Prioritising sensory systems for Queensland: An evaluation of alternative sensory systems using multiple criteria analysis

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PRIORITISING **SENSORY SYSTEMS** FOR QUEENSLAND

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AN EVALUATION OF **ALTERNATIVE SENSORY SYSTEMS** USING MULTIPLE CRITERIA ANALYSIS

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EXECUTIVE SUMMARY

Sensor technology is an extensive field – the Encyclopedia of Sensors comprises 10 volumes of more than 400 chapters. Although sensors have been in use for centuries, sensor technology is rapidly developing now; the digital age provides the opportunity for real-time decision-making based on data received from complex technical systems. New opportunities for sensor technology platforms are becoming available, and the benefits from the application of these platforms have greatly increased.

This study informs decision-makers within the Queensland Government about the relative priority of investing in sensor technologies that can enable the development of new products and services to create jobs, grow the State's economy, provide export opportunities, and benefit all Queenslanders.

This collaborative study between Data 61|CSIRO and the Queensland Government was conducted to make more-informed decisions with regard to investing part of the funding from the Advance Queensland initiative, in particular the $10 million Platform Technology Program'. This report aims to start a conversation about sensory systems as an investment opportunity for Queensland.

We scored and ranked the investment desirability of sensory systems using multiple criteria analysis (MCA) as decision analytic technique. This technique provides insight into which sensory systems are likely to generate the most positive return for the State using a comparative assessment of identified options against criteria that are critically linked to the objective. These measures were assessed using a qualitative scale and the combined views of experts from CSIRO, the Queensland Government, the Advance Queensland Expert Panel, and evidence from the literature.

Identification of criteria for analysis was based on the priorities of the Advance Queensland initiative and was destined to promote knowledge-based growth, customer focus and integrated approach to technology advancement. We identified the following criteria for rating the options:

- Job creation and productivity growth
- Economic diversification
- Commercial viability, pathway to market
- Building on our strengths
- Multi-disciplinary applications and spill-over benefits
- Increased investment, engagement and collaboration
- Global niche specialisation

Ten sensory system development options were selected based on the State's research and industry development priorities, scientific challenges and internal consultations (see Table 1). The process of identifying options was integrated with the MCA process (Figure 1).

We found that developing sensors for 'wearable technology' and health monitoring demonstrated the best value for investment by the Queensland Government, followed by sensory systems for biosecurity, and sensory systems for smart homes. 'Future policing' and sensors for advanced manufacturing ('factories of the future') garnered the lowest score and, accordingly, represent the worst value for investment of the 10 options. Sensory systems for smart infrastructure ('talking roads') and safe flights of unmanned aerial vehicles demonstrated medium performance – these options ranked lower than livestock and provenance; sensors for smarter mining; and disaster resilience (Figure 1).

TABLE 1. SENSORY SYSTEM DEVELOPMENT OPTIONS

SENSOR OPTIONS	DESCRIPTION	RANK
Wearable sensors for better health	Wearable sensor technology can address many of the challenges posed by an ageing demographic and prevalence of chronic diseases, and can assist in 'point of care' diagnostics, timely hospital admissions, improved workplace safety, and wellbeing programs—overall, leading to lower mortality and hospitalisation rates, and decreasing the cost of health services for remote communities.	**1**
Sensors for biosecurity	Sensor platforms integrated with robotics provide Queensland with a unique opportunity to use search-and-destroy protocols to methodically control some of its exotic or endemic pests across a diversity of environments. Monitoring species and diagnosing non-invasive early animal infections diagnostics are other promising applications.	**2**
Sensors for smart homes	Smart homes enabled by sensors, smart metering, and the IoT hold the promise of increased energy and water efficiency. The growing scale of distributed electricity generation (for example, solar), smart grids coupled with the advancement in energy storage implies a need to wider penetration of smart technology for households.	**3**
Disaster resilience	Better data and data quality from sensors and sensor systems provide new opportunities to analyse and manage disaster risks, such as remote, real-time sensing and fully integrated, inexpensive sensor systems suitable for mobile emergency asset management.	**4**
Smarter mining services	Sensor technology and systems provide a raft of opportunities for Queensland's significant METS industry. Examples include improving high-tonnage ore sorting, managing and optimising processes, mapping in three-dimensions, improving mine safety, and increasing productivity.	**5**
Livestock sensing and provenance	Linking sensors networks provides an enormous opportunity to differentiate products in Queensland's beef industry on the basis of genetics, grazing, and husbandry. Meat and other food products could be packaged and marketed like fine wine, extracting greater value from the supply chain.	**6**
Sensors for the safe flights of UAVs	Sensor-based collision-avoidance navigation and control systems for unmanned aerial vehicles (UAVs) are a limiting factor for this increasingly important industry, and Queensland has the capacity and opportunity to become an inventor and world leader in this field.	**7**
Talking roads	The emergence and deployment of autonomous vehicles and intelligent traffic control will require an increased number and variety of embedded sensors in infrastructure and vehicles. An affordable and reliable sensor network will be required to for vehicle-to-vehicle and vehicle-to-infrastructure communication.	**8**
Sensor-enabled factories of the future	Sensory systems and device connectivity will pervade all aspects of Queensland's priority advanced manufacturing sector which will participate in global value chains. Mass produced, low-cost micro-sensors such as produced from materials like graphene will deliver major benefits to innovative manufacturers.	**9**
Future policing	Combined with the Internet of Things (IoT) platform, sensor networks will give law enforcement agencies the tools to deploy a powerful new dragnet that lets them see and do more than ever. Embracing and rolling out new sensor connected technologies in Queensland will not only support law enforcement and protect its citizens, but will do so in a way that leads to greater accountability and safer outcomes.	**10**

Analysis also revealed that jobs creation and productivity growth was seen by Experts as the most important criteria, followed by economic diversification. Criteria reflecting commercial viability were moderately important, while building on existing strengths, multi-disciplinary applications, and investment and engagement were seen by Experts as less important. The least important criterion was global niche specialisation.

From the study, we also found that:

- Sensor system effectiveness is mainly determined by its integration with other technology platforms and data management. Synergies from using big data with sensor networks could be of significant benefit to Queensland.
- It is the convergence of platform technologies and the integration of sensory systems that can ultimately deliver innovative developments for Queensland.
- Technology platforms, such as sensory systems, are enablers by which certain outcomes may be achieved. It is the application of the technology, driven by consumer demand, that is likely to be the most impactful.
- A strategic approach is required to create the right environment for technology to advance. A crucial component of this environment is the availability of reliable and affordable digital infrastructure.

