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A master data management solution to unlock the value of big infrastructure data for smart, sustainable and resilient city planning

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Abstract

In recent years, many governments have launched various smart city or smart infrastructure initiatives to improve the quality of citizens' life and help city managers / planners optimize the operation and management of urban infrastructures. By deploying internet of things (IoT) to infrastructure systems, high-volume and high-variety of data pertinent to the condition and performance of infrastructure systems along with the behaviors of citizens can be gathered, processed, integrated and analyzed through cloud-based infrastructure asset management systems, ubiquitous mobile applications and big data analytics platforms. Nonetheless, how to fully exploit the value of 'big infrastructure data' is still a key challenge facing most stakeholders. Unless data is shared by different infrastructure systems in an interoperable and consistent manner, it is difficult to realize the smart infrastructure concept for efficient smart city planning, not to mention about developing appropriate resilience and sustainable programs. To unlock the value of big infrastructure data for smart, sustainable and resilient city planning, a master data management (MDM) solution is proposed in this paper. MDM has been adopted in the business sector to orchestrate operational and analytical big data applications. In order to derive a suitable MDM solution for smart, sustainable and resilient city planning, commercial and open source MDM systems, smart city standards, smart city concept models, smart community infrastructure frameworks, semantic web technologies will be critically reviewed, and feedback and requirements will be gathered from experts who are responsible for developing smart, sustainable and resilient city programs. A case study which focuses on the building and transportation infrastructures of a selected community in Hong Kong will be conducted to pilot the proposed MDM solution.

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Keywords: Big data; integrated infrastructure asset management; master data management; smart city; smart infrastructure

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1. Introduction

Reliable, resilient and sustainable city infrastructure systems are essential to both economic prosperity and the well-being of citizens [1]. However, the systems are encountering unprecedented challenges arising from rapid urbanization, growing demands, insufficient investment, component deterioration, climate changes, as well as man-made or natural hazards [2]. Over the past few decades, infrastructure asset management (IAM) practice has been adopted by many municipalities and industrial institutions to tackle the above challenges, and various sector-specific guidelines and computerized systems have been developed to accomplish the required level of infrastructure services in a cost-effective manner [3]. More recently, the smart city concept and a variety of smart technology enabled applications have begun to immerse into IAM and the architecture, engineering and construction (AEC) industry, and examples of these include the automated pavement condition reporting tool [4]; inspection robotics for structural healthy monitoring [5]; and applications of unmanned aerial vehicles, remote and noncontact sensing techniques for infrastructure operation and maintenance [6,7]. Despite that, wider applications of these smart information and communication technology (ICT) are indispensable to make infrastructure systems more interdependent and interconnected. Smart ICT can also help produce a high-volume and high-variety of structured, semi-structured and unstructured data, and such data can be used for support decision-making and policy formulation [8-9].

Existing standalone asset management systems work well to meet the specific needs of individual infrastructure stakeholders, e.g. pavement management system and bridge management system. However, a well-developed and robust data management solution is indispensable for multidisciplinary IAM approaches, in particular when trusted insights have to be derived from diverse and big infrastructure data [10]. Under an interdependent environment, any error-prone decision on one single infrastructure component could induce a cascading effect to the entire community infrastructures, and even result in catastrophic consequence under extreme circumstances (e.g. responding to disasters). A master data management (MDM) paradigm may be able to provide the AEC industry with new ways to handle the data quality issues that the industry has struggled to resolve for years, and help prevent the “data rich and information poor” dilemma. The aim of this paper is to develop a MDM framework to facilitate the exchange of useful infrastructure data for smart, sustainable and resilient city planning

