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Smart infrastructure technologies: Crowdsourcing future development and benefits for Australian communities

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ABSTRACT

Smart Information and Communications Technology (ICT) is envisaged to provide the capabilities to plan, design, construct, operate and manage Australia's key infrastructure. With over 75% of Australia's population living in cities and accessing public and private goods and services, ICT is positioned as a strategic resource for smart infrastructure developments. In this study, international and domestic stakeholder inputs on the future role of smart ICT in advancing Australia's infrastructure development and operations were crowdsourced for analysis. The study identifies several forms of smart ICT (e.g. building information modelling software) enabled infrastructure that possesses potential to deliver over A$9 billion per annum in domestic economic improvements, with commensurate advancement of communities, regions and urban environments. However, to be effective these smart ICT require enablement through open and interoperable data, sound governance and policy, and government leadership and coordination using dedicated resources. While smart infrastructure development is presently slow and lumbering, the identified smart ICT present as valuable strategic technologies for change and development in domestic communities.

1. Introduction

The United Nations World Urbanization Prospects Report provides a stark reminder that over 66% of the global population will likely live in urban structures by 2050 (United Nations, 2015). In Australia, over 75% of the population, or 18.5 million people are urban dwellers. These residents form part large and growing communities that requires access to public and private goods and services delivered through infrastructure (Commonwealth of Australia, 2015c).

Chang et al. (2017) note the growing ubiquity and emerging applications of internet of things (IoT) applications, especially in urban centres. The emergence of facilitating technology like 5G will further enhance the usefulness of such systems to transform the manner in which social entities like individuals and organisations (firms, schools and community groups, families) interact with one another and their physical environments.

Smart cities research seeks to investigate the current and potential future applications of such technology. Notable potential optimisation opportunities exist in systems providing transportation and logistics, energy use management and safety. At the background of these emergent "smart cities" applications will be better integration of physical infrastructure with these systems, to optimise logistical efficiencies and to minimise waste.

As an example, an audit of Australia's national infrastructure projected that $A377 billion in economic value would be derived from infrastructure assets by 2031, with cities using this infrastructure to contribute over $A1.6 trillion to the national economy (Commonwealth of Australia, 2015a). In this context, it is timely to examine the potential for countries like Australia to leverage strategic Information and Communications Technology (ICT) systems for infrastructure and associated community developments (Goodspeed, 2015; Neirotti et al., 2014; Piro et al., 2014). This investigation has also included complementary considerations of the administrative governance and policy actions required to create smart communities and regions (Harrison et al., 2010).

At the national level, Australia has moved beyond the more common smart city paradigm, and embraced the larger archetype of smart communities (Australian Smart Communities Association, 2016). This "communities" interpretation enfolds cities, regional alliances and states and is observed as an aggregate construct containing homes and residences, cities and local shires/councils, and states all linked by the fabric of infrastructure. One of the more notable examples falls under

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the smart state Queensland umbrella and includes the component cities of Ipswich and Toowoomba, and the Sunshine Coast region that integrates multiple suburban and semi-rural areas. These communities are implementing strategies for advanced digitised infrastructure development including dense broadband and wireless communications coverage; electronic business exchanges and platforms; and localised ICT skills training. These changes are aimed at improving the quality of life for individuals and advancing businesses in the local communities. This community perspective also conforms with the view of smart cities as a confluence of technologies and human actors, sitting within a larger framework of inter-urban dependent networks (Lee et al., 2014; Tranos and Gertner, 2012). Hence, while smart cities will continue to be studied, the need for broader and more penetrative smart ICT highlights the importance of researching the less examined infrastructure construct (Kortuem et al., 2010; Li et al., 2011).

The contemporary smart cities literature has also sought to draw critical linkages with fast emerging technology trends in the form of the Internet of Things (IoT) (Harmon et al., 2015; Vermesan and Friess, 2014) and the management of Big Data (Hashem et al., 2016; Lee et al., 2014; Piro et al., 2014). This suggests that the transformation to smart communities will be impacted and facilitated by large scale and ubiquitous ICT trends (Bughin et al., 2010). In this study, it is argued that the components of smart communities, such as public assets; energy, natural resources and water management systems; environmental and waste management systems; transport and logistics; and residential and commercial buildings are overlaid and infused with expansive smart ICT, thus providing a suitable meaning for the term “smart infrastructure” (e.g. buildings' design, maintenance and management supported by intelligent software and hardware systems) (Albino et al., 2015; Mattoni et al., 2015; Neirotti et al., 2014). Given the substantial and diverse urban population in Australia, it is important that a collaborative and collective set of stakeholders' views be synthesised to inform future smart infrastructure development (Alreemy et al., 2016; Letaifa, 2015; Ruohonen, 1991).

In this article, the Brabham (2013) crowdsourcing concept is used to collect and process stakeholder viewpoints and socio-technical information associated with the potential development of smart infrastructure in Australia. The dataset was provided from an open and transparent government inquiry into the potential use, benefits, challenges and governance associated with smart infrastructure (Commonwealth of Australia, 2015b), and has been subjected to a structured content analysis (Denzin and Lincoln, 2011; Miles et al., 2014). Arguably, the genesis of this study reinforces the global importance of smart ICT for positive societal change (IBM Corporation, 2009; Yigitcanlar, 2015) and improvements in urban life (Goodspeed, 2015). The study used expert advice from leading researchers and applied a consolidated data structure to process the crowdsourced data (Corley and Gioia, 2004) using the four structural nodes: (N1) the types of smart ICT used for developing and managing infrastructure; (N2) the benefits from introducing smart infrastructure; (N3) harmonised data standards and file formats that support smart infrastructure; and (N4) governance actions and policies to promote smart infrastructure. This allowed the research team to process and document the key smart infrastructure concepts, benefits and development directions in the Australian context.

