asset Data for Drinking Water and Waste Water Utilities (2012)
US Department of Transportation Federal Highway Administration	Data Integration Primer (August 2010)
Water Environment Research Foundation (WERF)	Water Infrastructure Asset Management Primer (Final report) (2014)
US Department of Transportation Federal Highway Administration US Environmental Protection Agency	Multi-sector Asset Management Case Studies (2015)
Institute of Public Works Engineering Australasia (IPWEA)	International Infrastructure Management Manual (IIMM) (2015)

Table 2. Interview themes and questions prepared

Theme	***Key questions prepared***
Policies, strategies and objectives	o **Q11**: Has your department enacted hierarchical AM documentations involving an AM policy statement, strategic, tactical, and operational plan? o **Q12**: Has your agency clearly stated the target level of service (e.g. customer performance measures, technical performance measures)? o **Q13**: When conducting maintenance work, does your department consider the existing interdependencies and make use of it? o **Q14**: Does your agency have plans to address climate change? o **Q15**: Does your agency plan for demand growth? o **Q16**: Does your agency have a resilience consideration (e.g. response and recovery time after an emergency, redundancy in network)? o **Q17**: Does your agency address coordination across divisions and even with other agencies?
Human resources	o **Q21**: Do your agency have a specified asset management group under the stewardship of asset manager? o **Q22**: Are your team members aware of benefits of AM? o **Q23**: Do your team members obtain a basic knowledge of AM and receive regular training?
Information system/database	o **Q31**: Has your agency formulated its data collection requirements (e.g. an inquiry scheme between public and private stakeholders, information screening, unified standard) o **Q32**: Does your agency have an asset register system (e.g. asset hierarchy, location data, functional data, condition data, maintenance and renewal history data, financial data) o **Q33**: Does your agency have a maintenance management system and condition monitoring system? o **Q34**: Does your agency leverage a Geographic Information System to facilitate AM? o **Q35**: Does your agency have a customer service system to timely monitor and solve the fault?
Condition monitoring and performance assessment	o **Q41**: What techniques has your agency adopted to execute condition monitoring (e.g. CCTV, Ground-penetrating radar, Sensors)? o **Q42**: Which maintenance scheme has your agency adopted, frequency-based, or condition-based? o **Q43**: Has your agency leveraged asset-specific monitoring indices and a condition grading system (e.g., roughness, surface distress, skid resistance evaluation, etc. for its pavement system)? o **Q44**: Does your agency have approaches to conduct deterioration modeling to determine the remaining life?
Risk analysis and criticality identification	o **Q51**: Could your agency rapidly screen the risk events? o **Q52**: How does your agency define the likelihood of risk? o **Q53**: How does your agency define the consequence of risk (e.g. asset attributes, operating context, and locational factors)?
Operation, maintenance, capital investment plans	o **Q61**: What decision-making techniques has your agency adopted to allocate budget (e.g. benefit-cost analysis, multi-criteria analysis, trade-off analysis)? o **Q62**: Does your agency plan for an emergency response? o **Q63**: Does your agency balance planned and unplanned work? o **Q64**: Does your agency schedule its maintenance, rehabilitation, and capital improvement from a lifecycle cost perspective?

List of the acronyms

AM – Asset Management

IAM – Infrastructure Asset Management
IIAM – Integrated Infrastructure Asset management
RSM-IIAM – Resilient and Sustainable Multisector Integrated Infrastructure Asset management
IIMM – International Infrastructure Management Manual

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