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## Towards sustainable and resilient high density cities through better integration of infrastructure networks

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# 1 **Towards Sustainable and Resilient High Density Cities through Better** 2 **Integration of Infrastructure Networks**

## 3 4 **Abstract**

5  
6 Many developed high density cities around the world are facing unprecedented challenges as  
7 their infrastructure facilities are aging while citizen demands are ever surging. The concerted  
8 efforts of different infrastructure stakeholders are indispensable to elevate the quality, reliability,  
9 and capacity of infrastructure systems to make high-density cities more sustainable and  
10 resilient against increasing climate change and manmade threats. To address these challenges,  
11 this paper proposes an integrated framework for multisector infrastructure asset management.  
12 For deriving the framework, case studies are conducted first on the best infrastructure asset  
13 management (IAM) practices of different countries in such diverse aspects as core process  
14 integration, contingency management, climate change response and adaptation, program  
15 coordination and orchestration, social value creation and sharing, risk management, resilience  
16 and sustainability. By using the criteria and a list of questions obtained from the case studies,  
17 interviews with different stakeholders in selected infrastructure sectors in Hong Kong are  
18 subsequently carried out to identify the barriers and possible solutions to enhancing the  
19 integrated management of multisector infrastructure assets in high-density cities. To facilitate  
20 such municipalities in managing their infrastructure assets effectively and efficiently, the  
21 proposed multisector integrated IAM framework is established from the holistic perspectives  
22 of information integration, process integration, collective decision, and harmonization between  
23 interdependent infrastructure systems.

24  
25 *Keywords:* High density cities; sustainability; resilience; infrastructure system; asset  
26 management

## 27 28 **1 Introduction**

29  
30 Infrastructure systems are widely acknowledged to be a lifeline in the community and play a  
31 pivotal role in sustaining economic prosperity and urban resilience and sustainability. However,  
32 urban infrastructures in high-density cities are encountering increasing challenges of decay and

---

1 deterioration, as many of their current infrastructure systems were built over 40 years ago and  
2 are approaching the end of their service lives. Insufficient maintenance and renewal budgets  
3 are exacerbating the problem, causing a continuously growing backlog; and many  
4 municipalities believe that it is more cost-effective to conduct renewal work only when a  
5 particular infrastructure component fails than have preventive and proactive maintenance and  
6 resilience management. Additional extrinsic pressures placed on infrastructure systems arise  
7 from increasing demand levels, more strict regulations, environmental issues, social inequality,  
8 climate change, natural hazards, and even human-induced incidents.

9  
10 The IAM practices of many municipalities are still at an early stage to tackle these challenges;  
11 they are implementing premature infrastructure asset management (IAM) frameworks and  
12 inadequate resilient and sustainable practices (Khan *et al.*, 2017). Despite the few IAM trial  
13 studies that are have begun to pilot process and data integration, the industry is calling for more  
14 innovative solutions, especially for such integrated management of cross-sector municipal  
15 infrastructure assets as roads, water supplies and drainage. A consistent integrated asset  
16 management framework across agencies is even more urgently needed to fill the gap.

17  
18 Moreover, an integrated IAM information system / platform is also required, as traditional  
19 software tools generally concentrate on the separate functionalities of IAM (Ossai, 2017).  
20 These tools provide few data exchange and data interoperability functions; and without a  
21 unified data regime, they are incapable of processing and analyzing the volume of static and  
22 dynamic infrastructure asset data for informed decision-making.

23  
24 Infrastructure interdependencies and the cascading effects of infrastructure failures have  
25 gradually received the attention of IAM practitioners and researchers. The life of a component  
26 of an infrastructure system is not only influenced by other facilities in its vicinity, its breakdown  
27 and disruption can also induce a knock-on effect to the entire infrastructure network, sometimes  
28 with catastrophic consequences. Maintaining a stand-alone asset management system for an  
29 individual infrastructure is a myopic endeavor, as it fails to acknowledge the interrelationships  
30 and interdependencies in the entire infrastructure network, *viz.* tracking and tracing

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1 interconnected assets, detecting inter-network failures and managing incidents. Thus,  
2 consolidating up-to-date data from various infrastructure system owners and operators for joint  
3 decision support at the strategic, tactical, and operational levels can radically streamline the  
4 decision-making processes and improve the accuracy, timeliness, effectiveness, and efficiency  
5 of IAM decisions.

6  
7 Failing to consider infrastructure interdependencies in such high-density cities as Hong Kong  
8 can be much more of a nuisance to utility agencies compared with other cities, as the  
9 infrastructures (e.g. pipelines and facilities) are usually constructed within a very limited space  
10 (Li *et al.*, 2017) and managed by diverse operators. For example, in Hong Kong, the  
11 underground space of one-mile of roadway usually has more than 30-miles of utility lines –  
12 3.5, 24 and 85 times that of Singapore, the United Kingdom and United States respectively  
13 (Wong, 2006). Engineers often have to endure inaccurate record plans to perform maintenance  
14 and rehabilitation works, and sometimes even leading to the accidental damage of lines.  
15 Moreover, from a maintenance and renewal perspective, it is common to find sections of road  
16 being re-excavated within few years of resurfacing due to a disregard of the interdependencies  
17 involved. Although executing such corridor upgrade works across organizations proactively  
18 could save costs and reduce disruptions to the neighborhood, utility departments currently lack  
19 the incentive to coordinate these practices.

20  
21 The fragmented, inconsistent, and incompatible asset management information and processes  
22 involved, together with insufficient and ineffective coordination and communication across  
23 organizations, restrict the ability of municipalities to evolve IAM to an advanced level or cope  
24 with external challenges in the near future. In response, this paper proposes an integrated  
25 framework to facilitate IAM in high-density cities. Initially, the current IAM practices in Hong  
26 Kong, as a representative international high-density city, are reviewed and compared with  
27 idiosyncratic best practices adopted in pioneer countries worldwide. The conceptual resilient  
28 and sustainable multisector integrated IAM (RSM-IIAM) framework is then presented aimed  
29 at providing an advanced, sustainable, and resilient IAM through information integration,  
30 process harmonization, and use of interdependencies spanning multiple infrastructure assets.

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

## 6 7 **2 Background**

### 8 9 *2.1 The IAM concept, frameworks and supporting tools*

10  
11 The IAM concept has two generally acknowledged definitions, with one from ISO 55000 and  
12 the other from the International Infrastructure Management Manual (IIMM). ISO 55000  
13 defines IAM as the coordinated activity of an organization to realize the value of its assets.  
14 IIMM concludes that IAM involves the systematic and coordinated activities and practices of  
15 an organization to deliver its objectives optimally and sustainably through the cost-effective  
16 lifecycle management of assets. Furthermore, IIMM identifies five key elements of IAM  
17 practice as defined level of service and monitoring performance; management of demand  
18 change; lifecycle approach; risk management and optimized long-term financial planning  
19 (IPWEA, 2015). There has been much research and industry work pertinent to sector-specific  
20 IAM regardless of different terms (e.g. facility management, public works management and  
21 utility management) being used interchangeably in the AEC literature (Uddin *et al.*, 2013). For  
22 example, Arif and Bayraktar (2012) proposed a theoretical framework for transportation IAM  
23 based on a thorough overview of asset management best practices in the transportation sector;  
24 while Grussing (2013) firstly applied asset management principles to building management  
25 and proposed a framework to improve facility information storage for actionable decision  
26 support. Myriad investigations have also been made from a lifecycle perspective, such as the  
27 framework devised by EI-Diraby and Rasic (2004) to evaluate and reduce the life cycle cost  
28 and emissions of infrastructure systems and Yuan *et al.*'s (2017) proposed linkage mechanism  
29 to integrate design, construction, operation and maintenance activities.

---

1 In addition, an easy-to-use information management system is the spine of effective asset  
2 management programs. Institutions worldwide are struggling to collect data from different  
3 sources and integrating existing databases within organizations. Mooney *et al.* (2005) described  
4 a web-based infrastructure management system with embedded structural, geotechnical data  
5 and analytics modules for planning project-level activities. A construction information database  
6 framework (CIDF) was developed to coordinate the processes of capital investment, schedule  
7 planning and performance measurement (Cho *et al.*, 2012), and a national-level knowledge  
8 portal WATERiD was built in the U.S. to facilitate experience sharing in water IAM (Jung *et*  
9 *al.*, 2013). As for enabling tools, information and communication technologies (ICT) have a  
10 promising potential to store, process and analyze gigantic volumes of heterogeneous IAM data.  
11 There are still a limited number of successful big data applications in the AEC industry however  
12 (Alavi and Gandomi, 2017). Pioneering work includes exploiting the potential of using big data  
13 and internet of things (IoTs) in automated infrastructure data collection (Martínez-Rojas *et al.*,  
14 2015), ontology-based representation of IAM knowledge (Shih *et al.*, 2009), data management  
15 and storage techniques for IAM information (Ng *et al.*, 2017), and BIM-GIS integration for  
16 visualization and IAM decision making (Halfawy *et al.*, 2008; Karan *et al.*, 2015).