In contrast to current examples of smart city research (Albino et al., 2015; Mattoni et al., 2015; Neirotti et al., 2014; Yigitcanlar, 2015), the findings of this study indicate that some specific forms of smart ICT, such as building information modelling (BIM) software, Asset management (AMS) and Intelligent transport (ITS) systems, can be applied to create smart infrastructure, thereby potentially bringing multi-billion dollar benefits to communities through more effective and efficient infrastructure operations and management (Gurbaxani and Whang, 1991). It is at the intersection of these functional technological systems that the integrated approach to smart infrastructure offers the most promise – in improving both economic and social benefits available to communities.

In a practical context, the research also found that establishing a single open data standard and technical file format is unfeasible at this point in time. Given the different infrastructure forms, an assemblage of open and interoperable data standards and file formats, supported by different software vendors and applications designers, will be required in the medium term.

The results also contribute to smart ICT systems research and practice. In the academic dimension, the study has expanded beyond the compact smart city construct and exposed various smart ICT that can be applied to infrastructure for large scale economic impacts and gains (Gurbaxani and Whang, 1991). Also, the study has added to our understanding of three-dimensional (3D) data interoperations, finding that a collection of open and interoperable data standards and files formats would be required to drive smart infrastructure technology solutions (Chang, 2017a). However, in a practical sense, any optimism displayed by the stakeholders is tempered with the understanding that the lack of a national smart ICT policy, disjointed pockets of smart ICT projects and initiatives, and the absence of central agency coordination will hamper future progress (Nam and Pardo, 2011).

The article is organised as follows. The following sections present the theory and background literature, covering smart ICT and our contextual model for the research. The research method id detailed, followed by a summary and discussion of the major results. As a further contribution a frank assessment of smart infrastructure developments using progress markers from extant smart programs and surveys is presented. The article concludes by positing the requirement to advance the pace of smart infrastructure developments and assess actual progress, while highlighting some future research opportunities.

2. Smart technologies, cities and governance

Since the early 2000s, scientists and engineers have been developing the fundamental building blocks of smart ICT from the small grain size sensor technologies (known as smart dust) that should support programming of inanimate items (Warneke et al., 2001) and remote telemedicine monitoring and treatment wireless networks (Pattichis et al., 2002) through to the activity and process aware, policy infused smart object technologies (Kortuem et al., 2010). However, while these developments are moving through a steady cycle of growth and innovation, it has become apparent that macro scale technology trends, such as Cloud Computing (Bughin et al., 2010; Sohal et al., 2017; Suciu et al., 2013), Big Data (Batty, 2012, 2013; Bughin et al., 2010; Moreno et al., 2017) and the Internet of Things (IoT) (Atzori et al., 2010; Chang, 2017a; Harmon et al., 2015; Perera et al., 2014), are impacting and facilitating smart ICT in varying ways. In particular, it was observed that the proliferation of highly mobile, fast flowing data is a critical component of smart ICT and information exchange processes across infrastructure forms (Kortuem et al., 2010; Piro et al., 2014); while the ongoing development of cloud environments and smart technologies will constitute the foundation for complex communications within the future IoT (Kortuem et al., 2010; Perera et al., 2014; Sun et al., 2017). Hence, arguably, future smart infrastructure developments identified in this research will likely be punctuated and impacted by more strategic and invasive shifts in technology that mediate the growth of smart ICT and infrastructure.

Relevant to this study, a large cumulative tradition of research has investigated the role for smart ICT in designing, developing and leveraging city assets and resources for the delivery of products and services to communities (Pérez-González and Díaz-Díaz, 2015). Indeed, some key services and product offerings enabled by smart ICT include water and energy provision; health, child and aged care; transportation; waste management; public safety and law and order; and education and training

(Chang, 2017b; Farahani et al., 2018; IBM Corporation, 2009, 2011b). While this research has rapidly expanded our understanding of how communities might use technology to cope with global population growth and potential overcrowding in urban environments (United Nations, 2015), one of our key criticisms of current literature is that many investigations concentrate on smart homes (Chan et al., 2009; Peine, 2008) and smart cities (Albino et al., 2015; Mattoni et al., 2015; Neirotti et al., 2014) as the unit of analysis, with relatively fewer investigations of smart technology enabled infrastructure and its benefits for society. Accordingly, this study builds into the fluid stream of smart technologies literature; and makes a further contribution by examining the strategic role and possible impacts of smart ICT in the development and continuing management of community infrastructure (Gable, 2010).

In the theory space, some concepts and models developed in the course of discovery, consulting and public policy research have depicted smart ICT as a “wrapper” construct, requiring a strong set of surrounding governance practices and policies in order to form part of regional or community strategies (IBM Corporation, 2011a). Importantly, other research studies show that the governance and policy (Albino et al., 2015; Nam and Pardo, 2011) and informed leadership (Letaifa, 2015; Nam and Pardo, 2011; Nolan, 2012) dimensions of smart ICT implementation are critical inputs for success.

Accordingly, an instructive research context model was created by overlaying an architectural frame on these constructs (The Open Group, 2011), with a picture emerging that suggests the currently “as is” closed systems approach (more formal, detached, proprietary) (IBM Corporation, 2011a) might undergo strategic change under enhanced governance (Coe et al., 2001; Letaifa, 2015) and coordinated leadership (Yoo et al., 2010). This, in turn, reflects the future “to be” systems that are largely accessible, inclusive and open in our cities and communities (IBM Corporation, 2011a) (see Fig. 1). Predictably, this highlights major concerns for governments and communities that expanding large scale, value adding services may result in the emergence of data privacy, information security, efficient data exchange, and leveraged decision-making problems, particularly when using big data filled public or hybrid clouds (Batty, 2012, 2013; Bughin et al., 2010; Sohal et al., 2017; Takabi et al., 2010). Thus, given the breadth of concerns, it is asserted that governance, policy and leadership should sensibly form part of our analysis (Nam and Pardo, 2011).

