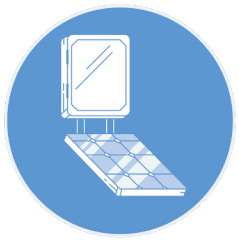

Recommendations for the DEVELOPMENT & IMPLEMENTATION of Distributed Sensor Networks

LEADS:

Christine Kendrick, PhD, Air Quality Lead/Smart Cities Coordinator,
City of Portland Bureau of Planning and Sustainability

Andrew Rodgers, Research and Applications Development,
The Enterprise Center

CONTRIBUTORS:

Khalid Elgazzar, PhD, Assistant Professor,
School of Computing and Informatics, University of Louisiana at Lafayette

Brian Miles, PhD, Senior Consultant U.S. Federal Market, *CGI*

Bureau of Planning and Sustainability
Innovation. Collaboration. Practical Solutions.
City of Portland, Oregon

GLOBAL CITY TEAMS CHALLENGE

CGI

THE ENTERPRISE CENTER

UNIVERSITY of LOUISIANA LAFAYETTE

Recommendations for the Development and Implementation of Distributed Sensor Networks

ABSTRACT

In nearly every modern civic infrastructure initiative, there are compelling reasons to leverage data and analytics to deliver the most value and impact to citizens. However, few resources are available that help communities understand the critical nature of the underlying sensors and infrastructure that support these applications, especially in a cross-sector, vendor agnostic way. This document strives to provide a robust orientation for those tasked with assessing, planning or deploying these advanced sensor networks. This document is not a prescriptive, step-by-step guide to a successful deployment, as the topical scope is far too large, and community and project variability far too broad to provide a monolithic solution. Instead, we seek to challenge the reader to discover the critical aspects of their project through coordinated effort with the appropriate stakeholders, and with full appreciation for the cultural, technical and resource constraints of their community.

We've divided our blueprint into 12 key project stages, ranging from problem identification to hardware end of life. These project stages were identified through two facilitated workshops in Washington DC and Portland, OR as part of the National Institute of Standards and Technology (NIST) Global Cities Team Challenge (GCTC) Transportation SuperCluster. Sensors, as discussed here, could represent a variety of specific applications such as devices for traffic counts, pedestrian activity, light metering, noise, air quality, water quality, climate-related measurements, etc.

For each project stage, key considerations are discussed and summarized. These considerations include lessons learned from other projects and questions to ask yourself when designing or planning a project to address common issues and major challenges. Communities may find themselves well beyond stage one, or even that certain stages are not appropriate for their specific scope and context, and we hope that each stage offers helpful insight regardless of your starting point.

A recurring theme you will find is the absolute dependency on good communication with stakeholders, and a realistic view of the limitations in expertise and resources within that group that you should seek to augment for maximum efficacy. As the available technologies and community needs evolve, we hope that keeping this theme in mind while addressing the various considerations identified here will help support successful planning and implementation of sensor networks.

1 Introduction

Increasing accessibility to sensors, computer processing units, and remote communication technologies has led to a large growth in the availability of sensor devices that can be deployed to create sensor networks across a variety of landscapes. These technologies combined into networks is also commonly referred to as the Internet of Things (IoT). Many communities are interested in exploring how these technologies and increased availability of data can be used to meet the needs for data-driven decisions, expansion of citizen science and civic technology communities and to spur economic opportunities.

Pilot deployments funded by combinations of grants and/or partnerships with private sector companies currently dominate the state of implementation for community based sensor network projects. This blueprint document is aimed at pulling together lessons learned, best management practices, and research questions revealed based on existing pilot projects for sensor network development and implementation. This blueprint can be used to help inform current and ongoing projects, provide

material for the planning of an upcoming project, or in the preparation of writing project grant proposals or other funding requests. As discussed in this document, sensors could represent a variety of specific applications such as devices for traffic counts, pedestrian activity, light metering, noise, air quality, water quality, climate-related measurements, etc.

This blueprint is authored by a working group of individuals with experience in academic research, public sector roles, and the private sector. The author working group was formed through engagement in the National Institute of Standards and Technology (NIST) Global Cities Team Challenge (GCTC) Smart Cities program. Through two facilitated GCTC workshops, we have identified 12 project stages for developing and implementing a sensor network project. In the subsequent sections, these project stages will be discussed along with the key considerations/questions that need to be addressed for each. We hope this blueprint is one of many collections of best practices for sensor networks as the number of deployments increase and the available technologies and community needs evolve.