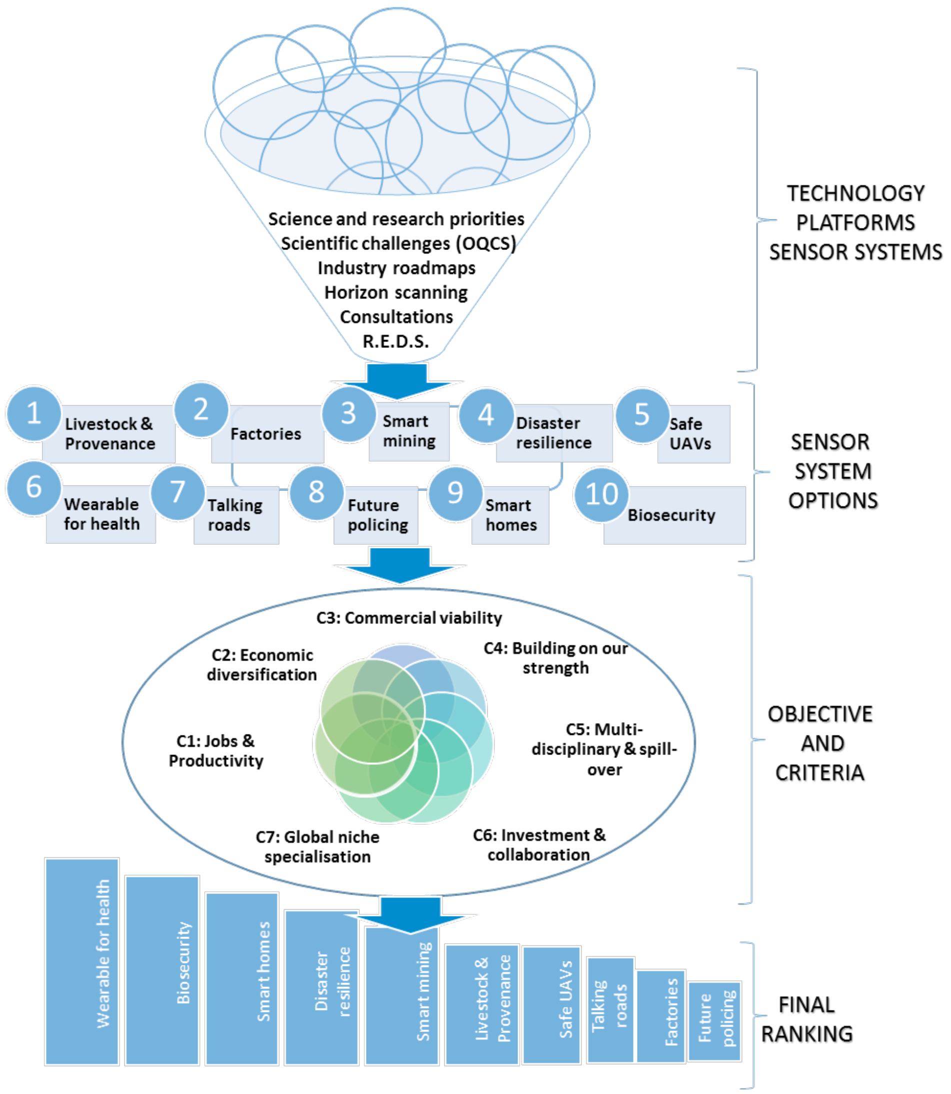


Figure 1: The MCA process, from selecting options to evaluating them

1 INTRODUCTION

1 | INTRODUCTION

1.1 Overview and objectives: Advising government about the best sensory system investments

Sensors today are applied for a wide variety of purposes: from space exploration to personalised gadgets, from ultrasound imaging to industrial manufacturing. Sensor technology detects and records data from the environment (from microbial to global scales) which can be used via humans or robotic devices to make decisions and take actions. The variety of sensors include acoustic, vibration, chemical, weather, moisture, pressure, optical, radiation, electric, radio, magnetic, proximity, thermal, heat, light sensors, sensors for transportation, navigation, imaging, displacement, positioning systems making applications of sensors nearly impossible to count. The Encyclopaedia of Sensors, for example, is a 10-volume set with over 400 chapters [1].

Although sensors have been in use for centuries, sensor technology is rapidly developing and changing. Sensors are becoming more capable and covering greater ranges: from within the human body to satellites in space. Sensors are crucial for technological progress, and the era of sensor technology is only just beginning [2]. For example, nanosensors – small enough to be able to move in a living body – are among the top 10 emerging technologies today and we will likely witness an inevitable rise of the Internet of Nanothings [3].

If we use the analogy of the human body, sensor networks could be considered as the engineering counterparts of human eyes, ears, taste buds and skin receptors – the sensors of the body. Visual sensors for eyes, acoustic sensors for hearing, and thermal and chemical sensors for touch and smell. Development of precise and reliable sensor systems, and their wider application in technology, is a crucial task to ensure technical systems receive the most valuable information for operation – just as having highly evolved eyes and ears is crucial for the operation of the human body. It is a starting point for further development, whether for a robot or a person. Further advancement in sensor technology with solutions – such as an artificial touch that converts pressure into a digital response [4] – will likely allow technical systems (for example, robots) to sense better than humans can.

Sensor technology, along with the internet and cloud computing, can be thought of as enabling technologies which subsequently facilitate developing other innovative and disruptive technologies [5]. Advanced embedded and interconnected sensor networks are at the heart of the Internet of Things (IoT), smart phones, smart grids and smart cities.

Smart phones are already packed with sensors including accelerometers, which helps you to swap between portrait and landscape view; location sensors for your GPS; proximity and infrared sensors which lets the phone know when its placed up to your ear; light sensor to adjust brightness of your screen; thermometer, barometer, pedometer, fingerprint sensors among others [6] [7]. Sensors and sensor networks are crucial for digitally-intensive innovations and our future interconnected and digitally-enabled world.

The digital economy provides the opportunity for real-time decision-making based on data received from complex technical systems. The objective of this study is to inform decision-makers within the Queensland Government about the relative priority of investing in sensing technologies that will enable the development of new products and services, ultimately creating jobs, growing the State's economy, providing export opportunities, and benefiting all Queenslanders. We consider sensor networks as systems of software and hardware which can allow us to monitor, collect, transmit, process, analyse, store and report data on the required parameters.

1.2 Policy context: Advance Queensland initiative drives innovation, jobs and the economy

On 13 June 2016, the Queensland Government announced its increased investment in the Advance Queensland initiative – from $180 million to $405 million – to accelerate the state's new economy, create jobs and encourage innovation [8]. The initiative was set up to drive innovation and attract investment in the region; translate innovative ideas into commercial products and jobs by establishing an environment for effective collaboration between entrepreneurs, industry, universities and government; and improving access for entrepreneurs to finance, business opportunities and management support.

Programs within the Advance Queensland initiative are of particular relevance to the study:

- **Platform Technology Program** – to test and develop groups of technologies for the next technological leap. Of particular interest are areas in which Queensland has scientific knowledge and emerging industry strength, with a focus on technologies such as autonomous vehicles, drones, sensors, robotics, IoT, blockchain, the cloud, and big data.
- **Small Business Innovation Research (SBIR) pilot program** – to help innovators from small and medium enterprises (SMEs) secure Queensland Government contracts to develop and test cutting edge products and technologies.

Most pertinent of the three 'challenges' in the SBIR program is the reef water quality monitoring project by the Queensland Department of Environment and Heritage Protection. The project aims to develop and supply affordable fine-scale water-quality monitoring for the Great Barrier Reef. The sensors are expected to be deployed in the Great Barrier Reef and to improve protection of the Reef and farming practices [9]. 'Challenge' initiatives in the United Kingdom and the United States are shown to be an effective alternative to government procurement tenders and contracts. In the rapidly evolving technological world, the challenge approach allows for rapid, yet cost-effective, response from the industry. It also creates a supportive environment for small businesses, startups and venture firms.

BUT WHY SENSOR NETWORKS INSTEAD OF OTHER TECHNOLOGY PLATFORMS?

Selecting technology for consideration, analysis and further investment is a complex process spanning interests of and benefits for multiple stakeholder groups. Experts believe sensor networks have a vast potential for Queensland at the current stage of technological development. Businesses and research institutions – including The University of Queensland, Queensland University of Technology, Griffith University and CSIRO – have gradually built expertise in research and development of sensor systems in Queensland, as illustrated by the following examples:

- The **wireless sensor network for environmental monitoring** established in the Springbrook National Park in 2008 as a collaborative project by the Queensland Department of Environment and Heritage Protection, the CSIRO and ARCS. The project aimed to provide real-time data on habitat quality and ecosystem dynamics of rainforest recovery after clearing. The project made an important contribution to building knowledge and experience in sensor networks applications [10].
- **eReefs project** – a collaborative initiative of the Great Barrier Reef Foundation, CSIRO, Australian Institute of Marine Science, Bureau of Meteorology, the Queensland Government and other partners. The project is developing a monitoring and forecasting platform for the Great Barrier Reef, from data collection to analysis and visualisation. One of the key components of the sensory system enabling the eReefs project is satellite remote-sensing of ocean colour for water quality [11]. The sensor-enabled monitoring system will provide variety of data on the current state of the Reef's physical processes, including ocean colour and water quality.
- An international **Unmanned Aerial Vehicle (UAV) Challenge** competition run annually in Queensland demonstrates how sensor-enabled drones can be applied in search and rescue operations. A good example of the growing technological capabilities of drones, and knowledge and skills of their application, is that over its 10-year history, the challenge task is increasingly complex. The competition is believed to have acted as a catalyst for the development of the most widely used, low-cost autopilots (APM:Plane, PX4 and Paparazzi), and in the development and commercialisation of some components (RFD900 communications modem, Millswood Engineering failsafe flight termination device) [12].
- **Sensor technology for Emergency Vehicle** Priority (EVP) has been installed in 300 emergency vehicles and 1100 intersections with signals in Townsville, Bundaberg, Sunshine Coast, Brisbane and Gold Coast. More are planned for introduction across the state [13]. EVP fitted in fire and ambulance vehicles, allowing them to automatically trigger the sequences of traffic lights and giving them green traffic lights along the emergency response call route [13]. This technology, rolled out in Queensland first, is reported to be able to save up to 20 per cent time to get to incidents [14].