2. Related Work

2.1. Integrated infrastructure asset management

There has been a huge amount of research and industry work pertinent to sector-specific IAM practices and integrated IAM regardless of the fact that different terms, such as facility management, public works management and utility management, could have been used interchangeably in AEC literature [3]. For example, Arif and Bayraktar proposed a theoretical framework for transportation infrastructure asset management after a thorough overview of the asset management best practices in transportation [11]. A collaborative mobile-cloud computing framework was developed for intelligent civil infrastructure condition inspection and image-based damage analysis [12]; while a probabilistic approach was devised to find an optimum management plan for fatigue-sensitive structures by leveraging the available information from inspection actions [13]. Grussing applied the asset management principles to building lifecycle management and proposed a framework to improve facility information for actionable decision support [14]. A considerable number of investigations have also been conducted from the life cycle perspective, and these include the framework devised by EI-Diraby & Rasic to evaluate and reduce the life cycle cost and emissions of infrastructure systems [15], and the linkage mechanism proposed by Yuan et al. to integrate the design, construction, operation and maintenance activities [16].

An easy-to-use information management system is very important for asset management programs. For instance, Mooney et al. described a web-based infrastructure management system with structural, geotechnical data and analysis functions embedded for planning project-level activities [17]. A construction information database framework was developed to coordinate the processes of capital investment, schedule planning, and performance measurement, while a national-level knowledge portal WATERiD was built in the US to facilitate the experiences sharing of water infrastructure systems [18]. Other research works include a multi-tier component-based framework for integrated municipal infrastructure asset management [19]; a computational model for assessing the interdependence among municipal assets [20]; a multi-tiered database schema for IAM [21]; a tools enabled by semantic technology for integrating BIM and GIS [22]; and the data warehousing techniques to explore interdependencies between multiple infrastructure networks [23].

Regardless of the aforementioned collection of effort, as commented by Halfawy and the FHWA, the data quality issues arising from the data ‘silos’ in term of data inconsistence, inaccuracy, incompleteness, delay and irrelevance have been the major obstacles impacting the efficiency and effectiveness of IAM, and this could hinder its large-scale adoption across multiple organizations and sectors, and impede the coordination among stakeholders [24,25].

2.2. Smart community infrastructures, smart, sustainable and resilient city, and big data applications

In recent years, the concepts of smart community infrastructure, sustainability, urban resilience and smart city have attracted increasing attention from multiple disciplines, and a large amount of initiatives have been launched around the world, e.g. the Edinburgh’s multichannel smart city platform for soliciting citizens’ opinions [26]; Singapore’s Smart Nation program [27]; Rio de Janerio’s integrated smart city operation center enabled IBM’s solution [28-29]; and Netherland’s city-wide crowd management platform for emergency response [30]. Besides, there are many relevant research in the academic community. For instance, Shah et al. devised a geotechnical asset management solution for enhancing the resilience of highways and railways [31]; and Bocchini et al. proposed an integrated model to assess the impact of infrastructure systems on community resilience and sustainability [32].

The hot ICT ‘hype’ topics such as IoT, big data analytics, artificial intelligence, cloud computing and social networking have also aroused the interests of AEC scholars in recent years [33-36]. There are frequent discussions of their applications in practice. Although big data technology presents promising potential to store, process and analyze gigantic volume of heterogeneous data, there are still limited successful big data application cases in the AEC industry [37]. The pioneering work includes a few critical review articles that exemplify the challenges of using big data and IoTs for automating infrastructure data collection, semantic based knowledge construction [38], simulation of system of infrastructure systems [39], and collaborative decision support for optimal planning of municipal infrastructure systems [40].

2.3. Master data management solution for enterprise applications

Over the last two decades, master data management (MDM) has been adopted by leading business companies to successfully implement business-enabling strategies by harnessing the large amounts of enterprise data for decision-making [41]. MDM has recently attracted increasing attention again due to the booming IoTs and big data applications [42]. Master data refers to “the consistent and uniform set of identifiers and extended attributes that describes the core entities of an enterprise, such as customers, prospective clients, citizens, suppliers, sites, hierarchies and the chart of accounts”. Master data management is considered as “a technology-enabled, business-led discipline, which could enable business and IT stakeholders within an enterprise to work together to ensure the uniformity, accuracy, stewardship, semantic consistency and accountability of the enterprise's official, shared master data assets”, and this should help stakeholders derive better-informed decisions with trusted data sources, actionable insights and holistic views of their customers, products or services [41].