17

## 18 ***2.2 Interdependency in infrastructure systems***

19

20 The scope of an infrastructure system can also indicate whether interactions exist between  
21 different systems. Some asset management activities can be integrated within one specified  
22 infrastructure management system. As for municipal scope, processes can be formulated to  
23 collate various data and functions into one management environment in order to obtain efficient  
24 and cost-effective operations and maintenance. Because of being defined within one specified  
25 system (e.g. water, drainage, or roads), such interactions can be regarded as intra-dependent.  
26 However, as Pederson *et al.* (2006) comment, failing to understand the impact of one  
27 infrastructure system on another leads to the disarrangement of resources, ineffective responses  
28 and inadequate coordination between decision makers and agencies. Inter-connection between  
29 infrastructure systems is acknowledged as inter-dependence (Vespignani, 2010). Rinaldi *et al.*  
30 (2001) define infrastructure interdependency as “a bi-directional relationship between two  
31 infrastructures, through which the state of each infrastructure influences, or is correlated to, the

---

1 state of the other”. He and his colleagues also classified interdependency as either physical,  
2 cyber, geographical or logical. Two infrastructure systems are physically interdependent if the  
3 state of each is dependent on the material outputs of the other, while an infrastructure has a  
4 *cyber-interdependency* if its state depends on information transmitted through the information  
5 infrastructure. Moreover, due to their intimate interactions with human needs, infrastructures  
6 formulate a system of systems incorporating human-cyber-physical interdependencies.  
7 Although interdependencies receive limited consideration in the municipal sector (IPWEA,  
8 2015), Halfawy (2008) and Nafi and Kleiner (2010) suggest that benefits can be derived from  
9 coordinating renewal plans co-located in a particular area, thus reducing duplication work and  
10 disturbance to nearby communities. Such interdependencies upon which municipal works  
11 could be coordinated are represented as geographic interdependencies (Rinaldi *et al.*, 2001),  
12 while the physical and cyber interdependencies of industry technical infrastructure systems  
13 generally act as basic nexus between systems (Duenas-Osorio *et al.*, 2007; Johansson and  
14 Hassel, 2010; Eusgeld *et al.*, 2011).

15

### 16 ***2.3 Sustainability and resilience of infrastructure systems***

17

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

27

28 As for resilience in infrastructure sector, current studies addressing engineering systems relate  
29 to defining and quantifying resilience (Hosseini *et al.*, 2016). Approaches adopted in the  
30 specified domain are comparable with those in community resilience analysis. These include  
31 the resilience index (Cimellaro *et al.*, 2016), multi-dimension and multi-stage resilience

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1 assessment framework (Ouyang *et al.*, 2012; Matthews *et al.*, 2015), dynamic inoperability  
2 input-output model (DIIM) (Baroud *et al.*, 2014) and probabilistic modeling approach (Ouyang  
3 *et al.*, 2014; Franchin and Cavalieri, 2015). Owing to the complexity of infrastructure networks,  
4 complex network theory is also harnessed for resilience analysis in road transportation, water  
5 and gas distribution, electricity transmission and telecommunication systems (Zhang and Wang,  
6 2016; Levenberg *et al.*, 2017; Krishnamurthy *et al.*, 2016). Interdependencies between  
7 interlaced infrastructure systems can induce cascading effects that lead to a sharp decrease in  
8 the urban resilience level. Although a resilience index considering interdependency is proposed  
9 to evaluate regional physical infrastructure systems disturbed by disasters (Cimellaro *et al.*,  
10 2014), research is further needed to reveal the relationship between the interdependency and  
11 resilience level of infrastructure systems (Feng *et al.*, 2017). Noticeably, Bocchini *et al.* (2014)  
12 and Lounis and McAllister (2016) first suggested that infrastructure resilience and  
13 sustainability are complementary and should be considered in a holistic manner, in which  
14 sustainability analysis accounts for normal operation conditions, whereas resilience analysis  
15 focuses on exceptional events.

16

### 17 **3 Research methodology**

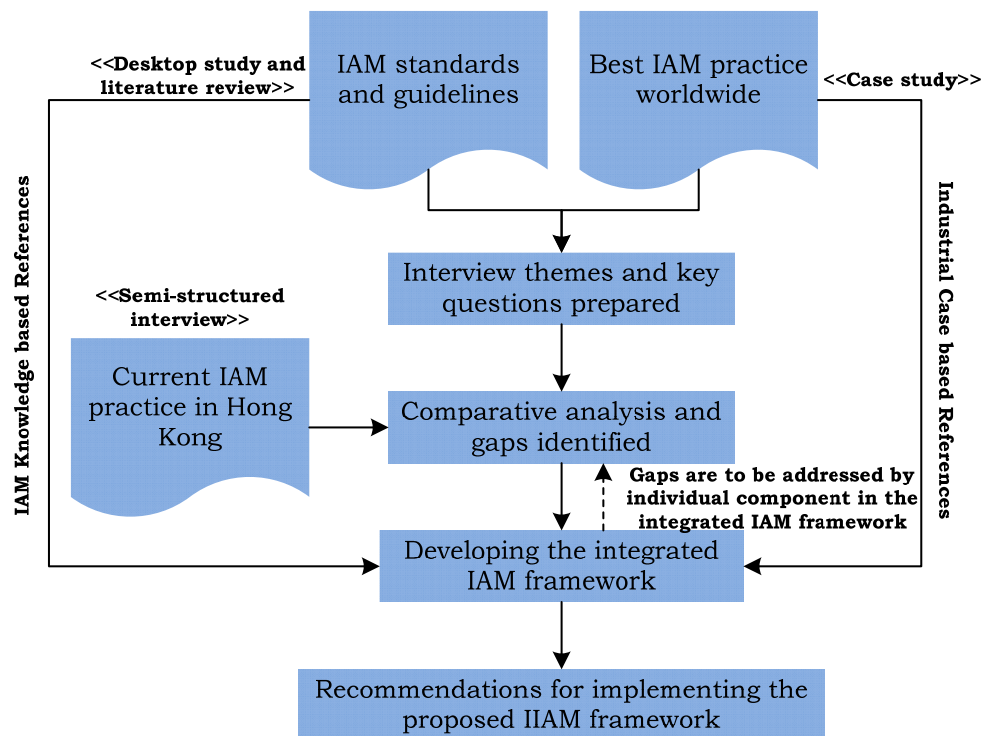
18

19 Owing to the exploratory and interpretive nature of this research, qualitative approaches are  
20 adopted to investigate the current practice of IAM adopted in Hong Kong and highlight the  
21 best IAM practices in pioneer countries worldwide. This involves twelve semi-structured  
22 interviews with asset management experts and industry practitioners in Hong Kong to obtain  
23 fundamental information to identify the issues to be addressed by the IIAM framework. For  
24 carrying out the interviews, a critical decision has to be made to define an appropriate unit of  
25 analysis (Hallowell, 2012). Since the objective of the study is to formulate an IIAM framework,  
26 it is necessary to identify current IAM practices throughout the various infrastructure sectors  
27 involved. Thus, the scope of the investigation is not simply limited to a single project. Both the  
28 maturity and merits of the current practices of each sector are examined to obtain an impartial  
29 account. The proposed integrated IAM framework in this research is developed through the  
30 overall research procedures illustrated in **Figure 1**. According to the work by Maclaren (1996),  
31 six types of methods can be leveraged when developing the framework, namely domain-based,



1 goal-based, sectoral, issue-based, causal-effect and combination methods. Since the  
 2 combination method can consolidate the advantages of several individual frameworks, we  
 3 choose the combination of goal-based and issue-based approaches to develop our framework  
 4 (Pan et al., 2018). The goal-based and issue-based frameworks are more suitable for dealing  
 5 with the distinction between global and local IAM issues; they reduce the number of problems  
 6 that have to be considered in a generic context to only those relating to specified IAM goals  
 7 and issues. Moreover, the overall research conforms to grounded theory, which is a “code-  
 8 concept-category-theory” based, hierarchical, and inductive research method; and the process  
 9 can be claimed to add to the validity and reliability of the study (Glaser & Strauss, 2006).

10



11

12

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

13

14 Several standards and specifications relating to IAM were consulted to prepare the interviews.  
 15 The standards include the ISO 55000 family and several sector-specific IAM guidelines and  
 16 reports issued by professional agencies and associations worldwide as listed in **Table 1** in the  
 17 Appendix. The essential features in these documents are generally clustered into six themes on  
 18 which the interview focuses, including policies, strategies and objectives; human resources; an

---

1 information system/database; condition monitoring and performance assessment; risk analysis  
2 and criticality identification; operation, maintenance, capital investment plans. Since the case  
3 study method focuses on understanding the full scope of targeting research problems (Creswell,  
4 2014), the best practices of the pioneer regions are complementarily scrutinized based on the  
5 cases provided by the guidelines and reports listed in **Table 1**. In this research, the United States,  
6 Canada, United Kingdom, and Australasia are acknowledged as pioneers, as they all have their  
7 own IAM guidelines and many municipalities in these countries are actively piloting principles  
8 and approaches of asset management to enhance their infrastructure system management  
9 capabilities. The objective of the case studies is to identify the idiosyncratic features of the  
10 asset management culture of each region; and the anticipated items consist of *Core process*  
11 *integration and contingency management* (United States), *Program coordination and climate*  
12 *change response* (Canada), *Broader social value and future-proofing* (United Kingdom), *Risk*  
13 *control and sustainable concerns* (Australasia). Moreover, the guidelines, reports, and best  
14 practices identified in these pioneer countries could be partially positioned as the benchmark  
15 for comparing prevailing IAM practices worldwide with that of Hong Kong, as well as  
16 providing implications for proposing the integrated IAM framework. Therefore, the key points  
17 in guidelines and merits identified through the case study of worldwide best practices are  
18 collectively referenced when formulating the interview questions, as stated in **Table 2** shown  
19 in Appendix.