Queensland also features technical capacity and human capital – skills, knowledge and experience – to grow in the field and aim for world leadership in some areas of sensor system applications. Unique and valuable environmental resources and conditions, including proximity to the Great Barrier Reef, tropical climate, and vulnerable ecosystems; regulatory framework; existing strength in agriculture, mining, health and other industries also contribute to the demand for applied sensor systems to collect detailed data and act wisely upon.

2 METHODOLOGY

2 | METHODOLOGY

2.1 Multiple criteria analysis: A rigorous technique for solving complex decisions

This study applies multiple criteria analysis (MCA) as a decision support tool which is used to structure and solve complex decision problems, often with conflicting stakeholder interests and multiple objectives. MCA is often used to support public investment decision making. Whether the government should invest in one option or another is a complex problem which requires considering multiple qualitative and quantitative criteria such as cost, employment outcomes, cross-sectoral engagement, scalability, and risks and uncertainty. MCA enables numerous options and criteria to be considered and guides decision-makers through exploring, determining, evaluating and consequently prioritising possible solutions.

MCA has a demonstrated record of efficient application for the policy development, public investment decision as well in the field of technology analysis and foresight [15]. National governments around the world, such as the UK government [16] and New Zealand government [17], have adopted MCA as a reliable and robust framework for decision-support and regulatory impact assessment. The State of Victoria has also adopted an MCA manual [18].

Applying MCA includes three generic interrelated stages (Figure 2). The first step, identification of the decision objective, is key. Criteria are then selected to reflect major features of the objective. Policy options addressing the objective are further developed. Objective, options and criteria often require several iterations before a consensus is reached by the stakeholders.

The next stage is decision analysis, which starts from building an evaluation table or 'performance matrix', with criteria as columns and options as rows. The cells of the matrix are completed with qualitative or quantitative estimates that reveal the performance of each option against each criterion. The estimates are further converted into scores. Stakeholders

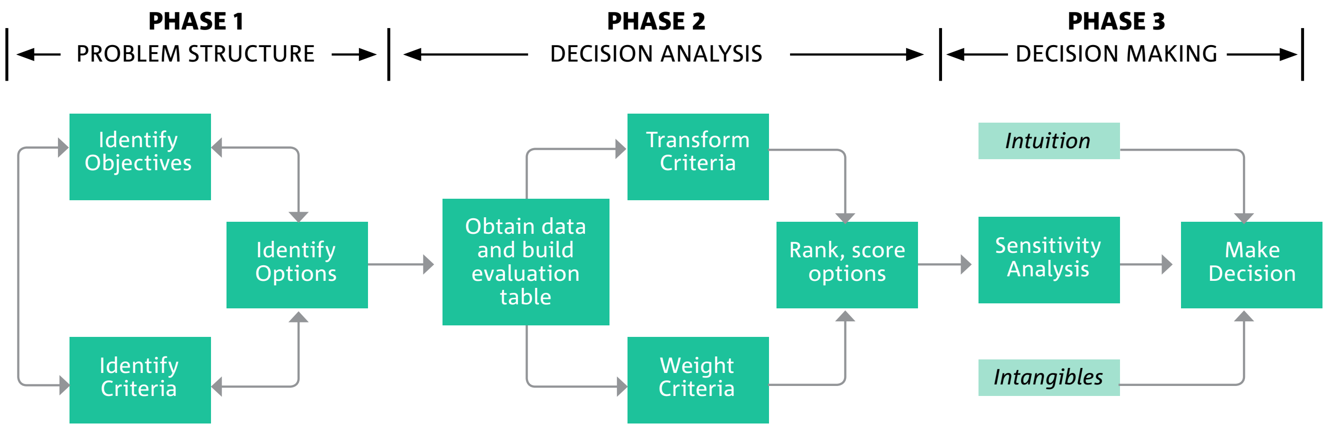


Figure 2: Stages of multiple criteria analysis (MCA) for decisions [19]

or/and decision-makers weigh the criteria in terms of the criteria's importance in meeting the objective. Once weights are determined, the performance matrix is analysed (taking into account criteria weights). Then a technical (mathematical) analysis is undertaken using one of the approaches from the MCA family of techniques. This analysis results in comparative ranking of the options.

The final stage of the MCA includes a review of the obtained ranking options and sensitivity analysis, which checks the robustness and reliability of the MCA results. At this stage, the MCA concludes, allowing for decision-making based on the provided evidence and analysed results. The human phenomenon of decision-making, however, does include intangible and intuitive aspects which are likely to play a role at this final stage.

The complexity of MCA as an evaluation tool comes from the variety of approaches to undertake scoring and the performance matrix analysis in Phase 2 (Figure 2). A large number of techniques have been developed to serve this purpose, including broader groups of compensatory and non-compensatory techniques, that are tailored to provide best possible solution for different types of decision problems, datasets, and analytical and software capabilities [16].

In practice, there exists a reverse relationship between complexity and transparency of MCA techniques – the more complex is the tool, the less transparent it is. To ensure the evaluation process of this study is transparent and accountable, we apply a straightforward linear additive model (weighted average) within the multi-attribute utility approach to determine ranking of the options.

3 OPTIONS AND CRITERIA DETERMINATION

3 | OPTIONS AND CRITERIA DETERMINATION

3.1 Criteria: Considering the priorities of Advance Queensland

The criteria for analysis are selected to reflect the key priorities of the Advance Queensland initiative. The set of criteria is also meant to promote knowledge-based growth, a customer focus and an integrated approach to technology advancement. Importantly, criteria are interrelated. The relationship between the criteria can be illustrated as a Venn diagram (Figure 1). However, only by integrating the criteria set can we reflect comprehensively on all key components of the objective. The set of criteria identified is provided in Table 2.

We used the following qualitative scores to estimate the impact of each option for the criteria under investigation:

- 1 – no benefit or a negative impact
- 2 – slight benefit
- 3 – moderate benefit
- 4 – high benefit
- 5 – extremely high benefit

3.2 Options: The sensor system possibilities for investing in

A range of options for potential investment by the Queensland Government was identified during this study (Table 3). To identify the options, horizon scanning and internal consultation processes were undertaken (Figure 1). Options were also identified based on the following key documents and priorities:

- industry roadmaps [30]
- Queensland science and research priorities [25]
- the REDS science and research investment rule (real future impact, external Commitment, distinctive angle, and scaling towards critical mass) [25]
- scientific challenges identified by the Office of the Queensland Chief Scientist [31].

Further, each option was examined in terms of:

WHY is the sensor option important? Does it open up opportunities for the region and is it a strategic fit for Queensland?

WHAT sensor systems would most likely assist Queensland in addressing future opportunities, problems, crises and needs; and which would build on current expertise?

WHERE and **HOW**, physically, and in what context, would/should these sensors be used?