Gartner has proposed a fundamental framework after more than ten years of observation of MDM best practices to meet the diverse demands of enterprises engaging in different vertical businesses for launching MDM initiatives. The framework comprises a set of building blocks as vision, strategy, metrics, information governance, organization and roles, information life cycle, and enabling infrastructure [41]. The ways in which enterprises scoping out and implementing their MDM strategies present various patterns and involve vectors of complexities, including industry differences (e.g. customer-oriented or product-oriented), differentiation in data domain definition (e.g. customer, product or service domain) and their sequence to be mastered, diversity of use case scenarios (e.g. operational or analytical MDM), the changes needed in organizational structure and processes, and the selection of different implement styles (e.g. registry or centralized style).

There are a number of off-the-shelf or open source MDM software products that could assist enterprises achieving the MDM objectives and reaping the benefits of their master data assets. The representative vendors include IBM, Informatica, Reltio, SAP, SAS, Talend, Teradata, and TIBCO Software, etc. [43]. Moreover, new trends have emerged in the MDM markets, such as new offerings for real-time data analytics, multi-domain and multi-vector solutions, and upgraded packaged industry-specific MDM solutions [42].

Nonetheless, here is limited academic research in the AEC domain which seeks to address the data quality issues via the lens of MDM for infrastructure asset management. Only few articles explicitly related to MDM are published in the ASCE journals (http://ascelibrary.org/). The great potential of MDM to tackling the data quality challenges motivates our work in this research.

3. Methodology

In this research, a MDM solution titled SIAM-MDM is proposed for IAM, smart community infrastructure and smart city planning and operation. The following stepwise approach is adopted to derive the solution. The research begins with a desktop study, literature review, online / offline questionnaire survey, and semi-structured interview with experts in different infrastructure sectors, city managers, citizens and government officials to investigate the strength and weakness of existing IAM practice and to collect new requirements. The research team then valuates the ability of the published integration frameworks, data models, enabling technologies, prototypes, sector-specific systems or tools, and emerging cloud-based platforms for tackling the IAM data quality obstacles. The pros and cons of these solutions are specially investigated from the seven dimensions of Gartner's MDM framework. An initial version of SIAM-MDM is designed according to the results obtained in the preceding step and with reference to the open source MDM software products (e.g. Talend MDM), asset management standards (e.g. ISO 55000 and IIMM), smart community infrastructures frameworks (e.g. ISO 37152), smart city frameworks (e.g. PAS 181), smart city concept models (e.g. ISO/IEC 30182), domain taxonomy or ontology (e.g. e-COGNOS), domain-specific knowledge depository (e.g. WATERiD database), BIM and GIS integration frameworks, and semantic web technologies (e.g. RDF and OWL). A focus group meeting is conducted with academic and industrial experts, IT professionals and other relevant stakeholders using the initial version of SIAM-MDM to align the stakeholders' understanding on MDM discipline, trigger their comments on SIAM-MDM, solicit their new requirements, and determine the scopes and use cases for piloting SIAM-MDM. The research is followed by the development of an enhanced version of SIAM-MDM solution based on the feedback solicited from the above studies. SIAM-MDM is piloted through a case study that focuses on the integrated management of building and transportation infrastructure assets of a selected community in Hong Kong before verification and validation on SIAM-MDM are conducted with transdisciplinary experts through the analysis of case study results and the other round of interview, questionnaire survey and focus group meeting. This would drive the next iteration of SIAM-MDM development.