2 Project Stages

2.1 Overview

A blueprint for sensor network development was the topic of two facilitated workshops through the GCTC program and as a subsection of the Transportation SuperCluster. These workshops combined people with experience and stakes in research, private, and public roles. The first workshop occurred in Washington DC in October 2016 and the second in Portland, OR in February 2017. A basic outline was developed and a list of the critical project stages was identified. These sensor blueprint discussions did occur under the umbrella of the Transportation Supercluster because many (but not all) sensor pilots are occurring with deployments in the public right of way. However, we kept the project stages and key considerations broad so that these best practices and questions can be applied to sensors with uses cases and deployments outside of the transportation environment. The workshop consensus found the following twelve project stages to be common and critical when developing and implementing a sensor network:

A. THE PROBLEM | Use Case identification: Determine the root of the issue your city/community is facing and if sensors are the best method to solve the issue
B. THE SOLUTION | Identify the right sensor package with specifications that meet your needs based on the use cases identified.
C. THE SENSOR IMPLEMENTATION STAGES:
    i. Privacy issues
    ii. Community engagement plan
    iii. Local procurement processes
    iv. Installation considerations
    v. Data communication and management plan
    vi. Data standards
    vii. Data integration
    viii. Data validation
    ix. Funding (public/private/integration with other technology & systems)
    x. Sensor end of life considerations (technology transitions & advancements)

Metrics and evaluating project performance are important elements across all the project stages so these will be discussed throughout rather than fall under its own section. The stages identified under (C) Implementation are not in a linear order. Some of these project stages may occur in parallel or occur in a completely different order than the list above. Any best practices identified that do require a specific order of project stages or recommendations to make implementation smoother will be noted in the following sections. For each project stage, key considerations are discussed and summarized. These considerations include lessons learned from other projects and questions to ask yourself when designing or planning a project to address common issues and major challenges.

2.2 Problem Identification

To set a sensor network project on the path towards the most useful outcomes, it is recommended to begin by spending some time determining the root of the issue(s) your city/community is facing. The next step would be brainstorming and discussing how and if sensors are the best method to solve this issue. Use case identification before searching for sensors may allow you to find the most applicable technology and avoid the pathway of technology for technology's sake.

However, the authors also acknowledge that there are benefits to communities to create technology testbeds such as creating new economic drivers and the need for exploration to find the best technology for your community's needs before committing to products and providers. Additionally, sensor workshop participants have pointed out that a common path to getting a sensor deployment project off the ground is through a product life cycle replacement or packaged as part of a larger infrastructure project. In these cases, there may not be a lot of discussion, community engagement, and investigation of use cases before deciding on a sensor installation. When sensors are an incorporated piece of a larger product replacement or infrastructure project, a city/community should still rely on existing community plans and needs assessments to help make decisions. Such plans typically have incorporated a rigorous evaluation and community engagement process to create community vision, goals and objectives.

A hybrid model of deployment can be one option to help facilitate a technology pilot while also making sure the project is focused on meeting public needs and expanding a community's access to technology. If a sensor device comes with five different features but only three of these align with existing city needs/goals, the community can leverage this with the provider. A community can emphasize there is only an existing need for three of the features, or we already have a system in place for one of the features and then a new agreement could be made on contracts to pilot the other two features to further understand needs and use cases.

When evaluating use cases, problem identification and how sensor systems fit in, people familiar with the problems and subject matter need to be involved. Sensor technology providers do not necessarily have knowledge in the field they are now offering measurement devices in. Those with subject matter expertise will not necessarily have knowledge in communication protocols and/or city policy of how to deploy and set up maintenance contracts. Use case identification and assessing the potential of sensor networks to provide data and information for those use cases will take a creative, interdisciplinary team with a range of expertise. This is not an easy step to get everyone in the same room but could be key to avoid deploying a system that does not provide the needed data for the problem you are trying to solve.