3. Methodology and data sources

The study's research method used a structured qualitative stakeholders' analysis (Miles et al., 2014; Denzin and Lincoln, 2011) to generate the results. The research team used the government smart ICT inquiry data sets that were crowdsourced from industry and the community (Brabham, 2013), filtering and sorting statements into the aforementioned structural branches of our analysis (Walsh, 2003). This initially enabled us to draw out the important stakeholder viewpoints and evidenced assertions; determine the types of smart technologies and benefits that were envisioned for the future; and document the data management, governance actions, and policies that would assist Australia through future changes.

In the second part of the analysis, the results have been used to create a radial causal flowchart using the research context model schema (Miles et al., 2014; Denzin and Lincoln, 2011). The flowchart provides a diagrammatic representation of the initiatives, practices and outcomes that would support the transition to future smart infrastructure (Miles et al., 2014). The flowchart also provides a contrast to actual progress in extant BIM and ITS implementation work packages.

3.1. Data

The stakeholder data was collected from the federal government inquiry into the role of smart ICT in planning, designing and operating infrastructure (Commonwealth of Australia, 2015b). The openly crowdsourced data (Brabham, 2013) took the form of 46 one directional written stakeholder submissions (provided as public disclosures) and 16 bi–directional question and answer Public hearings (PH) (58 witnesses provided sworn testimonies under legally binding parliamentary proceedings) transcripts with 789 coded inputs from the Business firms (Bus.); Federal, state and local governments (GO); Non–government organisations (NGO); and Individuals (Ind.) (see inquiry website for stakeholder organisation and witness details) (Commonwealth of Australia, 2015b). Each piece of input data was carefully and deliberately coded to the four structural branches of our analysis, and axially consolidated into four summaries (termed “axials”) (Corley and Gioia, 2004). The summaries were then used to construct the causal flowchart (Miles et al., 2014).

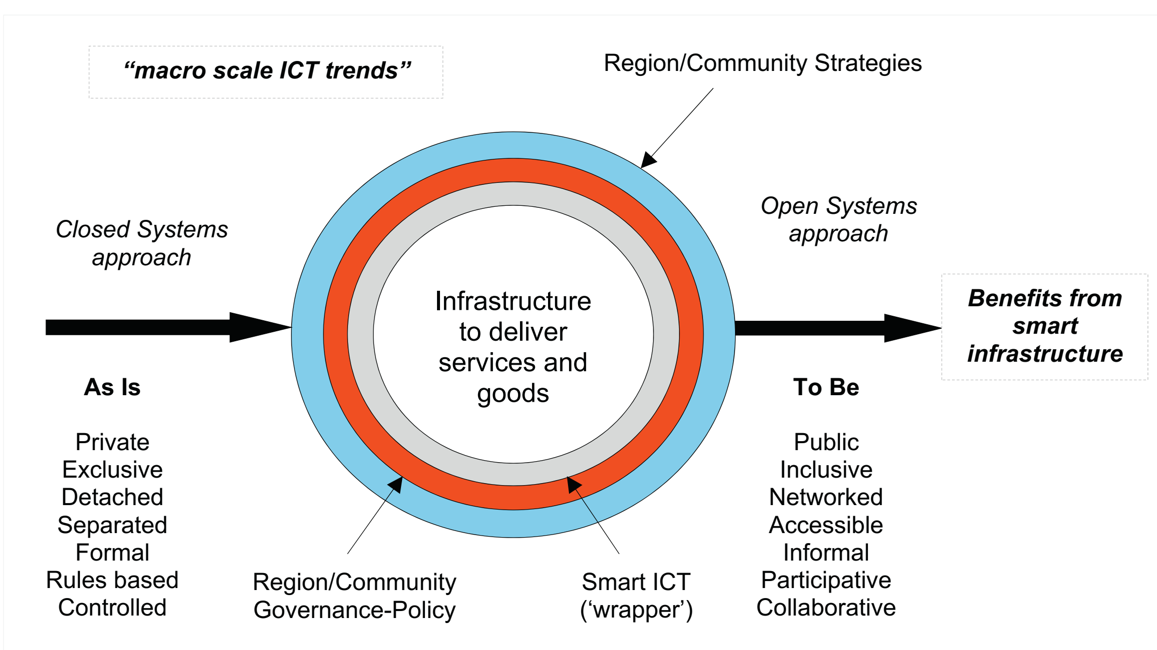

Fig. 1. Research context model for smart infrastructure (adapted from IBM Corp., 2011a).

3.2. Analysis process

In order to sort, categorise and present the data a project (named “Smart Infrastructure”) was created using QSR NVIVO Version 10 analytical software (Walsh, 2003). Submissions and transcripts were transferred verbatim to the internal documents folder of the NVIVO project. A four branch tree node structure was established for the project. Each stakeholder response was classified and matched to the associated data structure branch, noting the submission number; public hearing location and transcript identification number; and document dates, in order to maintain and assure construct integrity (Corley and Gioia, 2004; Miles et al., 2014). The branch nodes were then axially summarised and compared and cross–checked for any anomalies (Miles et al., 2014; Denzin and Lincoln, 2011). While the coders initially achieved 89% agreement on the first axial coding run, the noted differences were resolved through robust argument and conciliation of countervailing views of our ICT disciplinary peer group (Denzin and Lincoln, 2011). The causal flowchart was developed to summarise and depict the larger constructs of interest commended by the stakeholders, and consider which smart technologies, policies and actions may have substantial impacts (Miles et al., 2014).