4. Proposed Master Data Management Solution

4.1. Components of the proposed MDM solution (SIAM-MDM)

In the context of IAM and smart city applications, the proposed SIAM-MDM solution would consist of following core components (Fig. 1):

1) *Develop a MDM strategy that closely aligns with the policy and strategy of an organization or a city to implement the IAM and smart city initiatives:* IAM policy broadly outlines how and why asset management will be undertaken across an organization as a whole; while the asset management strategy provides details of what specific actions shall be undertaken by the organization to improve asset management capability and achieve specific strategic objectives. The organization's MDM vision and strategy should reflect both its business vision and its asset management policy and strategy. The MDM vision and strategy needs to clearly state what MDM would look like, why it needs to be created, how it supports the organization's asset management vision, and how to achieve the MDM vision. In general, the formulation of an organization's MDM vision and strategy requires the board's support and the organization-wide stakeholders' engagement, not just being the responsibility of senior IT leaders, chief data officers and IT department.

2) *Establish MDM metrics and incorporate them into the hierarchy of IAM performance measures and metrics:* Unless appropriate linkages between the MDM metrics and the asset management metrics are established and the benefits of MDM initiative are evaluated and justified objectively, the initiative cannot be accepted and leveraged by

IAM stakeholders to help them achieve the strategic, tactical and operational objectives. For example, any improvement in quality and availability of master infrastructure asset data could be correlated with the cost savings of asset maintenance and the improvement of asset service levels.

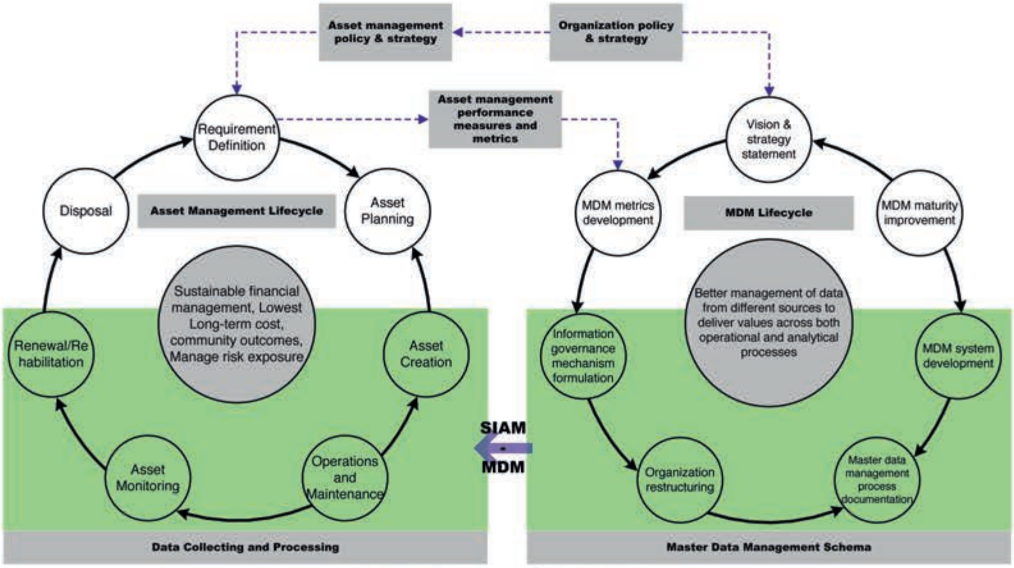

Fig. 1. Schematic concept of SIAM-MDM.

3) *Devise an information governance mechanism:* Numerous IAM stakeholders can be engaged in the creation, capture, storage, updates, valuation, use and deletion of master asset data. It is necessary to design an executable MDM governance framework which requires the identification of the roles and responsibilities of different stakeholders for managing master data, defining, documenting and managing MDM life cycle process; tracking and maintaining the meanings and contexts; and coding the MDM data in flexible formats, types and dimensions associated with different asset management operations and decisions. Effective master data governance could not only lead to the success of a MDM initiative, but it could also help ensuring the 'single view', consistence, accuracy and transparency of master asset data across the whole asset life cycle and across different infrastructure sectors.