20  
21 The extent to which the interview results are representative and generalizable is directly  
22 determined by the infrastructure sector selected. The selection consideration relates to the scale,  
23 nature, and relative maturity of the asset management practices, authority of the asset  
24 management agency, ease of obtaining information, etc. Interviews scheduled in all these  
25 sectors arguably provide a sufficient degree of comprehensiveness and diversity. The electricity,  
26 water-related, road and railway sectors are chosen because they are predominately governed  
27 by municipalities and because some organizations in these sectors are market leaders in Hong  
28 Kong. Moreover, the electricity and railway sectors are more automatic and intelligent,  
29 characterized by complex control and information systems, and by which practitioners can  
30 acquire accurate supervisory and real-time data (Johansson and Hassel, 2010). As is customary,

1 the interviewees for each sector were selected by convenience and snowball sampling (Lai *et*  
2 *al.*, 2011; Creswell, 2014; Zhang *et al.*, 2016; Yang and Chua, 2016). Of the 12 interviewees  
3 involved, 6 are from government departments, 4 from public organizations or non-government  
4 service providers and the remaining 2 are from consultancy companies (**Table 3**). All are  
5 working in infrastructure system operation and maintenance and quite experienced in asset  
6 management, which is demonstrated by 8 interviewees obtaining work experience over 5 years  
7 and 3 interviewees over 10 years. Two are from a power-related field and the same number of  
8 interviews was conducted in the railway sector. Each of three interviews was conducted in  
9 water related and road sectors. Over 90% of the interviewees are mid-level managers such as  
10 senior engineers and some even occupy such upper-management position as assistant directors  
11 or chief engineers. Each interview was conducted face-to-face for about an hour. For interview  
12 result analysis, descriptive coding and values coding are leveraged as main approaches  
13 (Saldana, 2016; Guo *et al.*, 2017). Particularly, interview transcripts are coded by using the six  
14 themes above, which is a process of descriptive coding. Comparatively, value coding is  
15 implemented by the proposed three-stage categorization method elaborated in section 5.2.  
16

**Table 3.** Particulars of Interviewees

<i>Code</i>	<i>Infrastructure Sector</i>	<i>Institution</i>	<i>Position</i>	<i>Experience (work years)</i>
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

17

18

---

## 1 **4 Case studies of IAM best practices worldwide**

2  
3 Advanced asset management practice is demonstrated in pioneer programs as consolidating  
4 condition assessment, system performance evaluation, and risk analysis to facilitate  
5 maintenance, rehabilitation, and replacement optimization. Best IAM practices in this paper  
6 refer to those systematically implementing the advanced IAM functions with forward-looking  
7 considerations. The following section summarizes the best IAM practices in the United States,  
8 Canada, United Kingdom, and Australasia to highlight the prevailing trends in different sectors.  
9 This not only enables the various emphases on asset management prevailing in each region to  
10 be compared, but will also benefit other municipalities sharing similar conditions.

### 11 12 ***4.1 United States – core process integration and contingency management***

13  
14 Asset management in the transportation sector was developed ahead of that in other  
15 infrastructure systems in the U.S., after which other infrastructure domains (e.g. bridges and  
16 underground utilities) followed suit (Uddin *et al.*, 2013). Research and development works  
17 continue to refine Pavement Management Systems (PMS), which include condition-based  
18 maintenance strategies founded on a sound understanding of the deterioration patterns,  
19 lifecycle cost analysis, criticality identification, and capital arrangements. For the bridge  
20 management domain, municipalities usually have a system that houses condition assessment  
21 data, with a separate bridge preservation program. However, the current trend converts from  
22 developing individual and exclusive functionality to integrating core and advanced asset  
23 management functions within one infrastructure asset system. In 2016, 55.2% of U.S. cities  
24 had such programs in development. Henderson in Nevada, Portland in Oregon and Saco in  
25 Maine, for example, are pilot cities aiming to implement a city-wide asset management and  
26 maintenance program with GIS-based asset inventories for the roadways, water and wastewater  
27 sectors, through both top-down and bottom-up approach (U.S. EPA and FHWA, 2015). Nearly  
28 20% of these pilot cities reported having already established relatively well-integrated systems  
29 (Underground Construction, 2016). Enabled by such systems, condition assessment, involving  
30 rehabilitation and replacement schedules, occurs at regular intervals, taking into account  
31 deterioration rates and useful life expectancy. Moreover, the cities are targeting ongoing work

---

1 through lifecycle and replacement cost analysis. Other useful approaches, such as criticality  
2 analysis, are also leveraged to drive maintenance policies and the optimization of operations  
3 and maintenance investment. City municipalities now realize the importance of having a  
4 strategic plan that pulls everything together in terms of resource allocation to provide a suitable  
5 framework for decision making (Younis and Knight, 2014; IPWEA, 2015).

6

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

18

#### 19 ***4.2 Canada – program coordination and climate change response***

20

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

30

---

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

17

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

29

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### 1 **4.3 United Kingdom – broader social value and future-proofing**

2  
3 With the formal publication of the ISO 55000 family of standards for asset management, the  
4 UK asset management philosophy has gradually converted from a least-cost to best-value  
5 orientation. The main drive of asset management also emphasizes performance and risk  
6 management instead of solely cost considerations. Compared with simply minimizing  
7 maintenance expenditure, maximizing performance and minimizing risk while satisfying  
8 budgetary constraints (rather than just meeting minimum performance requirements) is  
9 endorsed by a value-based philosophy (CSIC, 2015). Many utility departments have recently  
10 formulated their own sector-specific asset management guidelines built on the principles  
11 involved (UK Roads Liaison Group, 2016b). Pilot authorities also seek opportunities to  
12 embrace broader values when developing their asset management framework. For example,  
13 after identifying stakeholder expectancies by survey, London’s Islington highway authority  
14 correspondingly set social objectives in highway assessment management in addition to its  
15 engineering ones. Typical crime statistics are also entered into the asset management system,  
16 which allows highway assets to be appropriately valued and the identification of major  
17 prostitution, car crime, drug abuse and assault locations for further monitoring (Hooper *et al.*,  
18 2009) – social benefits therefore being obtained through an integrated asset management  
19 framework.

20  
21 Future proofing is suggested as a principle in formulating asset management objectives to  
22 address ageing issues, extreme weather events and demand changes (ICE, 2013). In doing this,  
23 the planning and design stage of infrastructure systems has the potential to create greatest value.  
24 The design of London’s Heathrow airport baggage-handling facilities, for instance,  
25 incorporates sufficient flexibility and redundancy by anticipating changes in technology and  
26 the quantity of passengers to allow the screening machines to be easily upgraded in future.  
27 Moreover, in anticipation of more stringent environmental policies and projected increases in  
28 temperature and precipitation in future, the airport has also established a carbon dioxide  
29 reduction target as well as new asset design standards for buildings and drainage (Masood *et al.*,  
30 2016; Lai *et al.*, 2017). Similarly, in addition to satisfying the current requirements, it also  
31 serves as an opportunity to consider the future when devising rehabilitation programs.