Approaches such as these are uniquely well suited to the analysis of substantial amounts of qualitative data. The use of automated approaches mitigates extensive distractions driven by the analyst's particular predilections or concerns, allowing for a more measured, but also nuanced, set of findings to emerge.

3.3. Summary of results

Table 1 is a presentation of the coding results by node, axial summary, and crowdsourced stakeholder. It should be noted that the focus of the study was shaped by the majority of submissions and testimonies provided by business, business advocates and government. Given this focus, it was not unsurprising that the results highlighted the importance of specific smart ICT and their facilitating technology trends; decongesting intelligent transport systems; open and interoperable smart data standards and file formats; and governmental smart ICT leadership and policies. Expressed mathematically, we note that the introduction benefit of smart infrastructure (β) is a function of N_1 (ICT system adequacy and relevance), N_2 (harmonised file arrangements to enhance interoperability) and N_3 (governance actions to enhance adoption and extension of smart infrastructure usage).

$$\beta = f(N_1, N_2, N_3)$$

The results are discussed in more detail as follows.

4. Smart ICT for infrastructure management

Stakeholders identified smart ICT that would enable the strategic management of infrastructure (i.e. planning, design, construction, operations, maintenance, disposal, replacement) with the two highest ranked summaries focused on four streams of systems and technologies. The highest concentration of statements asserted the need to pursue greater use of BIM software, AMS and geospatial and sub-surface information technologies within Australia (N1, axial A) (8.23%) (Eastman et al., 2011; Longley et al., 2011; Worboys and Duckham, 2004). Importantly, BIM and AMS technologies provide the dimensional information sets (width, depth, height, time, cost, sustainability, and asset management) that are used for planning, construction, operations and maintenance of infrastructure assets (i.e. roads, bridges, buildings, utilities, airports, ports) (Eastman et al., 2011). This result indicated that ongoing change and development of smart communities would depend on the competent management of digital representations of physical and functional infrastructure forms using the identified smart technologies. Some of the typical examples related to the use of these technologies include creation of digitised building plans and schemas, road maintenance master schedules, and maritime port construction workflows. Hence, this was observed as critical for the efficient management of those public and private assets that enable the delivery of goods and services into communities and regions.

Similarly, in the geospatial frame, the use of smart ICT such as Geographic information systems (GIS) (Longley et al., 2011), Digital Elevation and Terrain Modelling (DEM/DTM) software (Wilson and Gallant, 2000), Ground penetrating and imaging radar (GPiR) and Computer-assisted radar tomography (CART) (Daniels, 2007; Jol, 2009) were deemed essential technologies for developing and managing sub-surface community infrastructure (e.g. gas pipelines, utilities conduit, telecommunications pits). In particular, stakeholders emphasised the productivity multiplier value for communities that use smart ICT to process, integrate and model 3D surface and sub-surface representations using point cloud measurements, as per the following: “Increases in computing capability around GIS can bring geographic and location information (point clouds) to the palm of your hand. Information systems are at the threshold pushing well beyond traditional paradigms. The integration of these technologies (GIS and BIM) have provided several productivity benefits (e.g. 8-fold survey time reduction)” (BCE Surveying, sub. 26, 31 July 2015) (Commonwealth of Australia, 2015b).

The following example depicts the application of these types of technologies to community works activities. Due to the lack of sub-surface data, large to medium scale excavations or tunnelling works may unknowingly result in critical infrastructure damage, such as broken pipelines or severed telecommunications cables. The resultant additional costs, losses in productivity, and delays in schedule may be significant. However, using high precision 3D surface and sub-surface models, founded on the point cloud data acquired using smart technologies, may allow construction companies and contractors to obviate the potential damages, associated costs and schedule delays. Hence, in this example smart infrastructure is positioned as a key lever for improved capital works, development productivities, and lower costs in communities.

The second ranked summary (N1, axial B) (7.22%) indicated that stakeholders considered smart ICT as crucial for the sensing and acquisition of infrastructure data and processing of information (Thenkabail, 2016; Vosselman and Maas, 2010). In particular, stakeholders considered that the use of remote sensing technologies, such as global positioning satellites and synthetic aperture radars, were essential when acquiring positional, navigational and timing information sets (Thenkabail, 2016) required to support community infrastructure development and management. Also, when coupled with high resolution digital camera networks and Fixed and/or Mobile laser scanning (FLS/MLS) equipment (using Light detection and ranging (LiDAR) technologies) (Pu et al., 2011), these smart sensing technologies can provide an enriched information environment that supports improved urban developments and decisions in communities. As an example, 3D point cloud scans of roads, bridges and building structures can be carried in tablet computers by engineers and surveyors, and easily accessed for asset development or maintenance planning tasks. Once more, stakeholders envisioned these forms of smart infrastructure as supporting continued improvements in urban developments and goods and services delivery in communities.

The next ranked summaries (N1, axials C, D, E) were directed at high functioning smart ICT (7.98% in total). In this respect, these technologies served core functions in digital engineering and design; transport engineering and traffic shaping (course-plotting and control); and automated and autonomous services. Importantly, stakeholders stated how smart technologies, such as advanced virtual (and augmented) reality and sensor-driven decision making systems, have been integrated into their infrastructure operations. The two following examples highlighted the advantages of these technology functions.

Laing O'Rourke Australia explained how Oculus immersive technologies were strategically integrated into DE/CAD platforms for the

Table 1
Summary of crowdsourced stakeholder statements.