The initiation of a sensor network project may begin in several different ways; through an interest in sensors and trying new technologies, packaged as part of an infrastructure or product replacement project, a grant award, or a public-private partnership to help fund. No matter how a sensor network project discussion begins, use case evaluation involving a multi-faceted team with subject matter experts relative to your community problem and needed measurements is key.

2.2.1 Summary of Key Considerations

A. What public need are you serving or what specific problem are you trying to solve?
B. What existing data sources could be leveraged to address the issue?
C. What gaps in existing visibility for the problem exist?
D. Who are the stakeholders that are currently addressing this issue? Do they see the value in additional data?
    a. How can you create a multi-disciplinary team to help with use case development and evaluate how sensors can achieve solutions for the issue and data needs identified?
E. Do you have the political capital or buy in from the stakeholders to ensure the data you collect is used to address the issue?
F. What policies are in place within the city that may hamper the effectiveness of your deployment? Will the deployment be worthwhile without addressing those policies?
G. Identify methods, resources, and stakeholders for data analysis ahead of time to ensure the data collected can address the issue.

2.3 Sensor Selection

Within the same measurement application, sensor packages can have huge cost differentials. Some sensors are $10, some $2500 and some can even be called lower-cost at a price tag of $10,000. There are a range of reasons for such cost differentials; sensor quality and limits of detection, communication platforms, computer processing units, sensor packaging and enclosures, and/or research and development for the device.

A multi-disciplinary team with subject matter experts of your measurement application will again be key to understand these cost differences and select the sensor package that works best for your use case and project budget. To evaluate the range of selections out there, you will need to develop sensor selection criteria that is based on your project needs and use cases. If you only need a coarse measurement value, then you may be able to choose a sensor with less sensitive limits of detection and that could mean a lower price. If you do not need real-time data for your project and can have the data sent to you once a week or even monthly, then you can choose different communication platforms and may need a larger data logging capacity.

Thinking about future data needs for a project can also be helpful in selecting a sensor package. The ability to upgrade or add additional measurement capabilities later could help increase support for the project and potentially save money further down the road.

2.3.1 Summary of Key Considerations

A. Use a multi-disciplinary team with subject matter experts of the measurement application to design sensor selection criteria based on your project/use case needs.
B. What sensor data would be actionable for your issue, and also more broadly applicable for other city needs?
C. What subset or superset of the data needed does each package address?
D. Can you identify other stakeholders that may be willing to support the deployment if you include a key metric for them in your package?
E. What economic development outcomes can be realized with the availability of this new data, and how does each sensor package or platform support that outcome?

2.3.2 Case Study- City of Portland Air Quality Sensor Device Pilot

The City of Portland was awarded a NIST Replicable Smart Cities Technologies cooperative grant in August 2016 for a project called A Framework for Low-Cost Urban Air Quality Measurements. The project's objectives were to improve understanding about the types of use cases possible with low-cost air quality sensors through a three-phase deployment involving lab testing, field comparisons at the state Department of Environmental Quality station and field comparisons at the roadside at signalized intersections.

In order to select which sensor(s) to purchase for this project's deployments, the team put together a list of questions and specifications that could be used to review the growing list of low-cost air quality sensor devices that were available at the start of the project period. Table 1 lists some examples of the criteria developed and used to select the final sensors for the project.

Table 1 Sensor Selection Criteria Examples from City of Portland's Air Quality Sensor Pilot

Device Requirements	Background Information for Criteria
Device should be able to measure at least 3 of the following pollutants: CO, NO, NO_2, CO_2, O_3, $PM_{2.5}$	● Study objectives focused on transportation-related pollutants ● Transportation emissions are a mix of pollutants so did not want a device designed for only 1 pollutant at a time
Minimum and maximum detection limits to align with expected ambient pollution levels	● Refer to expected ranges in Table 2-2 Summary of some common air pollutants in 2014 US EPA Air Sensor Guidebook (1)
No metal oxide sensors are used for gas measurements	● Based on previous sensor testing, metal oxide sensors were either non-functional or stopped working quickly once deployed in ambient conditions