4) *Optimize or restructure the structures of existing IAM organizations or create a cross-department organization to orchestrate the MDM initiatives:* In the IAM environment, there are a variety of stakeholder roles (e.g. asset owners, asset manager, network operator and contractor) and responsibilities (e.g. planning, design, construction, information system management, inventory assessment, materials testing, financing and maintenance operations). Leadership and common data systems plays salient roles in keeping effective communication and coordination among these stakeholders. The involved groups or individuals may need to blend their roles and responsibilities in IAM and MDM for authoring, managing, consuming and maintaining master data. More likely, a MDM initiative could demand changes to established infrastructure asset management processes, cultures and organizational structures.

5) *Formulate agreed master data life cycle management processes:* Effective MDM applications in business enterprises suggest that the IAM industry shall also incrementally practice the MDM programs. An organization could start a MDM program with its enterprise asset data model, and then acquire, map, transform and update the master asset data from partners, different asset management processes, applications and platforms. After a few rounds of MDM exercises, the organization shall eventually be able to formulate a well-understood and accepted process for authoring, validating, enriching, publishing and consuming the master data assets, capturing current state and modeling the future-state life cycle for primary master data.

6) *Deploy a MDM system developed in-house or purchased from MDM software vendors and integrate the MDM system into an organization's overall information architecture:* An organization needs a MDM system to support it managing intricate MDM activities and enhance its MDM capabilities. The MDM system can be developed and

deployed using such technologies as middleware, data integration infrastructure, and service-oriented or event-oriented architecture. The system can assist an organization improve its MDM capability in terms of the MDM life cycle management, data modeling, synchronization and integration of business processes, management of data quality, data semantics and ontology, data privacy and security, and stewardship and governance management etc.

7) *Improve the MDM maturity levels through continuous capability assessment, deliberate extension and upgrade of initial MDM programs and by engaging more stakeholders:* Like improving the IAM capabilities, an organization needs years of efforts and long-lasting momentum in MDM to attain higher maturity and deliver values across both operational and analytical IAM processes and applications. MDM and IAM leaders can make reference to Gartner's MDM Maturity Model to assess their organization's MDM maturity objectively, compare it to best practices, and customize their own MDM visions and roadmap to the establishment of a successful and mature MDM discipline.

4.2. Use case scenarios of using the SIAM-MDM solution

The basic MDM use case scenarios in business applications which include: (i) a design/plan MDM for architecting and conceptualizing a new business; (ii) construction MDM for building the business; (iii) operational MDM for running the business, and (iv) analytical MDM for measuring and improving the business.

On one hand, these use cases can be used to complement the existing IAM applications, e.g. the operational MDM use case can be employed to coordinate community infrastructure maintenance operations while the analytical MDM use case can be integrated into the asset data warehouse program like what FHWA has been promoting for years. The FHWA's project aims to integrate segmented asset information into one system which serves as the official asset inventory, with a centralized GIS database, easy-to-use tools, integrated maps for editing and displaying asset data, and analytical functions for collaborative decision making [25]. Without a MDM approach to harmonize the data integration and analysis processes in this kind of project, the data quality issues could still remain in the core IAM processes and systems (e.g. PMS, BMS, TMS, construction management, project and financial management). In most infrastructure construction projects, the construction MDM could be leveraged to create new asset inventory as there are lot of procurement services, key materials and stakeholders, and volumes of structured and unstructured data being generated (e.g. building information model). The construction MDM can facilitate data sharing among the designers, constructors and the operators once the infrastructure is built.