TABLE 2. IDENTIFIED CRITERIA FOR THE MCA

CRITERIA
CRITERION 1: JOB CREATION AND PRODUCTIVITY GROWTH A central tenet of the Advance Queensland initiative is job creation, productivity growth and economic diversity [20]. Furthermore, the Platform Technology Program in particular is expected to create jobs and increase the productive capacity of the economy. Proponents of the program are required to have industry, supply-chain and research partners, along with a clear plan that demonstrates how their project will increase productivity and grow jobs in Queensland [21]. For example, the airspace awareness surveillance system research project – for which the Boeing Company has been awarded $1 million to develop and test remotely piloted aircraft systems technologies – is expected to generate up to 100 aerospace jobs in Queensland over the next five years. Up to half of those jobs are likely to be in small and medium enterprises [22].
CRITERION 2: ECONOMIC DIVERSIFICATION The Queensland economy has historically been underpinned by traditional industries such as agriculture, mining, construction and tourism. The recent decline in commodity prices and associated job losses in the resources industry highlights the importance of diversification for economic resilience and growth. The Queensland Government is committed to diversifying the state's industries to drive economic growth. As the state's economy transitions from the end of the mining boom, jobs for the future will come from innovation, knowledge services, and advanced manufacturing [23]. Service-based industries are expected to grow the most jobs over the next decade, although construction and manufacturing are still expected to remain large employers integral to the rest of the economy [24]. Successful options would contribute significantly to the economic growth across a broad range of industries in Queensland.
CRITERION 3: COMMERCIAL VIABILITY AND PATHWAY TO MARKET Through Advance Queensland, the Queensland Government is committed to supporting the development and commercialisation of new or improved products, processes or services to secure investment, launches into global markets, and growth of business. There is significant emphasis on the 'development' component of 'R&D' (research and development); relevant programs include the Business Development Fund; Ignite Ideas Fund; the Biofutures Commercialisation Program [20]; and the Startup Queensland Initiative, which includes 'Hot DesQ' to attract entrepreneurs to Queensland, the appointment of a Chief Entrepreneur, formation of a startup precinct and regional hubs, and a Small Business Innovation Research pilot program. Success in this criterion for a specified sensory option could include trademarking and patenting activity, formation of startup companies, and new business entries.
CRITERION 4: BUILDING ON OUR STRENGTHS Significant investment in Queensland research infrastructure by both the State and Commonwealth governments has created world-leading facilities and research excellence. Advanced, world-class research is already being performed by Queensland universities. One of the state's research priorities is to maximise its existing competitive advantage and create a critical mass for future breakthroughs [25]. For this criterion to be ranked highly, the option under consideration should add significantly to the cadre of researchers, innovators and entrepreneurs with highly developed skills, knowledge and expertise.
CRITERION 5: MULTI-DISCIPLINARY APPLICATIONS AND SPILL-OVER BENEFITS Investment in technology platforms that benefit many applications and industry sectors is most desirable. The most highly rated options should display significant spill-over benefits to many areas of the Queensland economy. A high impact on this criterion would mean that the option benefits a wide range of industries in Queensland and provides a positive impact on the Queensland economy.
CRITERION 6: INCREASED INVESTMENT, ENGAGEMENT AND COLLABORATION One of the core objectives of the Advance Queensland initiative is to create an environment that stimulates collaboration between industry, research, technology developers, startups and government to turn the best ideas into businesses and jobs. Participation in programs such as the Business Development Fund and Innovation Partnerships [26] require co-investment, where the funding provided by the Queensland Government is at least matched by investment from other participants [27]. Two of the 'REDS' decision rules for investment are premised on collaboration and investment from other sources (viz. external commitment and scaling toward critical mass) [25]. In an OECD ranking, Australia ranked last, at thirty-third, for innovation-active firms collaborating on innovation with universities and public funded research agencies [28]. Therefore, increasing collaboration is an important criterion for assessing relevant sensory options.

TABLE 3. OPTIONS FOR POTENTIAL INVESTMENT BY THE QUEENSLAND GOVERNMENT

SENSORY SYSTEM (OPTIONS)

LIVESTOCK SENSING AND PROVENANCE

WHY – Sensor networks are already embedded in many parts of agricultural supply chains but convey little information to the consumer about the product's origin or quality. Queensland is Australia's biggest beef producer, with a forecast gross value product of $4.3 billion for 2015–16 [32]. Sensors provide an opportunity to differentiate beef products based on genetics, grazing, and husbandry. Meat and other food products could be packaged with a description of unique characteristics and marketed like fine wine, extracting greater value from the supply chain. Sensor networks and linking information to current or historic spatial data could help to guarantee the integrity of the value chains to quality-conscious global consumers. The rapidly growing middle class in Asia is driving demand for quality Australian food, making the food provenance a key to global markets and a possible beginning of a new golden age for Australian and Queensland agriculture [33] [34, 35].

WHAT – Through the National Livestock Identification System with radio-frequency identification (RFID) scanners, graziers have valuable information from sensor networks for traceability and recall. However, little is conveyed to the consumer once products reach the processor. Linking sensor networks between producers, processors and logistics suppliers provide a raft of opportunities for better identifying provenance and quality. Further advancement in sensory systems can open up new global opportunities for Queensland and unleash the potential of digital agriculture [36].

WHERE and **HOW** – Data from sensor systems linking cattle properties and other agricultural producers, feedlots, processors, logistics suppliers, retailers and consumers. Beef and other food producers take greater control of their product deeper along the value chain. This option will be enhanced with advancements in the IoT, cloud technology and mobile internet [6].

SENSOR-ENABLED FACTORIES OF THE FUTURE

WHY – Manufacturing is Queensland's third-largest employer of full-time workers, providing jobs for nearly 170 000 people (at December 2015), and contributing over $20 billion to the state's economy (2014–15) [37]. Sensors are already enabling world-leading manufacturers to optimise production processes. For example, a General Electric sodium–nickel battery factory in the United States has installed over 10 000 sensors to optimise the duration of critical production steps [38]. Advanced manufacturing has been identified as a priority industry for Queensland [39] and sensory systems are viewed as an important enabler for Queensland's advanced manufacturing industry [29].

WHAT – Device and sensor connectivity platforms, and new-age mass-produced, low-cost micro-sensors such as produced from new-age materials like graphene will deliver major benefits to innovative manufacturers.

WHERE and **HOW** – Sensors can pervade all aspects of the manufacturing process and the IoT will enable the monitoring of products throughout the value chain, including tracking products throughout the supply chain and after sale [5].

SMARTER MINING SERVICES

WHY – The mining equipment, technology and services (METS) industry contributes $90 billion to the Australian economy and exports $15 billion of goods and services annually [40]. The Queensland Government is committed to supporting the state's METS [41] and contributed to establishing METS Ignited – an 'Industry Growth Centre' at QUT. Australian METS industry firms have pioneered and developed innovative mine safety solutions, and the sector is recognised as a world leader in environmental management, including mine site closure and rehabilitation. Sensors provide many opportunities for the industry, such as improving resource extraction through whole-of-stream integration [42], and monitoring water and air quality from disused mine sites.

WHAT – There is a multitude of sensor types that can assist in the METS industry, particularly with challenges including declining access to high-grade ores, factors concerning commodity markets and cost, and environmental and safety considerations. Examples include sensor technology and systems for improving high-tonnage ore sorting, managing and optimising processes, mapping in three-dimensions, improving mine safety, and increasing productivity.

WHERE and **HOW** – Innovative sensors and sensor systems can assist the mining industry to achieve major cost savings and increase efficiencies. Examples include: the FastGrade on-site elemental drillhole analysis using neutrons to characterise element concentrations in real time, X-ray rapid detection of gold in ore samples, a rapid large-scale ore-sorting sensor system, and wirelessly tracking underground mine workers to help increase productivity and save lives [43]

TABLE 3. OPTIONS FOR POTENTIAL INVESTMENT BY THE QUEENSLAND GOVERNMENT cont'd

DISASTER RESILIENCE

WHY – Queensland carries an excessive burden of natural hazards including floods, bushfires, cyclones, storms, landslips, droughts and extreme heat events [44]. The state accounted for almost 30 per cent of Australia's total 'house-equivalent' (building) losses, despite representing only 20 per cent of population [45]. Integral components of the state's strategy for disaster resilience are: providing disaster warning information with a coordinated approach, extending digital and communication networks, and capturing data to cover a greater portion of the state-controlled road network [46]. Better data and data quality from sensors and sensor systems play an important function in delivering on such actions.