---

1

2 **4.4 Australasia – risk control and sustainability concerns**

3

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

20

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

27

28 **4.5 Summary**

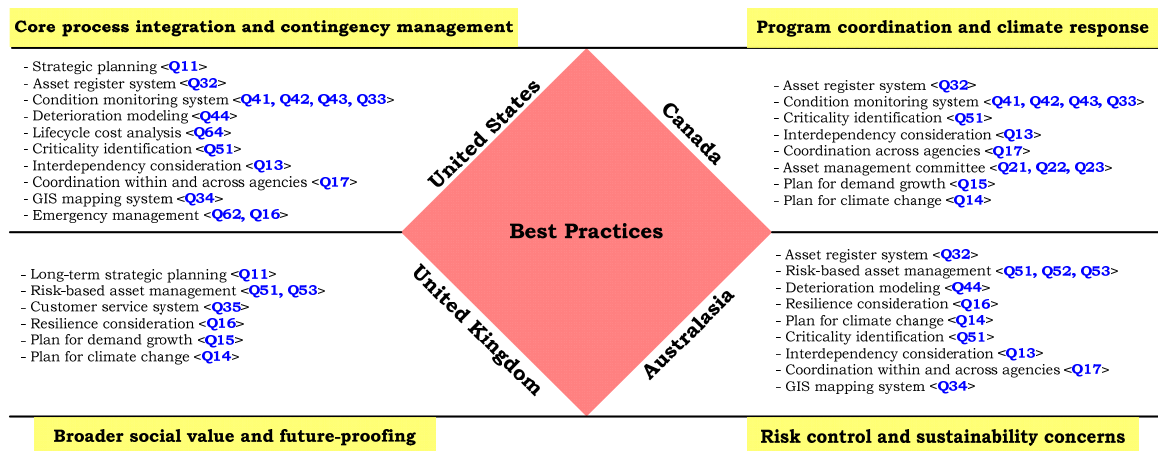
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30 The asset management systems established in these countries typically support the functional  
31 operation and maintenance management (e.g. condition assessment, deterioration, life cycle



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

21



22

23

Fig. 2. Summary of best IAM practices worldwide

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1

## 2 **5 Analysis of current IAM practices for high-density cities**

3

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

### 22

### 23 ***5.1 Experiences of Hong Kong's IAM practices***

24

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

---

1

2 **5.1.1 Case pertaining to electricity IAM**

3

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

22

23 **5.1.2 Cases pertaining to road and railway IAM**

24

25 The Hong Kong Highway Department's excavation-permit administration system illustrates  
26 the effectiveness of coordinating municipal work. Under this scheme, utility providers have to  
27 apply for permits through the Excavation Permit Management System (XPMS) when road  
28 excavation work is unavoidable (Hong Kong HyD, 2004). Moreover, a 'no-cut' rule or  
29 moratorium on excavation specifies that, except for emergencies, no excavation work is  
30 allowed for a certain number of months after pavement overlay. Excavation requests must be

---

1 registered through the XPMS and if there is a small time-gap or conflict between two planned  
2 works, applicants have to collaborate with each other to produce a coordinated arrangement for  
3 submission. This initiative aims to be both cost-effective and limit disruption to the community  
4 through work coordination.

5  
6 Hong Kong's MTR is representative of railway asset management excellence certificated by  
7 BSI ISO 55001 in 2014. As a member of the Community of Metros (CoMET), the MTR is also  
8 continuously ranked highly compared with its counterparts in the CoMET group in  
9 performance in terms of various evaluation elements comprising operational reliability, service  
10 quality and safety, the effectiveness of its processes and efficiency of resource inputs (MTR  
11 Corporation, 2015). The asset management strategy is clearly derived from the corporate  
12 strategic plan. Meeting the basic Standard Performance Requirement (SPR) stipulated by its  
13 Operating Agreement (OA), the MTR has further established its own Customer Service Pledge  
14 (CSP), which is more stringent in respect of the MTR's train frequencies and station facilities,  
15 including train service delivery, on-time journeys, escalator reliability, etc. Comprehensive  
16 asset replacement plans have been made for the future renewal of assets based on condition  
17 and performance. Nonetheless, continuous improvement is still needed to enhance the existing  
18 systems or to bring forward the roll out of the asset management system. The level of detail  
19 and scope to which condition assessment is conducted is also in need of further refinement.  
20 The basis of the intervention is formed by bridging performance appraisal with risk assessment  
21 and applying asset criticality down to all key sub-assemblies or components. Moreover, the  
22 MTR aims to enhance the asset information system, adopt state-of-art sensor technology, big  
23 data, and cloud computing to collect real-time operational data for comparison against pre-set  
24 alarm thresholds using sophisticated analytics and artificial intelligence to increase the  
25 efficiency of precautionary decision making.

### 26 27 ***5.1.3 Case pertaining to water-related IAM***

28  
29 Municipal sectors are seemingly lagging behind well-acknowledged electricity asset management  
30 practice, particularly in handling underground assets (Halfawy *et al.*, 2008). Owing to

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1 progressive development in many relatively mature districts over several decades, it is common  
2 to find organizations owning and managing extensive networks unable to report what  
3 infrastructure they have, its location, condition, value or performance and level of service being  
4 provided (Martin *et al.*, 2013). When conducting repair or renewal work, because of the  
5 complicated public and private ownership of underground municipal infrastructure systems,  
6 the proponent (e.g. the Highway Department) needs to communicate with other stakeholders  
7 (e.g. the Water Supplies Department and the Drainage Services Department) who are  
8 responsible for the management of geographically co-located infrastructure systems and  
9 soliciting the spatial layout of their components. Such common practice in Hong Kong lacks  
10 accuracy and efficiency in handling municipal work due to inconsistencies and even  
11 contradictions between different data resources. The Water Supplies Department (WSD), for  
12 example, has been using a System Control and Data Acquisition (SCADA) system to monitor  
13 the supply and distribution of fresh and flushing water. Hundreds of District Metering Areas  
14 (DMAs) and Pressure Management Areas (PMAs) have been progressively established since  
15 2000 and network monitoring data (i.e. flow, pressure, etc.) collected from the DMAs are been  
16 processed with discrete systems. Thus, in pursuing an integrated, holistic, and effective single-  
17 platform for performance analysis, the WSD is now working on establishing an Intelligent  
18 Network Management System (INMS) (Hong Kong WSD, 2016). Similarly, realizing the  
19 possible potential benefits from implementing systematic asset management, the Drainage  
20 Services Department (DSD) commissioned AECOM Asia Co. Ltd. in 2012 to provide  
21 consultancy support for implementing a Total Asset Management (TAM) scheme. This  
22 strengthened its developing lifecycle asset management policy and strategy, defining an  
23 appropriate service level and formulating a performance and risk management framework  
24 (Martin *et al.*, 2013).

25

## 26 ***5.2 Challenges and barriers to continuous improvement***

27

28 Since the vast majority of existing asset management systems still focus on operational  
29 management aspects (e.g. work orders, service request), with little or no functionality to  
30 support long-term renewal planning decisions (e.g. deterioration modeling, risk assessment,  
31 lifecycle cost analysis, renewal prioritization), there lacks a rational reference for funding

1 allocation. Therefore, the annual budget is merely based on historical records. Departments are  
 2 quite accustomed to making *ad hoc* decisions based on practical experience and operational  
 3 resources are allocated to the emergency rehabilitation of failed infrastructure components to  
 4 a large extent instead of preventative initiatives due to adequate funding to date. Though pilot  
 5 utility departments have initiated risk analysis underpinned by monitoring data in current asset  
 6 management practice, such condition-based inspection sheds limited light on the consequence  
 7 of possible component failure (Ugarelli *et al.*, 2010).

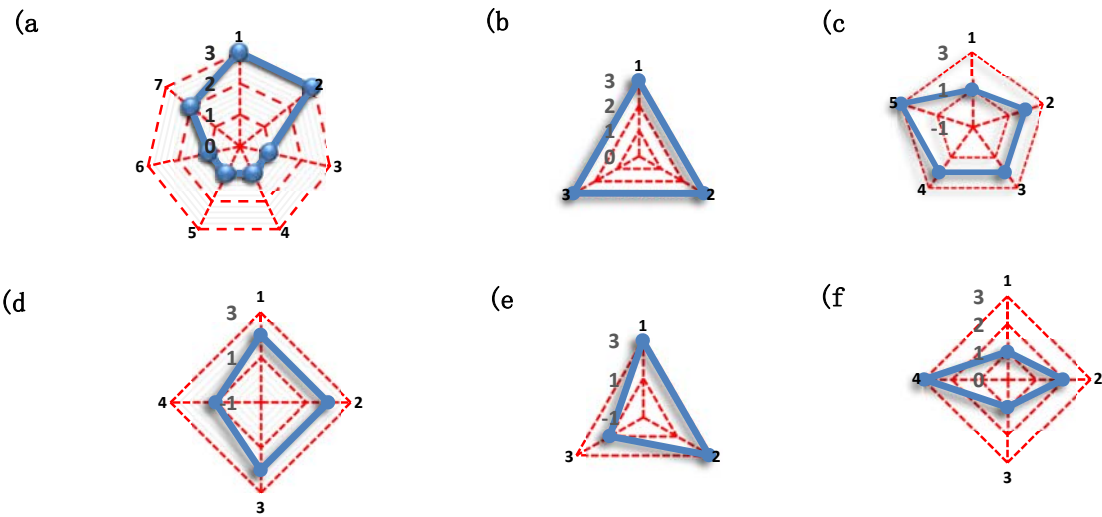
8  
 9 Moreover, data quality issues arising from data ‘silos’ - in terms of data inconsistency,  
 10 inaccuracy, incompleteness and irrelevance - have been the major obstacles that influence the  
 11 efficiency and effectiveness of IAM. Fragmented decision-making processes hinder both the  
 12 large-scale adoption of integrated IAM across multiple organizations and sectors and  
 13 coordination between asset management stakeholders, thus destroying the potential for  
 14 integrated decision making. Apart from modeling for short-term operational purposes, such  
 15 long-term considerations as interdependency, sustainability and resilience need to be  
 16 encapsulated in the integrated IAM framework as new requirements within the context of  
 17 growing complexity and uncertainty in infrastructure systems (Saidi *et al.*, 2018).