Cellphone modems with data plans for data communications or similar capabilities to transfer data frequently	● Wanted the potential for real-time communication and at least the ability to send stored data hourly
Additional calibrations (beyond factory), willingness to participate in comparison testing, and/or evaluation data from previous studies	● Looking for some type of additional validation data for the devices beyond the original sensor manufacturer's factory calibration sheet which are typically performed for only a certain set of temperatures and relative humidity conditions. Those calibrations are also not performed for sensors in their final housing or device configuration
Ready to be deployed in weather-proof housing	● We did not want to build or construct any enclosures ourselves so the device needed to be outdoor deployment ready
Other unique characteristics or specifications	● Outdoor, ambient air quality measurements are an emerging use for lower-cost sensor devices so we left these open criteria to be able to consider unique or novel features such as creative sampling inlet designs, ability to upgrade as sensor technology advances, etc.

2.4 Privacy Issues

As deployment of sensor networks in cities accelerates, privacy and protection of citizen interests is becoming a key discussion point during the planning and implementation process.

As established above, projects where the sensor networks are designed and implemented based on a deep understanding of the problem space, and how the data will affect citizen quality of life will have the greatest chance of success. Even if sensor networks are not initiated from a robust needs evaluation process, special care should be taken to have open communication with citizens around the types of data you will be collecting, how it will be used and how those uses will deliver value to those citizens. If private vendors will be involved in managing the data and analytics performed on the data, the scope of their access and the policies controlling their access should be clearly communicated as well.

It's important to understand several contributing factors to assure privacy is appropriately addressed in your project. Privacy, in this context is the assurance that data collected or observed can only be used for the intended purpose and will not be used to identify patterns and behaviors at an individual level. For privacy to be protected, your system will need to address trust, security and access control.

- Trust is the concept that an agent or actor within the system will continue to perform its prescribed function and will not begin to exhibit harmful behavior without being detected by other actors in the system.
- Security means that agents that have established trust can communicate with each other without fear of unknown actors observing or recording their communication, this is typically achieved through encrypted communication channels.
- Access control means that there is an established and understood process by which new actors, whether human users, new sensors or additional compute resources gain trust and begin to communicate within the system.

Starting from a position of communicating the value that can be realized for the citizen, and engaging in an open process that allows them to feel ownership in the project will go a long way towards ensuring privacy concerns are understood early in the project and addressed in a manner that still provides the data and insight required to solve the target problem. The perception of privacy can be as important or more important than the actual policies governing privacy. Ensure that you have an effective communications plan that provides clear, honest insight into the policies established for your project.

2.4.1 Summary of Key Considerations

a. Communication is key, providing clear, concise information to concerned citizens about how data will be collected, transmitted, and stored will provide citizens with assurance, and ensure that you've asked critical questions of the stakeholders around privacy.
b. Connecting the data collected or observed with the services citizens consume clearly is essential for effective buy in.
c. If data is required for a citizen service and must be available in vendor custody, ensure the policies protecting that data are clearly understood by all parties.
d. As data breaches in the private and public sectors are an almost daily occurrence, be sure you have a breach mitigation plan in effect, and that you've communicated how such a breach will be handled to your citizens.
e. Creating policies that are both effective and realistic is a delicate balance, made even more so by the rapid iteration of the technologies at play, inevitably there will be cases your policy does not deal with effectively arise. Ensure you have a clearly communicated conflict resolution process that can resolve such situations.

2.4.2 Case Study- Array of Things Governance and Operating Policies

Governance and privacy policies for the Array of Things, an urban sensing project in Chicago, were developed in cooperation between the operators of Array of Things- the Urban Center for Computation and Data (UrbanCCD) (a research initiative of the Computation Institute at the University of Chicago and Argonne National Laboratory) and the City of Chicago plus input from the American Civil Liberties Union, the Electronic Frontier Foundation, and the Center for Applied Cybersecurity Research (2). Gathering input on the governance and privacy policies was a key objective of the civic engagement process, see Section 2.5.2 for more details on the process and links to documentation of all feedback.