Node	Axial	Smart ICT item	No. of coded statements				
			Bus.	GO	NGO	Ind.	Total
N1 (n=230)	A	Building information modelling (BIM) software; asset management system (AMS)	28	6	4	–	38
		Geospatial and geological information systems and technologies	22	4	1	–	27
	B	Remote sensing and surveillance systems – positioning, navigation and timing	11	18	4	–	33
		Laser scanning systems and technologies (LiDAR, mobile laser scanning)	17	7	–	–	24
	C	Digital engineering and computer-assisted design (DE/CAD)	20	4	–	–	24
	D	Intelligent transport systems (ITS)	2	15	3	–	20
	E	Robotic and autonomous systems (UAV/AUV/AV)	11	7	1	–	19
	F	Generic ICT trends (Cloud computing, broadband/mobile networks, IoT, Big data)	18	21	6	–	45
N2 (n=277)	A	Transport sector – reduced traffic congestion	25	51	8	–	84
	B	Utilities and community services – improved services management and delivery	25	20	27	–	72
	C	Infrastructure construction sector – improved productivity and management	41	21	9	–	71
	D	Generic sectoral benefits – reduced costs, improved decisions, closer collaboration	21	14	15	–	50
N3 (n=121)	A	Open data strategy – strategic enabler of smart ICT driven communities	6	25	7	1	39
	B	Open data management – integration, mashups, privacy, security	4	11	18	1	34
	C	Open data specifications and standards (BIMXML, OGC, IFC, PAS-1192, COBie)	17	6	–	–	23
	D	Open data initiatives, projects (VANZI, FSDF, ADAC)	2	3	10	–	15
	E	Open data types (project, weather, object, traffic, research, front end loading)	2	7	1	–	10
N4 (n=161)	A	Smart ICT policy, regulations	11	11	15	2	39
	B	BIM targets, mandates, guidelines	17	10	9	–	36
	C	Central smart ICT agency	9	9	13	–	31
	D	Technology strategies and infrastructure strategies	7	14	7	–	28
	E	Government investment strategies – innovation, research and STEM education	8	5	11	3	27
Total			324	289	169	7	789

Fig. 2. Construction workers use the Oculus immersive technology goggles (sub. 15, Laing O'Rourke Australia Construction Pty Ltd).

creation of virtual 3D infrastructure walk-around and human interaction models (sub. 15, Laing O'Rourke Australia Construction Pty Ltd) (Commonwealth of Australia, 2015b). The example provided by the firm showed how the immersive technology goggles (see Fig. 2) provided construction workers and members of the effected community with virtual walk arounds and interactions with the design model for the Wickham Transport Interchange in Newcastle, New South Wales (NSW). This supported greater mutual understanding, joint collaborations and community feedback (Yigitcanlar, 2015) on the development of this transport infrastructure in the Newcastle region. Importantly, this example highlights the positive social impacts associated with using augmented reality technology in infrastructure development (Goodspeed, 2015).

The NSW government presented its Sydney Coordinated Adaptive Traffic System (SCATS) as an exemplar dense sensor network that uses strategic command and control protocols for community traffic engineering and management (sub. 33, Transport NSW) (Commonwealth of Australia, 2015b). The software system is a smart technology enabler of improved commuter and goods traffic patterns in built-up urban areas with commensurate benefits of reduced commute times and transit delays, improved fuel consumption, and reduced emissions and pollution (Goodspeed, 2015). In addition, the NSW government has estimated that SCATS currently delivers approximately A$3.6 billion per annum in economic productivity benefits to the residents and businesses in the greater Sydney region. The SCATS example shows the profound social and economic impacts sensor technologies can have in communities.

In addition to these examples, stakeholders also pointed to semi-autonomous robotic (airborne and marine) and fully autonomous (terrestrial) vehicle systems that possess the advanced sensor and decision-making capabilities currently reflected in smart ICT. These systems are undergoing evolutionary development and are aimed at reducing human errors and accidents, while improving goods and services delivery in communities. Some examples offered by stakeholders included self-driving cars for personal and family travel; delivery of goods and materials using autonomous trucks and vans; and semi-autonomous air vehicles and marine vessels for passenger and goods transport tasks. These types of smart ICT applications were observed as important for the future development of safe and efficient communities and regions (Yigitcanlar, 2015), while improving the general quality of urban environments for impacted residents and commuters (Goodspeed, 2015).

The collective results suggest that while advanced smart ICT can furnish important technical engineering and operating functions for infrastructure management, the technologies can also provide opportunities to improve urban constructions and the efficient delivery of goods and services. In line with more open systems, the final technology related summary (N1, axial F) (5.71%) identifies several generic ICT trends that provide strategic facilitation for evolving smart infrastructure. In essence, the research exposes the stakeholders' view that smart ICT applications are contextually dependent on the widespread growth of highly elastic cloud computing resources (Suciu et al., 2013), broadband and mobile network services, and the predicted billions of future IoT device connections (Harmon et al., 2015). Also, it is noted that the emergence of smart infrastructure will likely generate further volumes of data and information (Batty, 2013), thus becoming a sizable contributor to future big data trends.

4.1. Benefits of smart infrastructure

Stakeholders' asserted the benefits that would flow from smart infrastructure as their top priority (N2, axials A, B, C) (28.77%) (see coded statements in Table 2), and nominated three sectors that would benefit from the adoption of smart ICT. Stakeholders' modelling and estimates showed significant productivity impacts and service delivery benefits from introducing smart ICT to reduce traffic congestion (improve transport logistics), aid utilities and community services provision, and improve building and construction efficiencies. In net terms, stakeholders asserted that the development of smart infrastructure in these 3 sectors alone could yield an estimated A$9.7 billion per annum in benefits (2015 prices), providing valuable assistance to Australia's A$1.3 Trillion Gross Domestic Product (GDP) and national budgetary performance. Importantly, this modelling reinforced the economic importance of smart infrastructure, and the broader benefits for communities and regions.