18

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

<i>Themes</i>	<i>Electricity IAM</i>	<i>Road and railway IAM</i>	<i>Water-related IAM</i>
<b><i>Q1. Policies, strategies and objectives</i></b>	-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
<b><i>Q2. Human resources</i></b>	-Asset management committee -Regular training	-Asset management committee -Regular training	-Asset management committee -Regular training
<b><i>Q3. Information system/database</i></b>	-Asset register system -GIS mapping system -Customer service system	-Asset inventory -Condition monitoring system -Customer service system	-Consolidating asset register system -Customer service system
<b><i>Q4. Condition monitoring and performance assessment</i></b>	-Condition monitoring techniques	-Condition monitoring techniques -Condition indices and grading	-Condition monitoring techniques
<b><i>Q5. Risk analysis and criticality identification</i></b>	-Risk-based asset management	-Risk-based criticality identification	-Risk event identification
<b><i>Q6. Operation, maintenance, capital investment plans</i></b>	-Lifecycle cost planning -Emergency management	-Lifecycle cost planning	-Lifecycle cost planning

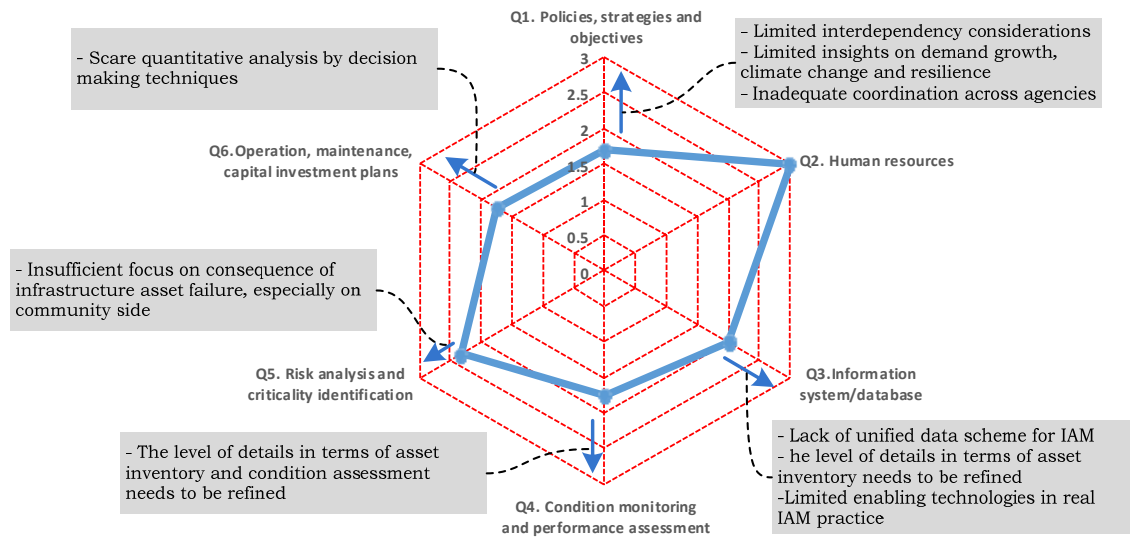
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12 **Fig. 3.** Current IAM practice with regard to each theme in Hong Kong, with (a) Policies, strategies and  
13 objectives, (b) Human resources, (c) Information system/database, (d) Condition monitoring and  
14 performance assessment, (e) Risk analysis and criticality identification, (f) Operation, maintenance, capital  
15 investment plans  
16

17 **Table 4** presents the interview findings pertaining to current IAM practice in Hong Kong. The  
18 interviewees' remarks from the above three sectors are reorganized corresponding to the six  
19 themes in the far left column originating from guidelines and international standards. The three-  
20 stage categorization (Saldana, 2016) method is used to delineate the level of development in  
21 individual themes, with stage 1 denoting fledging IAM practice in Hong Kong, stage 2  
22 representing IAM practice in progress in Hong Kong, and stage 3 indicating prevailing IAM  
23 practice in Hong Kong. The principles of classifying the IAM practice in each theme state are  
24 as follows. If interviewees in all three sectors mention a common feature in a certain theme,  
25 we allocate 3 points on this dimension. For example, interviewees all refer to *strategic planning*  
26 (Q11) and *target level of service* (Q12) in the first theme, namely policies, strategies, and  
27 objectives, so these two dimensions are both given 3 points. Contrarily, if the interviewees  
28 seldom emphasize certain dimension in one theme, we assign 1 point. In the first theme,  
29 dimensions of *interdependency consideration* (Q13), *plan for climate change* (Q14), *plan for*  
30 *demand growth* (Q15), and *resilience consideration* (Q16) are less addressed so they earn 1  
31 point. If the interviewees acknowledge the value of certain dimension in one theme, while

1 requesting further refinement in practice, the intermediate score of 2 applies. The detailed  
 2 scores for each theme are shown in the radar graph in **Fig. 3**. Moreover, assuming that the  
 3 individual dimensions in each theme carry the same weight, we can obtain the aggregated  
 4 appraisal of IAM practice in Hong Kong with regard to the six themes (see **Fig. 4**).  
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**Fig 4.** Gaps to fill in term of IAM in Hong Kong

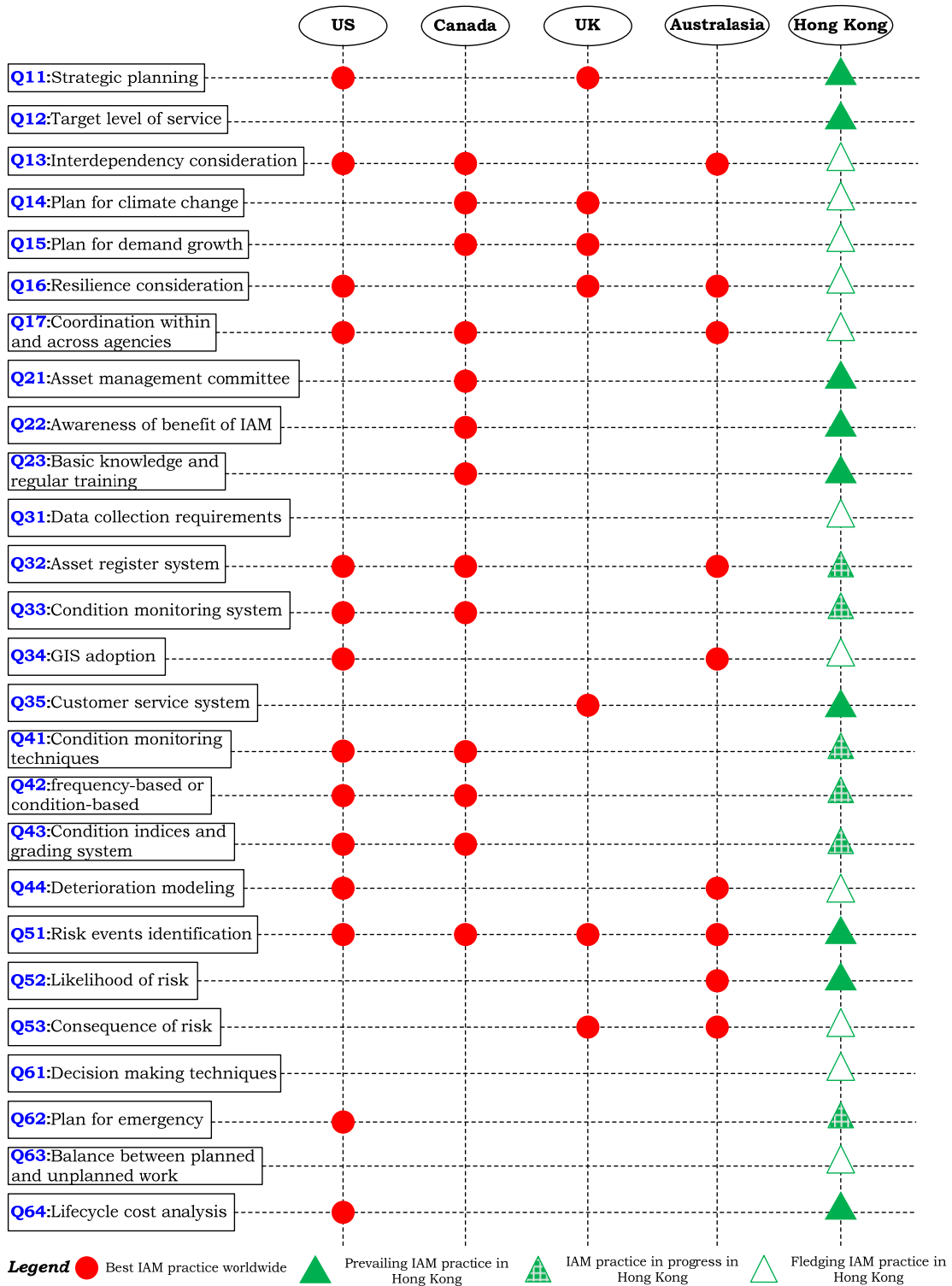
9 **Fig. 5** delineates the current IAM practice in Hong Kong compared with the worldwide best.  
 10 Although Hong Kong practitioners are proficient in adopting IAM principles in such aspects  
 11 as human resource training, there is still much room for improvement in other aspects in which  
 12 several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