WHAT – Remote, real-time sensing for analysis and management of disaster risks requires use of fully integrated, inexpensive sensor systems suitable for mobile emergency asset management.

WHERE and **HOW** – Remote-sensing satellites provide reliable, detailed, continuous and synoptic coverage of natural and anthropogenic phenomena. Emergency vehicle real-time data acquisition and hardware/software integration can improve the emergency vehicles' response. Sensing information from vulnerable watercourses, infrastructure, emergency vehicles and smart phone users will help to coordinate responses, empower citizens to make informed decisions and plan for future events. Significant benefits will arise from sharing and applying information from networked platforms.

SENSORS FOR SAFE FLIGHTS OF UAVs

WHY – In 2014–15 the aerospace industry contributed $600 million to the Queensland economy, with exports comprising nearly half of industry revenues. Queensland is home to world-leading aerospace research and maintenance centres, and training facilities. Queensland's advanced manufacturing environment, skills and geographical location near global aerospace centres hold a promise to maximise its presence in the rapidly growing Asia-Pacific market [47]. Unmanned Aerial Vehicles (UAVs, or drones) is an emerging sector which has vast potential for defence and civil aerospace. Queensland has the institutional and research capacity to prosper and innovate in the sector; centres include the Australian Research Centre for Aerospace Automation at the Queensland University of Technology [48], Centre for Hypersonics at The University of Queensland [49], and research divisions of Boeing and Insitu Pacific [50, 51]. However, a limiting factor for the industry is establishing sensor-based collision-avoidance navigation and control systems to ensure drones can 'see' better and react quicker than human pilots to operate safely.

WHAT – Sensor systems for safe navigation for unmanned and remotely controlled aerial vehicles are required.

WHERE and **HOW** – Safe operation of drones will open opportunities for their wide application for environmental monitoring, precision agriculture, natural disaster management, and numerous other services. Drones will be equipped with variety of sensors including visual, acoustic, chemical and more – and will become a mobile multipurpose sensory system on their own once they satisfy reliability and precision requirements and have integrated navigation and control systems.

WEARABLE SENSORS FOR BETTER HEALTH

WHY – As Australian population ages and the prevalence of chronic diseases increases, managing rising health costs and implementing preventative health care is becoming a major challenge for the national and regional health system [52]. Wearable technology for health monitoring and telehealth can effectively address this challenge by contributing to preventative health care and targeted health services [53]. Predictive algorithms of the sensor-enabled systems can contribute to more timely hospital admissions and targeted treatment – eventually resulting in lower mortality and hospitalisation rates. Telehealth has great potential to increase availability and decrease the cost of health services for remote communities in Queensland. Advancement in the sensor systems for wearable technology is also likely to contribute to improving workplace safety and managing workforce in harsh environment (for example, on construction sites in Queensland) [54]; and wellbeing, personal training and sports programs, which are expected to face a booming demand in the coming decades [55].

WHAT – This innovation requires affordable and user-friendly wearable sensors, with supporting predictive algorithms, integrated with smart phones, tablets, personal computers or other devices and telehealth systems to provide users with timely information and advice.

WHERE and **HOW** – Sensor systems will be designed to monitor health conditions of specific groups of people (for example, ageing people or people with chronic diseases) to address their health issues, and for the general population for wellbeing, fitness programs and preventative health.

TABLE 3. OPTIONS FOR POTENTIAL INVESTMENT BY THE QUEENSLAND GOVERNMENT cont'd

TALKING ROADS

WHY – Transport infrastructure is already employing a range of sensors. These include traditional traffic light sensors, tolling sensors and innovative solutions such as sensor-activated crossings ('puffin crossings') [56]. Elements of smart infrastructure such as electric vehicle–charging stations [57, 58] already contribute to the future of infrastructure with embedded sensor systems in Queensland. However, the emergence of autonomous vehicles and intelligent traffic control will require an increased number and variety of embedded sensors, both in the infrastructure and vehicles. Affordable and reliable sensor networks will be required for vehicle-to-vehicle and vehicle-to-infrastructure communication [5].

WHAT – Sensor systems (including data transmission and analysis) are required that allow for communication between infrastructure, and autonomous and conventional vehicles. Cost effectiveness and reliability of this sensor network is essential for its adoption and deployment.

WHERE and **HOW** – Sensors of various types will be embedded in the road surface, along roadsides or above lanes, in conjunction with sensors on/in vehicles. Information about the position of vehicles can be collected and exchanged in a timely way between road users and the enabling infrastructure. Sensors in the infrastructure can also collect data on how the driver uses the car for road safety and insurance, parking monitoring, structural health of infrastructure [59] and incidents, to generally improve the way cities function.

FUTURE POLICING

WHY – embracing of the new sensor connected technologies in Queensland will support law enforcement and protect its citizens, it will also lead to greater accountability and safer outcomes. For example, officers and the public reportedly act in a more positive manner when they were aware that a camera was present [60]. The introduction of body cams on police led to complaints against officers dropping by 90%, use of force by officers also dropped by 60% [60].

WHAT – As sensors become smaller, cheaper and more powerful, and combined with the IoT and geo-spatial data, sensor networks can give law enforcement agencies the new tools.

WHERE and **HOW** – From sensors mounted to drones and robots, to smart cameras with facial recognition and analytics capabilities, to weapon sensors and wearable devices. Sensors already pervade policing and crime prevention protocols, but the tools like 3D sensors to create a graphical models of a crime scene [61]; augmented reality for police training [62]; closed circuit television that transforms visual data into real-time intelligence [63] are likely to become commonplace.

SENSORS FOR BIOSECURITY

WHY – Application of sensors for monitoring and predicting biosecurity risks is one of the key considerations for Australia's biosecurity future [64]. Queensland hosts a unique and vulnerable environment, and sensors already play an important role in monitoring species' behaviour (for example, oysters and bees), ocean ecosystems and plant health [64]. Sensors which can detect pests and be combined with robotic platforms for precisely administering control agents can provide methodical and safe systems for biosecurity control. Application is being tested for crown-of-thorns starfish, but could apply to a range of other pests (such as fire ants).

WHAT – Integration of existing and new sensor systems could provide a holistic approach to surveillance and monitoring of pests and diseases.

WHERE and **HOW** – Sensory and robotic systems will be able to operate in a diverse range of environments and terrain; for example: RapidAIM (sensor-based wireless trapping technology for fruit flies) [65, 66] or COTSbot (autonomous robot that can administer a lethal injection in invasive crown-of-thorns starfish) [67].

SENSORS FOR SMART HOMES

WHY – Although the idea of smart homes enabled by sensors and the IoT is not new, the technology has not yet been widely taken up in Queensland. Smart homes and smart metering have the capacity to increase energy and water efficiency in households. The growing scale of distributed electricity generation (for example, solar), smart grids coupled with the advancement in energy storage (for example, Tesla power house) implies a need to wider penetration of smart technology for households.

WHAT – What is required are sensor systems integrated with the IoT to allow for smart and efficient operation of home appliances, energy and water systems.

WHERE and **HOW** – There will be a need for integration of sensor-based smart devices for household uses for new buildings, and retrofitting that satisfies requirements of affordability and ease of use. This would allow smooth communication between home appliances and users.