However, while the economy would stand to benefit from the development of smart infrastructure, another large segment of stakeholder responses (N2, axial D) (6.33%) posited that more general benefits, in the form of lowered consumer prices and business costs, improved decisions and acceptance, and closer engagement and collaborations in communities, would emanate from the use of smart technologies. Interpretively, the core stakeholder message is that smart ICT will bring ubiquitous and lasting change with the beneficial impacts felt deeply across the spectrum of infrastructure sectors and societal entities. This future view of smart infrastructure is consistent with our earlier theorised transition to more open systems models that deliver multiple change vectors and improvements across communities and regions (IBM Corporation, 2011a).

4.2. The need for open data

Consistent with smart technology theory (Kortuem et al., 2010; Piro et al., 2014), technical stakeholders opined that the development of smart ICT enabled infrastructure would require open and exchangeable data sets. To this end, the major summaries (N3, axials A and B) commended an open data strategy (4.94%) and installation of management protocols (4.30%) to deal with the technical and social issues surrounding large scale data integrations, as per the following: "Standardization in data management is an important consideration in the ongoing development of smart ICT. How we manage data effects the ability to create a cyber-physical system that has collaborating computational elements controlling physical infrastructure. With different organisations investing in developing technologies and software tools, there is a risk of a disparate approach to data management that prevents interoperability and therefore reduces the benefit for infrastructure owners and operators" (Downer Group, sub. 20, 20 July 2015) (Commonwealth of Australia, 2015b).

However, while advancing open data was observed as a necessary element of smart infrastructure, our analysis suggests that the implementation of a 'single' data standard is unfeasible at this point in time. This was clearly evidenced in the third node summary (N3, axial C) (2.92%), where stakeholders offered several data specifications-

Table 2
Node 2 coded stakeholder statements – smart infrastructure benefits.

Node	Axial	Coded statement
N2	A	Our infrastructure investments during the last decade have not improved productivity, so we must understand where to spend and how to use smart ICT. Logistics and freight adds A$131.6 billion to the Australian economy. A 1% improvement in logistics productivity increase GDP by A$2 billion. Road congestion is set to cost Australia A$20.4 billion by 2020. A 10% reduction in congestion adds A$2 billion to GDP – (National ICT Australia, sub. 23, 22 July 2015)
	B	Australian water utilities currently spend A$1.4 billion on reactive repairs and maintenance based on a 1% inspection regime. NICTA is developing an advanced statistical prediction tool that doubles the predictive power of inspections preventative repairs and maintenance programs saving approximately A$700 million – (Engineers Australia, sub. 25, 20 July 2015)
	C	Concerted government support for the use of BIM software could increase usage in 2025 by 6 to 16 percent according to conservative estimates from high level industry representatives. This accelerated rate of BIM software adoption could potentially produce a national economic benefit equivalent to A$5 billion added to Australia's GDP – (Aurecon, sub. 22, 20 July 2015).

standards including multiple versions of Extensible Markup Language (XML) (e.g. Land and BIM XML) and over thirty Open Geospatial Consortium (OGC) standards for data sharing in the construction and facilities industries. While these data integration and consistency problems (termed 'untamed' data by some researchers) have been highlighted in past studies (Goodspeed, 2015), it was noticeable that stakeholders were unable to identify a mechanism through which the large number of standards could be harmonised and the data openly shared.

In addition, the task of identifying a single standard was made more complex when it was determined that each standard may underpin various proprietary or non-proprietary data file formats depending on the software vendor and applications, as per the following: "In order to achieve harmonised infrastructure data, the (data) standards must be combined with a reliable open data file format. Open data, stored in a standardised, non-proprietary format is key to the successful implementation of Digital Engineering in the infrastructure industry. It enables interoperability across technologies and business platforms, resulting in true data exchange" (Transport NSW, sub. 33, 10 August 2015) (Commonwealth of Australia, 2015b). Stakeholders also warned that open data initiatives, such as VANZI (Virtual Australia and New Zealand Initiative for integrated 3D GIS and BIM data sets) and ADAC (Asset Design and As Constructed data specification) (N3, axial D) (1.9%), posed further complications for data integration as they support the creation of federated data sets, segregated storage banks, and specialised versions of standards (e.g. ADAC XML transport format) that do not enable open data exchange.

Overall, with experts acknowledging that data standards must be applicable to vertical and/or horizontal infrastructure forms, it would appear that singular data standards and file formats that could cope with the breadth of data types identified by stakeholders (N3, axial E) (1.26%) are likely to be untenable in the near term. Indeed, the results support a group of specifications and standards with interoperable open data file formats that would form the basis of smart infrastructure. This result suggests that the economic and community benefits identified by the stakeholders are likely to depend on those longer-term capabilities for coordinating and managing the smart infrastructure data for urban developments.

Businesses, through the decisions of managers, stand to benefit substantially from the wider and more comprehensive adoption of smart technologies generally, and smart infrastructure in particular. Whole of life asset values are optimised when better integration of transportation and community infrastructure occurs with private assets. The adoption of shared data standards also offers the promise of more extensive network economies in relation to connectivity between asset and asset users. Furthermore, the wider adoption of standardised technologies and systems will lower the cost of adoption and sharply influence the experience curve for users of all types.