- 15 (1) limited consideration of interdependency issues;
- 16 (2) limited insights into demand growth, climate change and resilience;
- 17 (3) inadequate coordination across agencies;
- 18 (4) lack of a unified data scheme for IAM;
- 19 (5) the level of detail needs to be refined, in terms of asset inventory and condition assessment;
- 20 (6) insufficient focus on the consequences of infrastructure asset failure, especially on the
- 21 community side;
- 22 (7) scarce quantitative analysis by decision-making techniques, e.g. trade-off analysis; and



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

2



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

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## 1 **6 The proposed resilient and sustainable multisector integrated IAM** 2 **framework (RSM-IIAM)**

3  
4 This section proposes the resilient and sustainable multisector integrated IAM framework  
5 (RSM-IIAM). The framework comprises the integration of IAM information throughout the  
6 lifecycle, integration of IAM processes, integration of IAM by interdependencies, and  
7 integration of sustainability and resilience with IAM. Integration of heterogeneous information  
8 sources and fragmented processes serves as the premise for integrated decision-making.  
9 Integration by interdependency constitutes an effective entry point to link together different  
10 infrastructure systems since physical, cyber and geographical interdependencies are all tangible.  
11 Sustainability and resilience concepts emerge as new requirements that need to be embraced to  
12 develop the new version of IAM. Details are discussed as following subsections.

### 13 14 *6.1 Integration of IAM information throughout the lifecycle*

15  
16 Data fragmentation always hinders management process integration because of the  
17 sophistication of the lifecycle asset management processes involved. Moreover, data available  
18 is often proprietary and the limited acceptance of standardized data format and exchange  
19 scheme blocks coordination between different operators (Halfawy, 2008). Data always need to  
20 be reinterpreted and reentered into a separate processing system. However, a standardized IAM  
21 data schema is key enabler to realize interoperable, consistent, and integrated IAM. Since the  
22 data schema accommodates all the related information used for IAM, each disparate data  
23 source implements a subset of, and could be mapped to, the standard data model. Since  
24 substantial data models have been developed by such reputable associations as the  
25 Environmental Systems Research Institute (ESRI), Federal Geographic Data Committee  
26 (FGDC), CADD/GIS Technology Center and the OpenGeoSpatial Consortium (OGC),  
27 ISO/TC211 Committee, it is economical and practical to harmonize and integrate the available  
28 models to identify the gaps and exclusive implementation requirements of IAM (Halfawy,  
29 2010). Considering the geo-reference attribute of infrastructure assets, spatial data standards  
30 are preferable for reference, such as the Spatial Data Standard for Facilities, Infrastructure, and  
31 Environmental applications (SDSFIE) and the Municipal Infrastructure Data Standard (MIDS).

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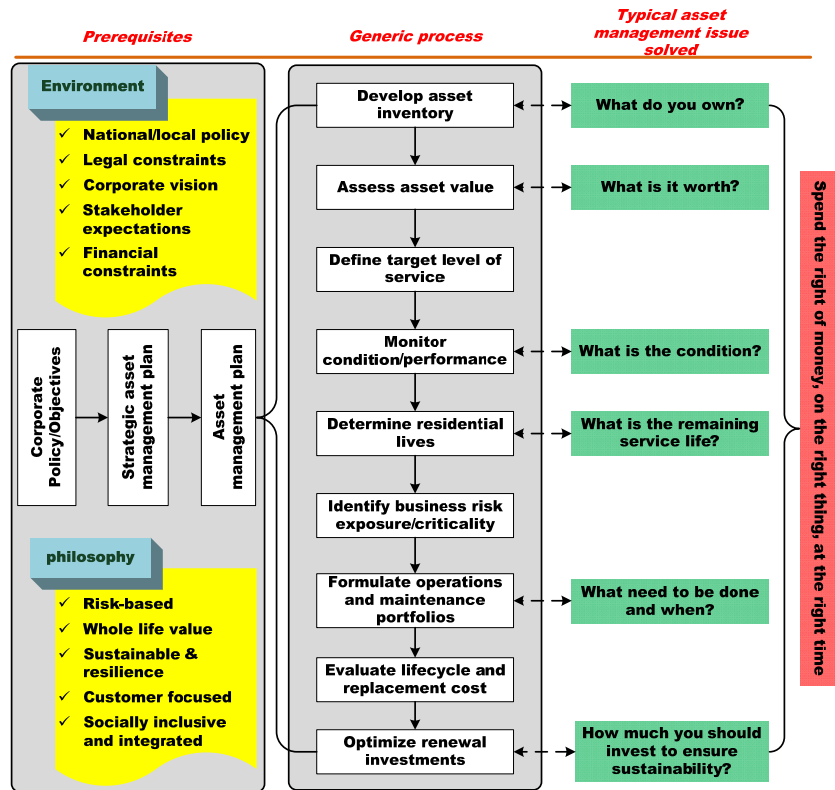
1 However, some data models focus less on lifecycle aspects, regardless of physical elements of  
2 systems and the implementation specification. There is an increasing trend in the construction  
3 industry to use XML as a prominent data encoding and exchanging format; the Geographic  
4 Markup Language (GML) is essentially a type of XML encoding for modeling and exchanging  
5 spatial and non-spatial attributes of infrastructure assets (Gröger and Plümer, 2012). Available  
6 commercial GIS software packages support the GML format for data schema representation.  
7 Moreover, BIM tools are acknowledged as a rich information repository for the lifecycle of  
8 buildings and facilities and have powerful editing function compared with that of GIS software  
9 (Cheng and Deng, 2015). A GIS-BIM integrated pattern is expected to fit the purposes of  
10 integrated IAM, in which a BIM module serves as a lifecycle semantic editor, with the GIS  
11 component leveraged for visualization and information query and analysis (Kang and Hong,  
12 2015).

13

14 As a mature data schema contains a conceptual class hierarchy, geometric data model and  
15 semantic data model, the lifecycle semantics of an infrastructure asset should be encapsulated  
16 in an asset inventory database and ultimately utilized in IAM processes (Cheng *et al.*, 2016).  
17 The design stage provides the key attribute information (e.g. geometry, location, and materials  
18 data) of an asset. Due to constructability considerations, some design information would need  
19 to be rectified. Asset information collected during the construction stage is therefore also  
20 indispensable. The operation and maintenance history needs to be recorded promptly in the  
21 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  
22 management with the short-term of construction for a portfolio of assets should deliver real  
23 savings (BSI, 2014a). Moreover, the concept of level of details (LODs) should be inherited  
24 from BIM, in which models are organized into different LODs (depending on BIM uses and  
25 the project phase), to IAM to improve computational efficiency (Deng *et al.*, 2016). Another  
26 important consideration for establishing IAM systems is the level of integration and  
27 interoperability with other systems already in use. It is much more cost-effective and pragmatic  
28 to allow legacy applications to be bridged with the platform via adapters when building the  
29 IIAM environment as a modular platform (Halfawy, 2010).  
30

1  
2 **6.2 Integration of the IAM process**  
3

4 Data integration serves as only the first step. Implementing data analysis and decision support  
5 modules that would automate some aspects of the decision process serves as a core function of  
6 a successful IAM system. Although previously specific software tools targeting a particular  
7 function (e.g. work schedule or benefit cost analysis) have largely improved the productivity  
8 of IAM, these stand-alone function modules are not incorporated into an integrated process.  
9 For example, most commercial asset management systems are essentially work management  
10 systems without lifecycle cost analysis and performance assessment functions (Halfawy *et al.*,  
11 2006). ISO 55000 standards designate basic elements that need to be considered in  
12 implementing the asset management methodology. Municipalities worldwide have  
13 successively developed their own guidelines for specific infrastructure asset sectors. Integrated  
14 process models share common requirements and characteristics despite inconsistencies in the  
15 various asset-specific detailed guidelines of the management processes.  
16



17  
18 **Fig. 6.** Prerequisites, integrated asset management processes, and typical asset management issues solved

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**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

- 
- 1 management strategy corporate vision and strategies (BSI, 2014b; Younis and Knight,  
2 2014). This sub-process helps to answer the question “What is the condition?”
- 3 (5) Determining of remaining life of asset components to quantify their deterioration rate and  
4 understand the inherent mechanisms involved to assist in predicting their future condition  
5 at any given stage of the life cycle. This step can help to answer the question “What is the  
6 remaining service life?”
- 7 (6) Identifying the critical components of infrastructure assets requiring consideration of both  
8 the likelihood and consequences of potential risks (Halfawy *et al.*, 2008; Salman and  
9 Salem, 2012). Failure mode analysis is also required since the probability of failure is  
10 measured in terms of asset performance and is related to the primary failure mode.  
11 Expected failure modes may contain condition or structural failure, end of useful life,  
12 under-capacity, not meeting the established service level, no longer economic to own and  
13 operate, etc. The most frequently used indicator of probability of failure in practice is the  
14 remaining asset life when handling asset failure due to aging. Special attention should be  
15 given to low probability-devastating impact risks (Kopljenovic *et al.*, 2016).
- 16 (7) Formulating renewal portfolios underpinned by risk assessment serves as an initiating step.  
17 Evaluating lifecycle and replacement costs of renewal portfolios facilitates the  
18 optimization of capital investment strategies (Shahata and Zayed, 2012, 2013). Thus, final  
19 answers to questions “What needs to be done and when” and “How much to invest to  
20 ensure sustainability?” are obtained that can be treated as rationales for priority funding.