4 MCA RESULTS: THE ASSESSED CRITERIA IMPORTANCE AND OPTIONS' PERFORMANCE

4 | **MCA RESULTS:** THE ASSESSED CRITERIA IMPORTANCE AND OPTIONS' PERFORMANCE

The Advance Queensland Expert Panel members were engaged to undertake scoring of the sensory system alternatives against selected criteria and to weigh the criteria. The Panel unites leaders from business, research and education sectors to provide an expertise and advice to Queensland Government on the design and implementation of the Advance Queensland initiative and programs [68].

The developed set of criteria, options and the evaluation methodology were presented at the Expert Panel meeting in August 2016. The performance matrix was then circulated between the Experts to complete. Eight responses were received; seven were complete and used for the analysis. The following three subsections explain the MCA results. The survey questionnaire and the row scoring from the Experts are provided in the appendix.

4.1 Criteria weighting: Which priorities were considered most important

Weights allocation for the criteria is illustrated in Figure 3. Job creation and productivity growth was seen by the Expert Panel as the most important criterion. On average, it was weighted at 24 per cent, reaching as high as 30 per cent for some of the Experts. The second-most important criterion, weighted 18 per cent on average, was economic diversification. The weighting of this criterion is also the most variable, because its weighting varies considerably between Experts – from 5 per cent to 30 per cent.

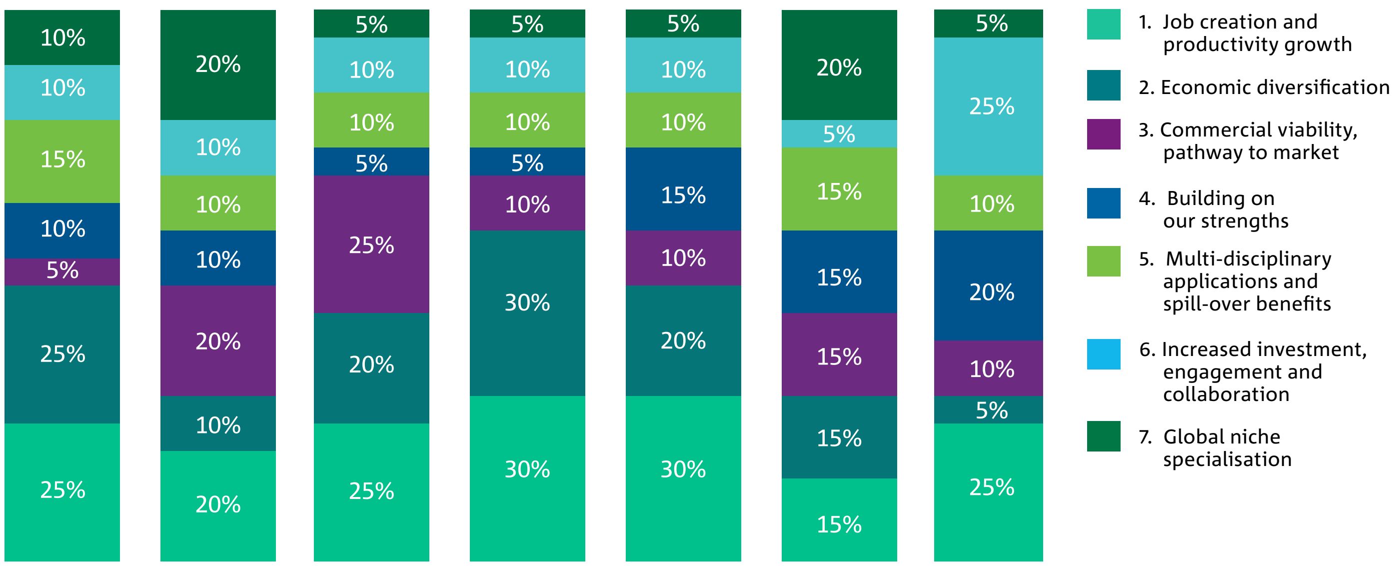


Figure 3: Weights allocation by Expert Panel members

Criteria reflecting commercial viability were weighted with moderate importance: on average, 14 per cent. Building on existing strengths, multi-disciplinary applications and investment, engagement were seen by the Experts as less important, with average weightings of 11 per cent.

The least important criterion was global niche specialisation, which received an average weight of 10 per cent. No criteria received 0 per cent weight, which means all of them were considered essential in choosing sensory system development options.

4.2 Performance matrix and ranking results: How the investment options differed

The MCA resulted in the option ranking illustrated in Figure 4. The final MCA performance matrix is provided in Table 4. A sensitivity analysis demonstrated the robustness of the rankings for the sensory system options.

Development of wearable sensors for better health received the highest weighted score. Its weighted average score was 30: well ahead of other sensory system options for investment. Sensors for biosecurity ranked second, closely followed by sensors for smart homes.

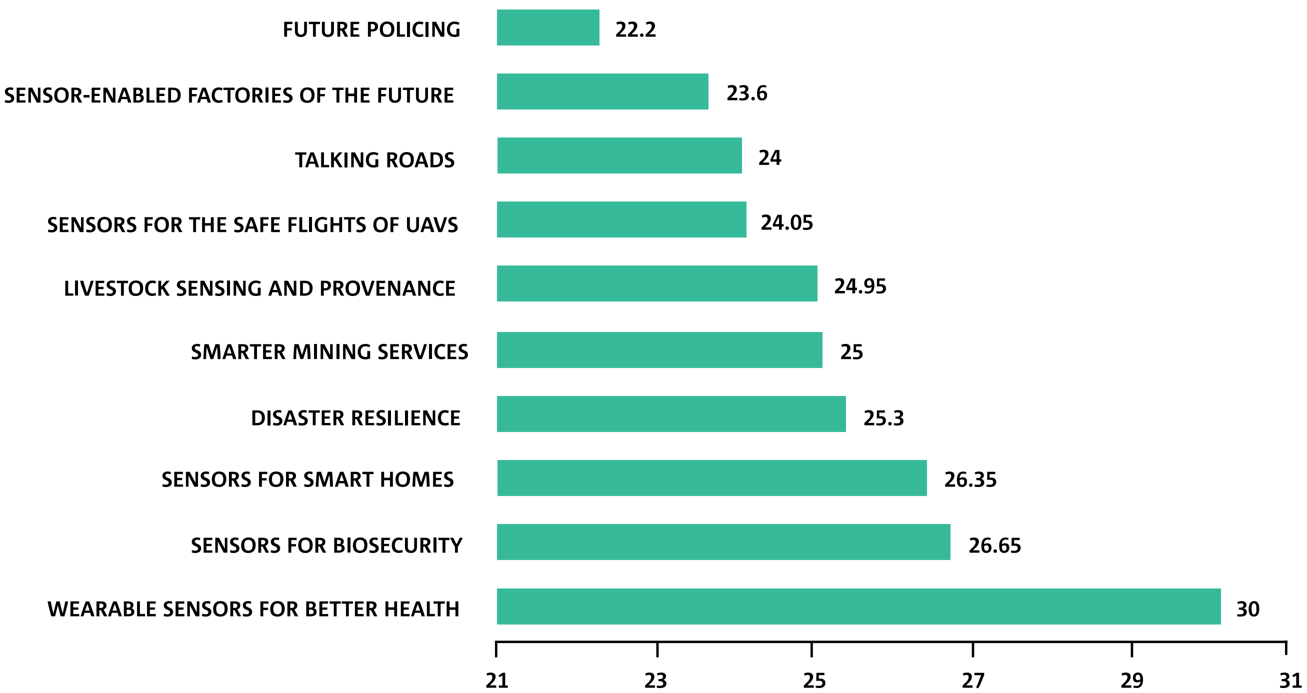


Figure 4: Overall weighted MCA results for each investment sensor option

Medium performance for investment was for scores between 24 and 25.3, received by sensor systems for disaster resilience, METS services, livestock and provenance option, sensors for the safe flights of UAVs and talking roads. The lowest ranks were obtained by the sensor-enabled factories of the future option followed by the future policing option.