4.3. Smart infrastructure governance and leadership

As far back as 2010, the Australian federal and state governments were urged to demonstrate leadership and mandate use of BIM software across infrastructure and construction industries (Allen Consulting Group, 2010). In this context, smart technology theory extolls the importance of leadership as a key input to success and productive interorganisational coordination (Nam and Pardo, 2011). In this study, the building and construction industries commended the leadership role as critical for delivering the aforementioned A$5 billion increase in GDP by 2025. Given this quantum of potential economic improvements, stakeholders strongly expressed the strategic nature of national BIM software implementation, and the forceful requirement for good governance, effective policy, and insightful leadership by domestic governments in Australia (N4, axial B) (4.56%).

At the broader level, the analysis also exposed the requirement to treat smart ICT as a strategic technology initiative with resourced central government coordination and the rollout of strategies, policies, regulations and investment programs for innovation, research, and education (N4, axials A, C, D, E) (15.84% in total). This part of the analysis was consistent with contemporary smart city literature (Nam and Pardo, 2011; Yigitcanlar, 2015), and commanded an urgent and more coordinated approach to implementing smart ICT in communities.

Specifically, the stakeholders were keen to see more integrated collaborations between the Council of Australian Governments (COAG) (transport and infrastructure), and the ICT policy and programs groups within the federal government. At the time of writing, it was notable that Australia had failed to formalise a national level policy for smart ICT, and advance domestic intergovernmental coordination.

Australia has experience with inconsistent policies at regional and state levels leading to problems in later economic coordination. Legendarily, at state borders prior to Federation passengers and cargo were disembarked as rail gauges were unmatched. For the benefits of national coordination, and also for interoperability with emerging global standards, national leadership is of paramount importance.

4.4. Smart infrastructure: a plausible approach, but slow progress

In summary, the causal flowchart depicts a dynamic set of smart technologies (black) that are applied to infrastructure and are controlled by governance practices and policies (red). This technology wrapped infrastructure and controlling governance and policy then forms an intrinsic part of government strategies (blue) for future smart communities (see Fig. 3). However, while this may appear plausible in practice and consistent with our research context model and smart theory, closer examination and scrutiny of extant government programs (Austroads, 2016; buildingSMART Australasia, 2012, 2016), shows limited progress in the two key areas as follows.

In targeting construction productivity, the national BIM initiative study in 2012, recommended mandating the use of BIM software (based on open data standards) in all federal government construction work by 1 July 2016, and a coordinated set of work programs (education, guidelines, data libraries, data exchanges) to be delivered by a national taskforce (buildingSMART Australasia, 2012). However, while reviewing the recommendations and programs, it was noted that only some lower level working groups (with limited resources) have been established. In the past three years, progress has slowed markedly with several groups missing their July 2015 work delivery deadlines; the data objects library working group still seeking adequate federal government financing for its work; and, the education program working group unable to attract sufficient resources to progress its three work packages (buildingSMART Australasia, 2016).

In relation to ITS, since the release of the reference network architecture in 2012, progress has been limited to a single ITS performance and benchmarking tool release in January 2016 (note, Austroads ITS programs apply a 2 year review and roll-over as required) (Austroads, 2016). These Austroads ITS projects exhibited the resource limitations associated with using public sector staff already engaged with full time equivalent workloads (Austroads, 2016). Note, the COAG Transport and Infrastructure Council revised the ITS policy framework and action plans in August 2016 (COAG, 2016), pushing the initial parts of the ITS program further out to the 2019 timeframe.

Disappointingly, these results show limited advancement in the development of domestic smart infrastructure. Coupled with the absence of a national smart ICT policy and a central coordinating agency in government, the multibillion dollar benefits modelled by some experts appear to be some way off in the future.

5. Contributing to smart technologies theory

The results of the study shine a light into several areas of smart ICT and expand beyond current academic and practice discourse on smart cities research. While many previous studies have concentrated on smart homes and cities and associated technologies, this research