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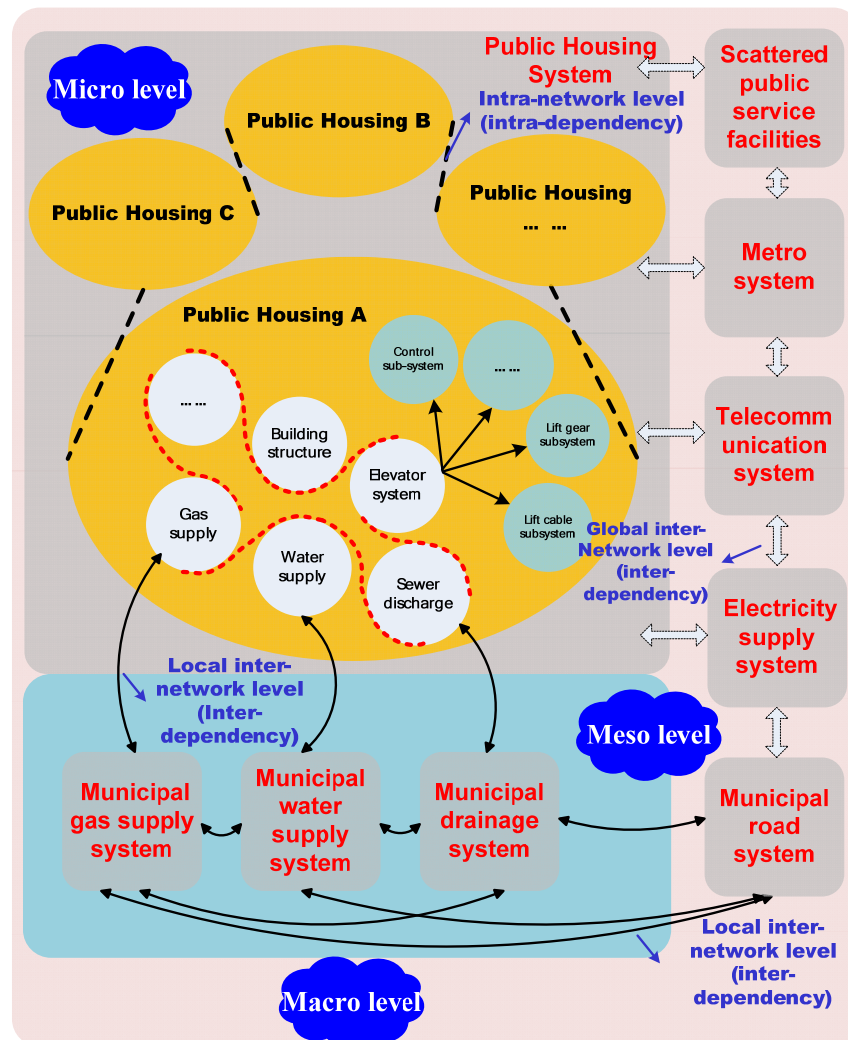
### 22 **6.3 Integration of IAM by interdependencies**

23

24 Although an integrated asset management process could be achieved *within* an infrastructure  
25 sector by the intra-dependency presented in **Fig. 7** on the scope of micro level, collating asset  
26 management practices *across* sectors involves consideration of the interdependencies between  
27 different infrastructure asset systems. Water supply pipelines in a public building need to be  
28 connected to municipal water supply mains. Corresponding to Rinaldi *et al.*'s (2001) types of  
29 interdependency, the interdependency between the public housing system and municipal water  
30 supply system can be identified as a physical attribute; likewise, with municipal gas supply and  
31 municipal drainage systems. Therefore, when carrying out renewal work, the relative utility

1 involved needs to take into account demand changes in the public housing system in the near  
 2 future that may have an unavoidable impact on the municipal water system. Moreover, for  
 3 maintenance purposes, co-located infrastructure assets (e.g. water mains, sewers and road  
 4 assets within the same corridor) at a particular site could be optimally upgraded in a bundle,  
 5 thus minimizing duplicated renewal costs and disturbance to the nearby community (Elsawah  
 6 *et al.*, 2016; Shahata and Zayed, 2016). Clearly, geographical interdependency also acts as the  
 7 basis for bundling renewal work in this way (Nafi and Kleiner, 2010; Islam and Moselhi, 2012).  
 8 Physical and geographical interdependencies are therefore commonly prominent at the local  
 9 level, while infrastructure inter-networks occur at the meso level.

10



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12

**Fig. 7.** Levels of integration between infrastructure asset systems

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

11

#### 12 ***6.4 Integration of sustainability and resilience with IAM***

13

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

18

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



---

1 to progress beyond considering sustainability as a “bolt-on issue” to be embedded in “business  
2 as usual” IAM practice.

3  
4 Community resilience is the ability of a community to prepare for anticipated natural or man-  
5 made hazards, adapt to changing conditions, withstand, and recover rapidly from any ensuing  
6 disruptions (NIST, 2015a, 2015b). Since the social functions of a community determine the  
7 functional requirements of its buildings and infrastructure systems, focusing on the resilience  
8 of the built environment operationalizes the resilience concept in the form of regional or  
9 national resilience strategies (Jabareen, 2013). The objectives of IAM are to sustain a cost-  
10 effective system and make future-proofing capital investments and, while resilience is  
11 previously perceived as separated from the asset management system, such objectives can be  
12 maintained either under normal or disruptive event conditions; if IAM is undertaken during  
13 exceptional disrupted conditions, then resilient requirements could emerge. For such high-  
14 density cities as Hong Kong, operationalization of the resilience concept by formulating open  
15 frameworks, inclusive resilience metrics, integrated decision-support toolkits, interdisciplinary  
16 knowledge and easy-to-use management and collaborative systems should be introduced into  
17 IIAM to improve the resilience and smartness of its built environment.

## 18 19 **7 Recommendations for implementing the framework**

20  
21 The stakeholders are encouraged to implement and operationalize the proposed RSM-IIAM  
22 framework according to the following steps: strengthening the awareness of adopting advanced  
23 IAM; standardizing asset management processes within and across infrastructure sectors;  
24 enhancing coordination between IAM agencies; seeking end-user engagement during IAM  
25 practice; and building up an agile inter-network IAM platform by virtue of interdependency, as  
26 demonstrated in **Fig. 8**. The detailed interpretation of each step is depicted in the following  
27 subsections.

28

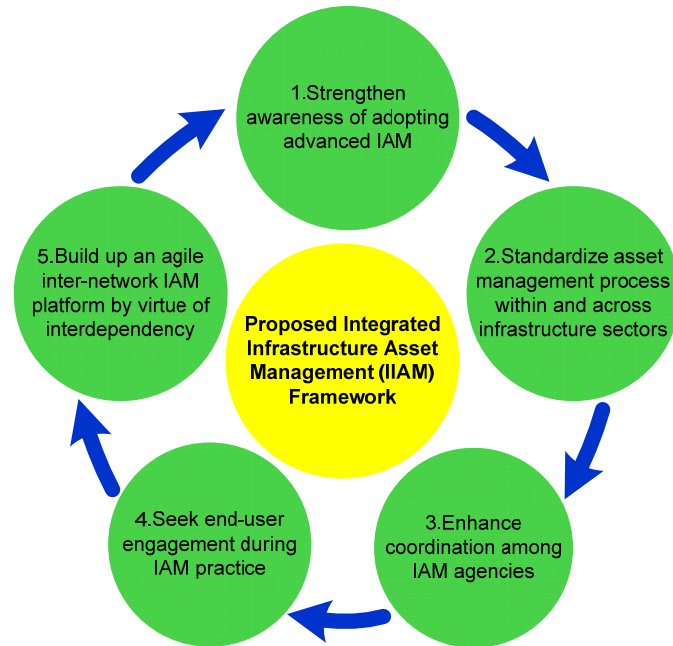


Fig. 8. Recommendations for implementing the proposed IIAM framework

### 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.

---

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

### 10 ***7.2 Standardize asset management process within and across infrastructure sectors***

11  
12  
13 Where public and private ownership exist within one infrastructure sector, asset management  
14 can clearly be developed in different ways. However, although many processes within and  
15 across departments and organizations are performed in an unstructured and inconsistent manner,  
16 such processes still can share a generic framework as detailed in Section 2 regardless of the  
17 size and characteristics of the infrastructure systems involved. For an IIAM framework, the  
18 systematization and structuring of processes is essential and standard asset management  
19 processes both reduce subjectivity in decision making and serve as benchmark for  
20 encapsulating asset management practices within and across departments and organizations  
21 into a homogeneous network upon which more efficient resource allocation decisions can be  
22 made from a global perspective. Noticeably, considering the inherent nature of different  
23 infrastructure systems, the generic process model allows flexibility for selecting suitable  
24 assessment and prediction tools to achieve a desired level of functionality.