4.3 Limitations of the study

Given the purposes of the study, the options and criteria were defined broadly, therefore options are not mutually exclusive and mutually independent. Investment in one option might result in benefits for the other(s). Cost and other quantitative measures were also not accounted for in the analysis due to the broad definition of the options. Therefore, once the investment priority is determined, additional qualitative and quantitative analysis is required to determine specific actions to implement the options.

Multi-attribute utility approach was selected to ensure the analysis process is transparent and robust. However, other MCA techniques could have been applied and resulted in different outcomes. Portfolio analysis should also be considered for future research because it is likely that synergies can be created when multiple options are implemented simultaneously.

Participation of the Experts in the study was voluntary and no personal data has been collected to judge what the area of expertise of each participant has. This differing expertise could have resulted in unequal representation of the industries and sectors in the analysis. Furthermore, scoring of options and weighting of criteria could be criticised as being subjective. However, these concerns can be set aside if we consider the Expert Panel as a single decision-maker. The opinion of the majority and the most proactive Experts determine the decisions of the Panel, and this process is captured by MCA.

TABLE 4. OVERALL PERFORMANCE OF INVESTMENT OPTIONS

OPTIONS	CRITERIA							TOTAL WEIGHTED SCORE	RANK
	JOB CREATION AND PRODUCTIVITY GROWTH	ECONOMIC DIVERSIFICATION	COMMERCIAL VIABILITY AND PATHWAY TO MARKET	BUILDING ON OUR STRENGTHS	MULTI-DISCIPLINARY APPLICATIONS AND SPILL-OVER BENEFITS	INCREASED INVESTMENT, ENGAGEMENT AND COLLABORATION	GLOBAL NICHE SPECIALISATION		
Livestock sensing and provenance	6.2	4.2	3.0	3.2	2.9	2.8	2.8	24.95	**6**
Sensor-enabled factories of the future	5.5	4.4	3.1	2.7	2.7	2.9	2.5	23.60	**9**
Smarter mining services	5.7	4.0	3.4	3.1	3.1	2.9	3.1	25.00	**5**
Disaster resilience	5.8	4.5	3.0	2.9	3.3	3.0	2.9	25.30	**4**
Sensors for the safe flights of UAVs	5.3	4.9	3.1	2.8	2.8	2.7	2.7	24.05	**7**
Wearable sensors for better health	7.1	5.4	3.9	3.5	3.7	3.5	3.1	30.00	**1**
Talking roads	5.4	4.7	3.1	2.9	2.9	2.6	2.6	24.00	**8**
Future policing	5.2	4.5	2.7	2.7	2.4	2.6	2.3	22.20	**10**
Sensors for smart homes	5.8	5.2	3.7	2.9	3.1	2.9	2.9	26.35	**3**
Sensors for biosecurity	6.3	5.4	3.2	3.0	3.1	3.0	2.8	26.65	**2**

5 DISCUSSION AND CONCLUSION: SENSOR SYSTEM CHALLENGES AND OPPORTUNITIES FOR QUEENSLAND

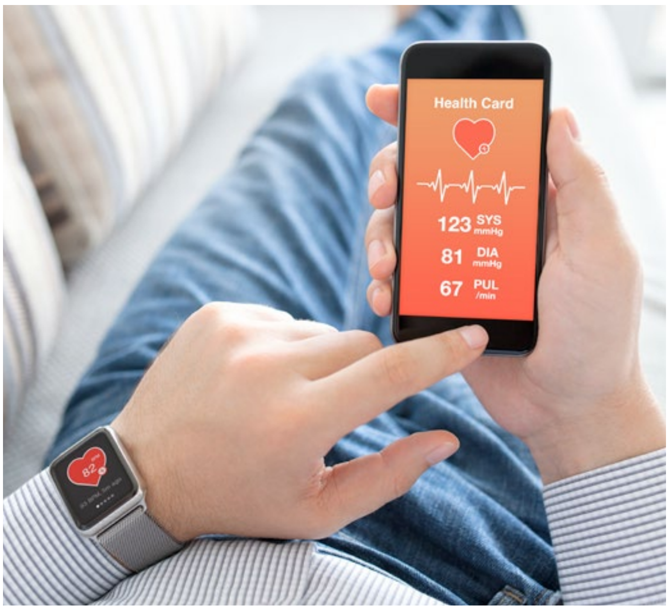
5 | DISCUSSION AND CONCLUSION: SENSOR SYSTEM CHALLENGES AND OPPORTUNITIES FOR QUEENSLAND

This report provides findings from a collaborative study between CSIRO's Data61 and the Queensland Government to enable more informed decisions for investing part of the Advance Queensland initiative. We ranked and scored the investment desirability of sensory systems using a decision analytic technique called multiple criteria analysis.

Wearable health monitoring sensors ranked the highest in terms of expected benefits for Queensland. This finding is of significance, given the strength of bio-sensor advanced manufacturers located in the state [29]. Sensors for health applications were followed by sensors for biosecurity, smart homes, disaster resilience, METS and others in the descending order of their expected benefits for Queenslanders.

However, a fundamental component of the effectiveness of any sensor system is its integration with other technology platforms and systems. Without data collection, storage, transmission, processing and analysis, sensors are not useful. Development and integration of advanced sensor networks can be considered a first and critical step to leverage Queensland's technological advancement and innovative growth of the future. This step, however, needs to be taken in conjunction with further development of data management systems and approaches.

Establishment of data management along with other challenges and questions faced by Queensland with respect to the sensor systems advancement are outlined below.



DATA VERSUS INFORMATION: MAKING EFFECTIVE USE OF BIG DATA

The present and future of the sensor technology can fall prey to the known dilemma of 'data-rich but information-poor' environment. Having data does not directly imply having useful information. The data collected by sensors today are often referred to as underused. For example, according to the McKinsey Global Institute, less than 1 per cent of the data produced by the 30 000 sensors on an offshore oil rig is used [5]. These data are primarily used to chase production irregularities rather than for decisions about optimising production [5]. Geoscience Australia, in another example, report that "limited capacity to integrate different data streams and to process the sheer volume of satellite data are preventing its full value from being realised" [5]. As the sensor technology advances, digitalisation takes hold, and sensor dissemination increases, these concerns will intensify until proper integration and data processing mechanisms are put in place, and system interoperability issues are resolved.

As the well known wisdom hierarchy (Figure 5) by Russell Ackoff [69] illustrates: "An ounce of information is worth a pound of data. An ounce of knowledge is worth a pound of information. An ounce of understanding is worth a pound of knowledge" [70]. Value and meaning of the information increases as you go up the pyramid with decreasing computer programmability and increasing need for human input [71].

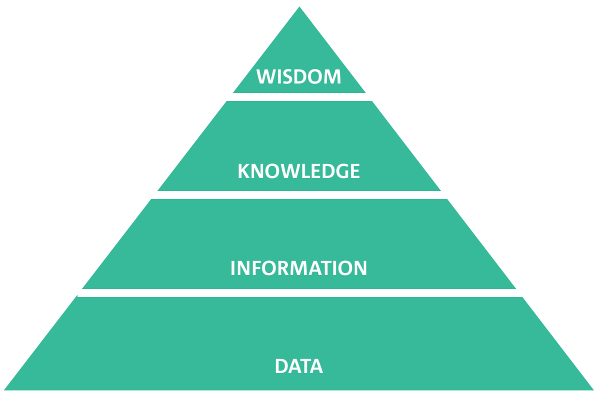


Figure 5. Wisdom pyramid [71]

TECHNOLOGY CONVERGENCE AND SYNERGIES BETWEEN TECHNOLOGY PLATFORMS

Ultimately, it is the convergence of technology platforms that will create significant value for Queensland industry and create jobs. For example, advanced manufacturers are embracing a raft of technologies in their production processes, including:

- information-driven intelligence arising from advanced analytics, big data, cloud computing and social technologies
- greater connectivity through the IoT, wireless networking and device connectivity platforms
- use of smart devices to monitor production machinery, supply chains and products
- production processes engaging robotics and three-dimensional printers
- augmented reality to improve training and worker safety [29].