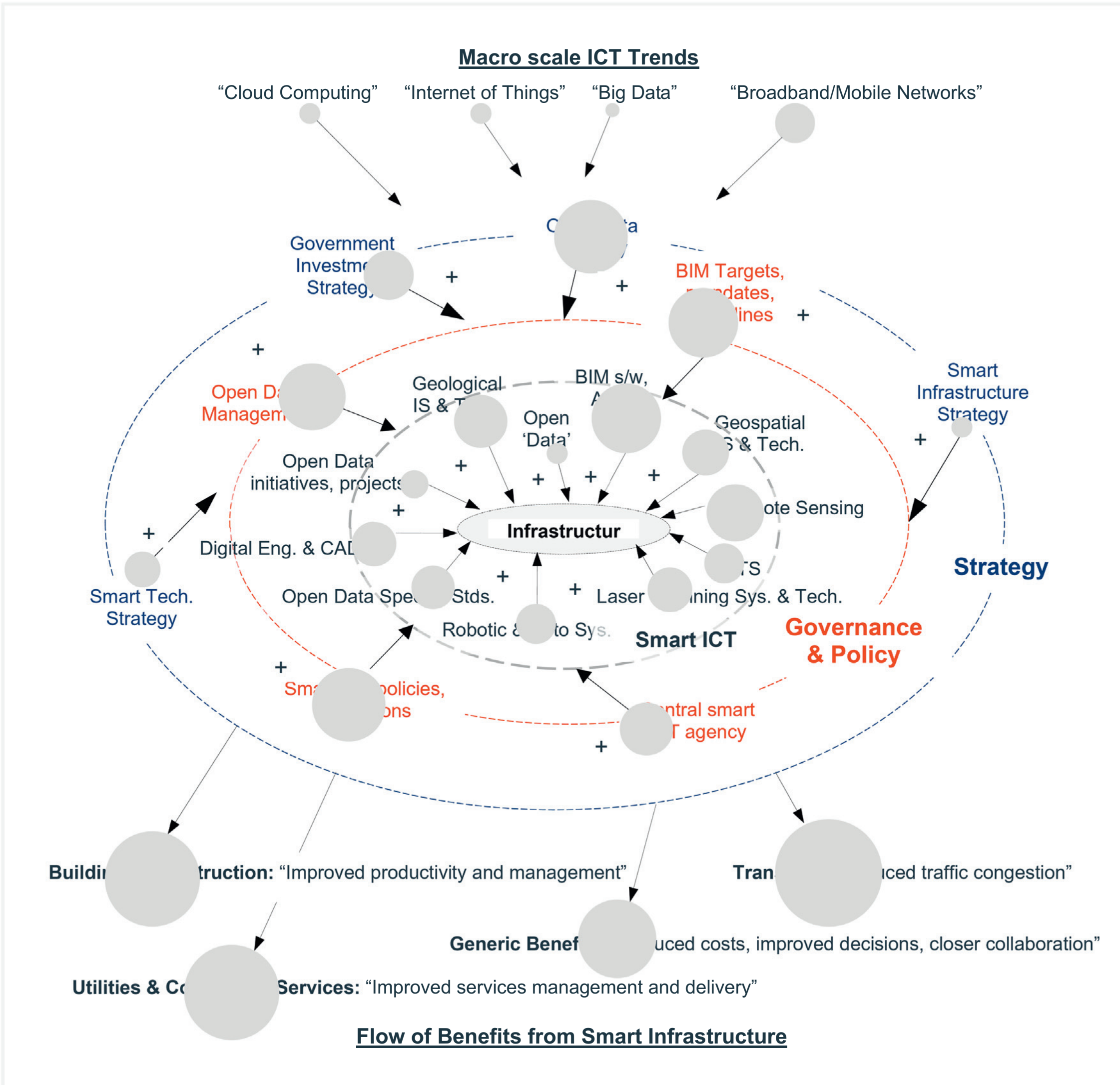

Fig. 3. Smart infrastructure causal flowchart (developed using Fig. 1 scheme and Table 1 results).

adopts a lens of multiple cities bonded into communities and regions through smart infrastructure assets. Through the findings, there is confidence that smart infrastructure can provide operationally effective and economically efficient connective tissue to support domestic communities requiring ongoing critical services.

The study has provided a concentrated explanation of why smart technologies should be adopted for infrastructure management and the crucial roles they play in community development, particularly for delivering public assets, goods and services. The economic analyses coded from stakeholder statements highlighted that the evolving development of collaborative ITS and smart water and energy grids represent important community and regional developments underpinned by strategic technologies and systems. Importantly, the expert economic modelling and estimates illustrated that multi-billion dollar benefits can be derived by those communities embracing domestic smart infrastructure management.

The issue of open and interoperable BIM, GIS and other 3D data was also examined with the selection of singular data standards, specifications and file formats found to be unfeasible currently. The analysis of expert stakeholder opinions showed that a group of data standards and file formats, supported by various software vendors, should in theory provide a workable data interoperability scheme for developing communities. In addition, the use of the various standards would usefully allow infrastructure designers and managers to tailor the data and information models to the different linked infrastructure forms (e.g. roads and bridges, streets and buildings) in urban and regional areas of Australia.

Contextually, the enabling technology foundations of smart infrastructure (e.g. cloud computing, wireless networks) are likely to change and evolve over time. In prospect, future trends like Artificial Intelligence (AI) and Web 3.0 technologies will potentially have profound shaping and enabling impacts on smart infrastructure. As examples, AI technologies offer the potential to create cognitive infrastructure that has internal decision-making capabilities, while a Web 3.0 search engine may be a smart ICT that supports high precision vertical searches for specific infrastructure data sets and processed information. This process will be ongoing as new technologies continue to appear and evolve, thus shaping future smart infrastructure and the associated development of communities and urban environments.

5.1. Some practical issues for creating smart infrastructure

In practical terms, the future for smart infrastructure has obstacles that must be overcome. As a starting point, Australia must develop a coherent and consolidated national smart ICT policy. While the central policy agency has established headline policies for technology directions such as cloud computing and data centres, a smart ICT policy would provide a useful anchor for future projects and programs.

Once the policy has been firmly established, a central agency that can coordinate work, allocate resources and guide outcomes is a pragmatic and necessary condition for successful smart infrastructure. Given Australia operates as a democratic federation of governments, a resourced coordinating body that represents public and private interests might sensibly move the agenda forward. In contrast, the current mix of working groups, associations and forums are making slow progress, with some initiatives stalled.

6. Conclusions

The study shows how the application of smart ICT to infrastructure can ground the concept of smart infrastructure, add to our understanding of smart cities, and broaden our research frame to smart communities and regions. Unlike other studies, specific smart ICT for infrastructure have been identified, while drawing on expert economic modelling from stakeholders to show the multi-billion dollar impacts these technologies can have when applied to operations and management. In examining these technologies, the research determined the pragmatic requirement to support smart infrastructure with a group of open and interoperable data standards and file formats, backed by software companies and applications designers. So, in theory terms, it can be asserted with some confidence that smart infrastructure has a rightful place in the literature next to smart homes and smart cities. However, in more practical terms, the limited advancement in smart infrastructure development gives pause for thought, particularly in light of the visible policy and coordinative governance voids that have been identified. With much work to follow, the establishment of other longitudinal studies of BIM, AMS, ITS and smart grids may offer a pathway to theory expansion and ongoing practice improvements.

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