### 25 26 ***7.3 Enhance coordination among IAM agencies***

27  
28 Suitable role definitions and organizational designs are fundamental for effective asset  
29 management, with an asset management framework to provide information for supporting  
30 decision-making in close collaboration with financial, information systems and strategic  
31 planning teams. Moreover, asset managers commonly need to coordinate different function

---

1 teams (e.g. financial planning team, customer service team) within specific asset management  
2 organizations and a steering group of cross-organization representatives is beneficial for the  
3 integrated management of a utility in capturing opportunities to coordinate across utilities. One  
4 approach, adopted by the Hong Kong government, is to establish a formal committee with  
5 delegates from a variety of service areas to ensure open lines of communication. This can not  
6 only meet basic requirements of avoiding potential work conflicts but reducing repeated work  
7 that could cause extra expenditure and neighborhood disruptions. Governments approving  
8 budgets on a program level for roads, drainage, water etc. as opposed to an individual project  
9 level, also allows significant flexibility to change priorities between individual projects.

#### 10 11 ***7.4 Seek end-user engagement during IAM practice*** 12

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

26  
27 End-users are encouraged to participate in the asset management processes since they can  
28 update and communicate timely service requests; for instance, when confronted with a sudden  
29 breakdown of an infrastructure component. Field operations and information monitoring can  
30 be witnessed by means of portable devices (e.g. PDA device, mobile phone). The ability of the  
31 browser-based wireless Internet to access a centralized terminal platform also enables the AM

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1 team to capture and apply these real-time data to support reliable asset inventory and location  
2 tracking, condition appraisal, failure detection, emergency responses, maintenance planning  
3 and resilience prediction and reaction decisions.

#### 4 5 ***7.5 Build up an agile inter-network IAM platform by virtue of interdependency*** 6

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

17  
18 In Hong Kong and other similar high-density big cities, infrastructure facilities are located in  
19 close proximity to each other or housed in common service tunnels. It would be much more  
20 beneficial for asset managers to arrange their maintenance and rehabilitation activities jointly  
21 for different infrastructure systems located in geographically spatial proximity. This would  
22 apply to, for instance, a corridor upgrade assisted by a GIS-based inter-network platform, since  
23 it maintains pre-defined links between assets and street addresses. Such links would also  
24 facilitate the identification of and serving proper notices to, customers who may be affected by  
25 asset failure. By considering interdependencies, renewal plans could be coordinated to span  
26 multiple infrastructure assets, thus minimizing the costs, disruptions, and risks to the  
27 community.

28  
29 Managing information across various infrastructure service areas is still very immature,  
30 especially with a large volume of incomplete and incompatible data from fragmented data  
31 sources and processes. Moreover, the data maintained by infrastructure asset owners are based

---

1 on unique data collection methods and kept in diverse systems. Therefore, asset managers from  
2 different service areas in Hong Kong need to confirm the data required for inter-network IAM  
3 decision support at the strategic, tactical, and operational level and to define suitable asset  
4 classification standards, generic asset hierarchies, asset attributes, and key performance  
5 indicators for collaborative IAM. This could lead to the formulation of a set of universally  
6 acceptable asset attributes for asset identification and location, physical condition, maintenance  
7 history, failure risk, repair cost, service level and resilience predication to drive the design of  
8 the unified data regime. Instead of reinventing existing IAM systems, it is feasible and practical  
9 to integrate the strengths of emerging information technologies by capitalizing on the  
10 established infrastructure asset classification hierarchies, existing good framework and various  
11 software architectures and integration technologies when developing the next generation of  
12 agile and interoperable IAM systems.

13

## 14 **8 Conclusion**

15

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

25

26 The potential implications of the study for current IAM practice in Hong Kong are an enhanced  
27 awareness of advanced IAM, public engagement, strengthened coordination between utility  
28 departments and agencies, and the establishment of an agile inter-network platform. The  
29 formulated IIAM framework is clearly meaningful and valuable for the infrastructure  
30 management of high-density communities. It is also comprehensive and generic enough to be  
31 adopted by cities of varying sizes and building density. Additionally, municipalities could hone

1 and customize the generic integrated framework to meet their unique needs as well as align  
 2 with their own IAM capabilities. For future research, detailed scenarios could be devised to  
 3 further validate the proposed framework and demonstrate its use in achieving IAM excellence.  
 4 Further research could also incorporate enhanced resilience and sustainability performance  
 5 assessment and management practices into the proposed framework to identify continuous  
 6 improvement opportunities of built environment management towards higher community  
 7 resilience and sustainability.

8

9 **Appendix**

10

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

<i>Agencies and Associations</i>	<i>Asset Management Guidelines</i>
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)

12

1 **Table 2.** Interview themes and questions prepared

<i>Theme</i>	<i>Key questions prepared</i>
<i>Policies, strategies and objectives</i>	<ul style="list-style-type: none"> <li>○ <b>Q11:</b> Has your department enacted hierarchical AM documentations involving an AM policy statement, strategic, tactical, and operational plan?</li> <li>○ <b>Q12:</b> Has your agency clearly stated the target level of service (e.g. customer performance measures, technical performance measures)?</li> <li>○ <b>Q13:</b> When conducting maintenance work, does your department consider the existing interdependencies and make use of it?</li> <li>○ <b>Q14:</b> Does your agency have plans to address climate change?</li> <li>○ <b>Q15:</b> Does your agency plan for demand growth?</li> <li>○ <b>Q16:</b> Does your agency have a resilience consideration (e.g. response and recovery time after an emergency, redundancy in network)?</li> <li>○ <b>Q17:</b> Does your agency address coordination across divisions and even with other agencies?</li> </ul>
<i>Human resources</i>	<ul style="list-style-type: none"> <li>○ <b>Q21:</b> Do your agency have a specified asset management group under the stewardship of asset manager?</li> <li>○ <b>Q22:</b> Are your team members aware of benefits of AM?</li> <li>○ <b>Q23:</b> Do your team members obtain a basic knowledge of AM and receive regular training?</li> </ul>
<i>Information system/database</i>	<ul style="list-style-type: none"> <li>○ <b>Q31:</b> Has your agency formulated its data collection requirements (e.g. an inquiry scheme between public and private stakeholders, information screening, unified standard)</li> <li>○ <b>Q32:</b> 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)</li> <li>○ <b>Q33:</b> Does your agency have a maintenance management system and condition monitoring system?</li> <li>○ <b>Q34:</b> Does your agency leverage a Geographic Information System to facilitate AM?</li> <li>○ <b>Q35:</b> Does your agency have a customer service system to timely monitor and solve the fault?</li> </ul>
<i>Condition monitoring and performance assessment</i>	<ul style="list-style-type: none"> <li>○ <b>Q41:</b> What techniques has your agency adopted to execute condition monitoring (e.g. CCTV, Ground-penetrating radar, Sensors)?</li> <li>○ <b>Q42:</b> Which maintenance scheme has your agency adopted, frequency-based, or condition-based?</li> <li>○ <b>Q43:</b> 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)?</li> <li>○ <b>Q44:</b> Does your agency have approaches to conduct deterioration modeling to determine the remaining life?</li> </ul>
<i>Risk analysis and criticality identification</i>	<ul style="list-style-type: none"> <li>○ <b>Q51:</b> Could your agency rapidly screen the risk events?</li> <li>○ <b>Q52:</b> How does your agency define the likelihood of risk?</li> <li>○ <b>Q53:</b> How does your agency define the consequence of risk (e.g. asset attributes, operating context, and locational factors)?</li> </ul>
<i>Operation, maintenance, capital investment plans</i>	<ul style="list-style-type: none"> <li>○ <b>Q61:</b> What decision-making techniques has your agency adopted to allocate budget (e.g. benefit-cost analysis, multi-criteria analysis, trade-off analysis)?</li> <li>○ <b>Q62:</b> Does your agency plan for an emergency response?</li> <li>○ <b>Q63:</b> Does your agency balance planned and unplanned work?</li> <li>○ <b>Q64:</b> Does your agency schedule its maintenance, rehabilitation, and capital improvement from a lifecycle cost perspective?</li> </ul>

2

3 **List of the acronyms**

4

5 AM – Asset Management



---

1 IAM – Infrastructure Asset Management  
2 IIAM – Integrated Infrastructure Asset management  
3 RSM-IIAM – Resilient and Sustainable Multisector Integrated Infrastructure Asset  
4 management  
5 IIMM – International Infrastructure Management Manual  
6

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12

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