For example, a wearable medical device such as a 'diabetes skin-patch' has the ability to combine information indicating hyperglycaemia (abnormally high blood sugar level) and take remedial action by injecting insulin using micro-needles [72], and will ultimately convey data to the cloud for access by a patient's doctor, and use big data analytics to help in their future diabetes management.

It is convergence of platform technologies such as sensor networks, drones, autonomous vehicles, robotics, big data, the cloud, and blockchain which will ultimately make the most impact and deliver innovative developments to benefit Queensland. Technologies can reinforce each other, multiplying the combined impact on the economy.

INTEGRATION OF SENSOR NETWORKS – NETWORKING THE NETWORKS

Many of the options identified in this report support the integration of sensor networks to leverage the most value from this platform technology. Combining the information from a multitude of reference points provides a more accurate view of the situation and allows for better decisions to be made. For example, in disaster resilience and response work, real time sensing and analysis from satellites, critical infrastructure, water courses, emergency response vehicles and personnel, and social media provide a far better understanding of the impacts of emergency situations and how they should be managed – compared to unlinked, disparate datasets.

The integration of sensor networks to extract value from datasets is not a new concept. For example, CSIRO's Data61 Sense-T initiative, which is combining data from different sources, aims to create the world's first economy-wide intelligent sensor network in Tasmania [73]. The task is challenging, given that existing sensor networks are owned by a range of government departments, energy and water utilities, and businesses. Data61 is working with the University of Tasmania and the Tasmanian Government to conduct the work. It is hoped the network will ultimately allow relationships to be identified across the whole economy – leading to social, economic and environmental benefits for Tasmania.

The benefits that would arise from a more coordinated effort to integrate sensor networks should be considered by the Queensland Government when making policy decisions about investment in platform technologies.

THE NEED FOR CUSTOMER FOCUS OVER DEVELOPING TECHNOLOGY FOR ITS OWN SAKE

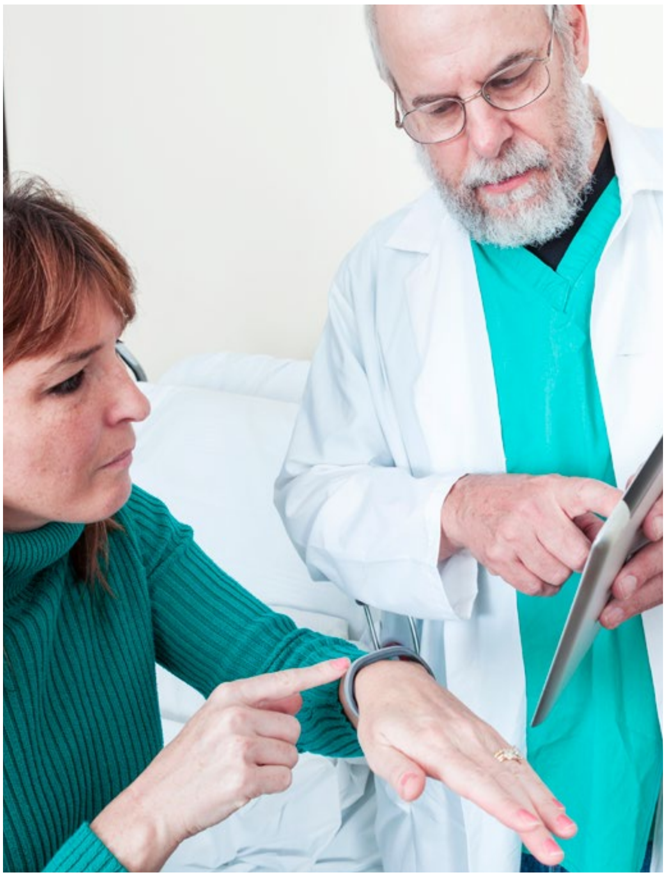
Technology platforms such as sensory systems are enablers by which certain outcomes may be achieved. This study suggests a robust and transparent ranking of potential investment options, based on stakeholder expertise and facilitated by the multiple criteria analysis. However, the decision about which platform to choose and how to develop it is still a moot point – the first consideration should be on what the customer wants and then which technology should be used to achieve it. This implies a transformational shift in the focus for decision maker and policy agenda from 'how we develop the technology' to 'what service the customer needs', and sensing-as-a-service approach. One example of this shift is the RapidAIM technology, which provides services of trapping, identifying and notifying about fruit flies [66].

ESTABLISHING CORE DIGITAL INFRASTRUCTURE – ENABLING THE ENABLERS

Availability of reliable and affordable digital infrastructure is one of the key factors determining innovation and effectiveness of sensor networks. Communications infrastructure providing a gateway for the sensors to connect to the internet, such as a low-power network (LPWAN), is a crucial part of this.

This problem will need a solution both at technological and policy levels as Australian cities are reaching the point of spectrum crunching (Goldman, 2012) and 'peak data', where user demand for wireless connectivity might no longer be met [74, 75].

LPWAN for the sensors operating in the IoT can be seen as a supplement to mobile phone networks, in the lack of which each sensor installation has to have its own gateway to the internet. In remote areas this will include expensive hardware such as 4G modem, computer, and energy supply (for example, solar panel and battery). Although providing LPWAN for the IoT can be commercially viable in some areas, it will not in others, including many regional agricultural areas. In this regard, some governments consider wide-area, public communications LPWAN a public good which requires government investment to help establish the core infrastructure for sensor networks and the IoT. For example, Netherlands has become the world's first country rolling out a nationwide LPWAN (LoRa) network for the IoT which faces increasing demand, will be able to connect millions of devices in a cost-effective way [76] and is expected to enable innovations in sensor systems applications.



ETHICAL IMPLICATIONS OF DATA COLLECTION AND CYBER SECURITY

Monitoring and recording personal data, including health-related data, is associated with ethical concerns. Implementation of sensor-enabled monitoring systems will require a holistic understanding of ethical issues and consensus between researchers, patients and medical practitioners. Similarly, the aerospace industry will need to overcome a hurdle of privacy before drones can be allowed to collect data and record video information. Smart infrastructure and autonomous vehicles will generate increasing amounts of data on road use, which will need to be managed taking into account privacy concerns and the safety risks from malicious attacks [5]. Acceptance of technology and the readiness of people to rely on the technological platforms and invest in them (for example, investing in smart home equipment) is another challenge; for instance, older customers have very strong opinions about technology and metering [77, 78].

SENSOR TECHNOLOGY AS A POTENTIAL DISRUPTER FOR INDUSTRY PLAYERS

As a greater utilisation of sensor technology takes place, existing technical systems, financial and workforce management practices might face new challenges. For example, sensor-enabled mobile and digital platforms in policing are likely to require a shift from traditional to more flexible strategies in staff deployment – from district and regional staff allocations to policing hubs [45]. Another example is optimisation of waste collection routes based on information from sensors on waste bins. Although this opportunity holds a promise of resource use optimisation and cost-effectiveness, it might disturb revenue flows for current operators in the industry, creating financial risks for them.

Overall, as the world progresses further into the knowledge and digital economy, efficient data management becomes a key to success. Establishing and using quality data resources, including developing sensor systems for data collection and analytical capacities for data management, require dedication and significant investment. This investment is associated with risks and does not necessarily promise quick returns. This situation of a market failure requires governments to think strategically and play a leading role in investment for the future. Once the key investment in data collection and management is made, and digital infrastructure is established, the introduction of new data-based products and services can be prompt [5, 79]. This creates an environment for businesses and startups to flourish, and for the economy to grow in an increasingly data-driven age. Sensor-enabled technological solutions may not only be able to solve existing problems and address current needs, but also create new markets and jobs for sensor-enabled services. This principle is one of the driving forces of the open-data initiatives undertaken by the world's leading government, one of the key motivators for this study, and the Queensland Government's strategic decision to invest in sensor systems.

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