The Array of Things governance and privacy policies can be found here:
https://arrayofthings.github.io/final-policies.html

Summary of feedback related to privacy issues are listed below and come from the detailed Array of Things Civic Engagement Report (2): https://arrayofthings.github.io/engagement-report.html#page_10

Residents, institutions, and commenters asked for more details and/or clarity on:

- The Array of Things partners and their roles such as who is accountable and who owns the data?
- Image Management- What will or will not be captured in the images? How will data be encrypted? Who will have access? How long will images be stored? How will images be deleted?
- Made recommendations that the privacy policy include a clear process for when residents believe their personally identifiable information (PII) has been publicly shared accidentally and would like it removed.
- Who are the potential third party researchers who would have access to raw, calibration data? What systems of accountability would govern their work?
- What extent would any PII collected be subject to Freedom of Information Act disclosure requests?
- How would data collected from Array of Things sensors interact with Chicago's law enforcement and other third parties, specifically related to warrants?

2.5 Community Engagement Plans

Community engagement strategies need to be implemented before sensors are deployed and throughout the lifetime of the sensor network. Sensor networks may involve installing new infrastructure, collecting data about the community and their surrounding environment, and creating new datasets and knowledge that the community will want to use. Engagement, feedback, input, and responsiveness with the community is at the center of creating a successful sensor network project.

To develop such a comprehensive strategy, sensor network project teams should find partners with established public engagement experience and connections with the communities you are trying to engage. This could include public sector employees who specialize in community engagement, community groups, non-profit organizations, private firms who specialize in community engagement and facilitation, and civic technology organizations. For example, the City of Portland's Bureau of Planning and Sustainability District Liaison Program has a City Planner assigned to each of the city districts to help listen, connect and problem-solve with the neighborhood on a variety of topics. The district liaisons could be helpful contacts to involve in developing a community engagement plan for a sensor deployment project.

Community engagement for sensor network projects may need to occur in multiple stages. First, there is technical background information to share such as what the sensors can and cannot measure, how data will be collected and aesthetic and infrastructure information such as what the devices will look like and how it will be installed in your neighborhood. Feedback from the community on these topics then needs to be gathered and any other additional questions or comments from residents. For the urban sensing project in Chicago called Array of Things, a broad civic engagement strategy was key because the engagement's purpose was to not only inform residents about the devices but also to identify public concerns and questions, and provide answers with responsive solutions to these questions such as

revising the governance and privacy policies for the sensor nodes (2). The Array of Things Civic Engagement report does note lessons learned on how informing and engaging at the same time was a challenge, See the case study below in Section 2.5.2 for more details (2).

Working with community liaisons and community engagement specialists will help to identify the residents whom you need to engage with. To get representative engagement, there needs to be more than one avenue or opportunity for community members to learn and provide feedback. Not all residents will have the time or ability to physically attend a public meeting, not all residents will have access to get online, and there are many other reasons or lack of resources that could inhibit engagement. The Array of Things civic engagement report notes that having multiple platforms to collect feedback was more complicated to manage, but the various options including offline and anonymous options was important to create accessible modes of engagement (2).

For smaller stakeholder engagement meetings, providing stipend resources, food, or childcare can be very helpful to encourage and show the value the team places in community member's time and inputs. Providing trainings of how to access and use the online tools as well as providing forms and tools in multiple languages is also critical to creating accessible modes of engagement.

Tracking feedback and comments is an important deliverable. Questions, answers, and comments may be ongoing for a sensor technology project especially as interaction with the data collected occurs. Using an online tool or repository to consolidate feedback can be helpful to allow residents to understand the full history of a project and ask new questions. There are many municipalities, public-private-academic partnerships working on developing such civic technology tools. The Array of Things project used the OpenGov Foundation's Madison tool which is a government policy co-creation platform that collects public edits on policy or legislation (2). If access to such a tool is not possible, creating and posting timely reports on publicly available websites and keeping an active or updated frequently asked question section is another route. Trainings on how to use digital tools or access content available online is another consideration to enhance community engagement.

2.5.1 Summary of Key Considerations

A. Sensor project teams should partner with existing community liaisons, individuals or groups with established community engagement experience to develop a comprehensive strategy.
    a. Examples include community and nonprofit organizations, private sector firms specializing in engagement and facilitation, civic technology organizations, and public sector employees who specialize in community engagement
B. Community engagement strategies will have multiple stages.
    a. Inform the community on the technical, measurement capabilities, aesthetic and deployment logistics of the infrastructure, and background information on data access.
    b. Solicit feedback and responses on the informative pieces and new questions/comments.
    c. Respond to feedback and offer changes and solutions to address questions/comments.
    d. Continue these informative and responsive channels as sensors are installed, data is collected, and residents begin to view and use the data collected.