On the other hand, he traditional MDM use cases need to be modified or enriched with new elements to adapt to IoTs and big data driven IAM and smart city applications (e.g. carbon emission hotspot and resilience analysis of interdependent infrastructure networks). For instance, real-time data has emerged as a MDM priority for data analytics with high availability of master data; graph-style multi-domain and multi-vector MDM to replace the single domain MDM; and an increasing amount of external data sources captured from IoT and social networking despite such data could threaten the semantic consistency of the established master data objects.

4.3. Alternatives to implement the SIAM-MDM

There are four basic types of MDM implementation styles: (i) consolidation style suitable for traditional business intelligence and data housing applications; (ii) coexistence style used primarily when master data authoring is distributed; (iii) registry style that is ideal for low-control and autonomous environments; and (iv) centralized style where master data is authored, stored and accessed from one or more MDM hubs [41].

For the implementation of SIAM-MDM, these styles are not mutually exclusive. An organization needs to determine the right style according to its unique data domain focus, different uses of data domains, and its objectives and priorities for improving the IAM performance. The MDM system can be developed using popular modeling languages (e.g. XML and UML), RDBMS, graph databases, semantic technologies, visualization tools, natural language processing and query technologies etc., and subsequently deployed on-premises or as a service on the cloud.

5. Case Study and Preliminary Results

To demonstrate the applicability of the SIAM-MDM solution, a case study is being conducted via several on-going research projects awarded by the authors. An integrated urban infrastructure carbon emission hotspot hub is being developed to capture, assimilate and analyze the static and real-time data of different infrastructure facilities at various locations and timeframes for identifying the spatial-temporal-behavioral emissions and resilience patterns of facilities. The data is gathered from heterogeneous sources, e.g. smart sensors, smart meters, social networking platforms, crowdsourcing mobile applications, department-level ERP systems, facility management systems, transportation management and building management systems. Since the hub system does not have a MDM module, it seems impossible to orchestrate the data crowdsourcing and integration processes from different stakeholders and fragmented systems in order to obtain a trusted view of the urban infrastructure's hotspot map. The case study focuses on the integrated asset management of buildings and transportation asset management as buildings and transportation are the two top infrastructure sectors contributing to the Hong Kong's carbon emissions.

In the case study, the multi-domains (e.g. citizen, asset, place and service) master data objects are constructed using the Talend open source MDM tools (https://www.talend.com/products/mdm/), and the MDM is implemented with the registry style. Stakeholders can access the master data objects through web user interface or open web service APIs. The very preliminary results obtained via the case study demonstrate that a complete MDM life cycle management process could facilitate the integration of municipal infrastructure asset management processes and data; assist the stakeholders co-authoring collaborative building BIM models and infrastructure BIM models; enable a smooth integration of BIM and GIS information; enhance the accuracy, transparency, uniformity, stewardship, governance and semantic consistency of building and transportation master data assets; and help unveil the emission hotspot and identify resilience priorities of urban infrastructures.

6. Discussion and Future Work

Rapid advances in information and communication technology, such as IoT, social networking and mobile applications and big data analytics, may open up new ways to accurately capture the static and dynamic data of urban infrastructure facilities, as well as to assimilate, aggregate and analyze the data for strategic, tactical and operational decision-making for infrastructure asset and city management. Despite the benefits rendered from the pervasive adoption of these technologies, the newly generated high-volume and high-variety of data pertinent to the condition and performance of infrastructure systems as well as the behavior of citizens when using the infrastructure services could exacerbate the data quality problems that the industry has been struggling to solve for decades.

Based on Gartner's MDM framework, this paper proposes a master data management solution (SIAM-MDM) to unlock the values of big infrastructure data in today's complex high-density city environment. The master data management solution being proposed in this paper should help improve our understanding on how to capitalize on the data available from different network owners and operators for smart, sustainable and resilient city planning, operation and management. The preliminary case study demonstrates that the SIAM-MDM solution could assist stakeholders improving the consistency, accuracy, integrity, timeliness and transparency of infrastructure asset data, and thus help escalate the reliability and credibility of decision-making through the big infrastructure data analysis.

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