C. An informative and responsive engagement process requires multiple channels through which the community can participate, including options that are offline and online, anonymous, and other methods to address the resource limitations that could inhibit your community members form participating in any one of the channels you set up.
    a. Providing food, child-care, ensuring good transportation access to public meetings and even stipends for smaller stakeholder engagement processes will make the engagement process more successful for all involved.
    b. For in-person or online channels, try to offer translating services and multiple language options.
    c. For digital and online tools, think about education and training opportunities to help create more access for residents who speak various languages, have varying digital literacy skills, and disabilities.
D. Documentation tracking feedback, comments, and responses is a key deliverable for community engagement processes. Using online tools or repositories may be a good option to maintain updated documentation.
    a. Work with community members to explore other non-digital options for documentation as well. If online and digital reports are the only option, think about training that can be provided to help the community know how to access this material.

2.5.2 Case Study- Array of Things Civic Engagement Process

The Array of Things Civic Engagement Report is available online and provides a full, detailed summary of public feedback and the civic engagement process (2). The case study below is a summary of the content from this report (https://arrayofthings.github.io/engagement-report.html).

Project:

Array of Things- Urban sensing project to place sensors in Chicago to measure livability factors such as climate, pedestrian traffic, air quality, and flooding. The data collected about the city will be released publicly for residents and researchers.

Project Operators:

The project is operated by the Urban Center for Computation and Data (UrbanCCD)- a research initiative of the Computation Institute at the University of Chicago and Argonne National Laboratory. The project is implemented in partnership with the City of Chicago.

The civic engagement work was implemented in partnership with the Smart Chicago Collaborative which is a civic organization devoted to improving lives in Chicago through technology with the guiding principles of technology, open, everyone, and Chicago. The organization is guided by three organizations: City of Chicago, the MacArthur Foundation, and the Chicago Community Trust.

Goals of Engagement Work:

1. Build citywide awareness around Array of Things
2. Aid the operators of Array of Things in their research to address community needs
3. Aid the City of Chicago in gathering input on Array of Things governance and privacy policies

Multiple methods to collect public feedback and create accessible modes of engagement including offline and anonymous modes:

1. Public meetings
    a. Occurred at library locations close to sensor deployments. Library locations selected because:
        i. Close to public transportation
        ii. Regularly host community programming
        iii. Are trusted, familiar neighborhood institutions
        iv. Beacons of information in communities
    b. Meeting Components
        i. Presentation on Array of Things from project operators
        ii. Community discussion and Q&A
        iii. Resources for further action
        iv. Food
        v. Spanish language support and/or support for how to sign up for MyMadison.io user account
    c. Advertisement
        i. Online
        ii. Flyers at public computing centers, coffee shops, anchor institutions, small businesses, Alderman offices, and other community organizations
    d. Documentation of responses to questions can be found here: https://arrayofthings.github.io/policy-responses.html
2. Online forms
    a. An anonymous, low-barrier channel to provide feedback
    b. PDF of the form: https://drive.google.com/file/d/0B75hXlxAwjAZNWVHVy1DaDI3bU0/view
    c. All responses can be found here: https://drive.google.com/drive/folders/0B75hXlxAwjAZeU5TN21JVVRpems
3. OpenGov Foundation tool MyMadison.io
    a. The draft Array of Things Privacy and Governance Policies was posted here. There was a 2-week online comment period where the public could post comments and edits or annotations to the document.
    b. All feedback collected in person and online during the public comment period can be seen here https://mymadison.io/documents/array-of-things-privacy-policy

Lessons Learned

1. **Informing and engaging at the same time is a challenge.** Because there was so much background information on the Array of Things to share in the public meeting, there was not much time left in the meetings to spend on public feedback.
    a. Recommendation: Undergo a wider awareness campaign to inform residents of the who, what, where, when, and why of the project before asking residents to react to it.

2. **There are trade-offs between technical transparency and accessibility.** Some commenters called for less technical language while others called for more to increase transparency.
    a. Recommendation: One solution could be to layer the public policies. Publish a transparent, technical policy that is very thorough. Also publish a second policy document with a glossary and summary points that is more accessible.
3. **It's just as important to communicate what the sensors cannot do.**
4. **Be tool agnostic when it comes to public feedback collection.**

2.6 Local Procurement Processes

Creating a sensor network will involve hardware, software, and data communication plans that are unlike previous purchases for a local municipality and involve technologies that are evolving rapidly. These elements can create difficulties for traditional procurement processes. The following discussion highlights certain issues that need to be thought through so that you can work with your procurement office to develop an appropriate procurement process for your sensor application.

The variability in sensor packages is high. The elements developed by the interdisciplinary project team for sensor selection discussed in section 2.3 should be closely integrated into the procurement process to ensure the product purchased will provide the best overall outcome. Purchases based solely on the lowest bid will not necessarily be able to meet your project's objectives due to the current state of technology for sensors and range of use cases.

An important criterion to include in the procurement review is the ability to upgrade a sensor package or modify the device as technologies change. This element could increase the price but the value it provides in terms of sustainability to produce less waste, increase the lifetime of a device, and potentially save money over time needs to have a higher value in procurement review over lowest bid.

Unfortunately, even with clearly defined sensor selection criteria, it is not a straightforward process to evaluate if a sensor package does or does not actually meet that criteria. A procurement officer performing a review would need to be able to identify what is marketing cruft versus tangible assets. If possible, project team members should work closely with procurement officers in the review process or develop an education process or material to help procurement officers navigate this issue.

Another difficulty for municipal procurement offices working with these rapidly evolving technologies is managing the much shorter lifetimes of these products versus traditional civic infrastructure. Project budgets may need additional allocations for maintenance and staff time to remove, replace, and keep track of sensor products in the established asset management systems. Project team members should also work with procurement offices ahead of time to let them know of these different lifetimes and pathways compared to other civic and technology infrastructure projects and see if it is possible to create new mechanisms for pilots.

2.6.1 Summary of Key Considerations

A. The sensor selection criteria (Section 2.3) designed for your sensor project should be closely integrated into the procurement review & selection process to ensure the product purchased leads to the best overall project outcome and purchasing decisions are not made based solely on the lowest bid.
B. Can the sensor device be upgraded or modified as technologies change?
C. Project team members need to be a part of the review process with procurement officers or create an educational process on how to evaluate the sensor selection criteria to make sure actual sensor parameters are met and marketing material does not incorrectly meet criteria.
D. Can you allocate additional funds in your project budget to help with maintenance and staff time to remove, replace, and keep track of sensor products in existing asset management systems?
E. Work with procurement offices ahead of time to discuss alternative pathways of purchasing and management for pilots because the rapidly evolving technologies in sensor networks will have shorter lifetimes versus traditional civic infrastructure purchases and contracts.

2.7 Installation Considerations

Location is one of the most important considerations for sensor deployment, after all, the technical capabilities of your sensors won't matter if they don't have access to the phenomena they're intended to measure. Equally significant are the costs of installation, and the accessibility costs for ongoing maintenance. As IoT and sensor technologies progress, there is the real possibility that the installation and maintenance costs will eclipse the actual hardware cost for your project. Having a comprehensive understanding of the sensor environmental requirements, location optimization, and location-type installation costs will ensure your project is successful and within budget.

Scoping installation costs and potential issues requires fully understanding the location requirements of your project. You will want to understand the required proximity to the measurement target, hardware durability, access and frequency of maintenance, and the requirements for power, communications, etc.

You will also need to establish what entity is responsible for installation and maintenance, and whether that entity controls available locations that fit the above criteria. If the responsible entity does not have control of those locations, you will need to determine what entity does, and establish agreements that permit their use. These access needs underscore the requirement for having strong community engagement and ensuring all stakeholders needs are considered during the planning process.

With installation representing such a large portion of the cost of sensor initiatives, preemptively creating infrastructure to host sensors during other infrastructure projects can be worth it. Many cities are adopting permitting processes for commercial small cell deployments that require the commercial entity to provide "service ports" for municipal projects that provide a mounting point, power, and communications capacity at each node of the small cell deployment.

2.7.1 Summary of Key Considerations:

A. What are the technical location requirements?
    a. Does the vendor have requirements relating to mounting, location, elevation etc.?

b. Do candidate locations have proper access to observable phenomena? Do these observable phenomena correlate with the location of the problem you're trying to solve?

B. What are the accessible locations in the context of your project?
    a. What is the Mean Time Between Failure (MTBF) for hardware you're installing, as established in a real-world deployment?
    b. If unknown, or not suitably tested to a certain confidence level, are there opportunities for pilot scale installations in easy, low-cost locations to evaluate longevity for yourself?

2.8 Data Communication and Management Plans

Proper planning for data retrieval and management is key for successful deployments. Understanding both the type and amount of data generated by your sensors, as well as the requirements of your applications will ensure that the right infrastructure is deployed the first time to operate a sensor platform that delivers value to your citizens reliably.

The first step is understanding your proposed use cases for the data, and the latency and bandwidth implications of those use cases. This will set the baseline for what your data transmission, storage, and management systems must deliver.

Next you need to understand the infrastructure and assets available to your city for communications. Does your city have a municipal fiber network? What LTE carriers does your city have existing contracts with? This is also constrained by your deployment location; what services are available at your ideal deployment points? What existing city services that require communications are deployed that you can leverage?

For data storage you can deploy to on premise city IT infrastructure, cloud infrastructure, or hybrid. How you will make use of the data and what systems already exist are important factors in choosing your storage system. If you are primarily integrating with existing systems it may make sense to deploy to the same infrastructure those systems reside in.

If you are building primarily new services on your platform, you may want to use existing standardized cloud services that will allow easy interoperation with future systems, as well as attract entrepreneurs to build new services on your platform. Your use cases and data format will dictate what type of storage you need, and what workload it is optimized for.

With careful consideration and understanding of the use case, infrastructure and expertise available, and strategic long-term goals, this data infrastructure can support projects in your city into the future.

2.8.1 Summary of Key Considerations:

A. Technical implications of proposed use cases
    a. Bandwidth
        i. What is the minimum interval you will need?
        ii. How much data does each sample require?
    b. Latency
        i. How soon do you need to know that an observed condition has changed?

ii. Do you need streaming data or are batch downloads ok?

c. Data format
    i. What metadata needs to be available in real time?
    ii. What other systems will need access to this data and with what level of context?

d. Engineering
    i. Is the deployment environment compatible with the proposed communications system?
    ii. What systems will be in place to measure the performance of the network and prove network reliability in the case of a vendor blaming the network for an application issue?

B. Policy implications of proposed use cases

a. Networks
    i. Can the data from this deployment coexist on a network deployed for other services?
    ii. If sharing a network deployed for other services, how will you ensure the necessary partners for your project have sufficient access?
    iii. What specific privacy concerns need to be addressed at the network level?
    iv. Is the application Service Level Agreement(SLA) compatible with the proposed network resource SLA?

2.9 Data Standards

Assessing the existing and developing standards before starting a sensor project can help support interoperability with other sensor systems within your community, allow for sharing and comparisons of data across communities, and enhance data integrity as technologies and systems change. Identifying the appropriate and applicable data standards for your project can also enhance data management and communications processes.

If you are planning to use the data from the sensor network for regulatory purposes, there may be accuracy, calibration, validation, or other quality assurance/control standards or protocols required by regulatory agencies to whom you will submit the data. This includes standards or protocols for assessing and correcting for sensor calibration drift over time. Because the application of regulatory data quality protocols may be resource intensive (e.g. staff time, access to a laboratory for calibration), you should apply these protocols only to those phenomena that are essential for current or anticipated regulatory needs.

There may be data representation (i.e. serialization formats) and access (i.e. application programming interfaces; APIs) standards that you can take advantage of as part of the data management hardware/software solution you plan to use and/or hardware and software solutions you will want to integrate datasets with. This can include official standards ratified by standards bodies (e.g. OGC, ISO, etc.) as well as *de facto* standards developed by government agencies (e.g. NWS Mesonet, USGS NWIS). Further, some standards are applicable to data from arbitrary phenomena (e.g. OGC SOS, OGC SensorThings), while others are domain specific (e.g. OGC SOS Hydrology Profile; OGC WaterML, GroundwaterML).

The advantage of using established data representation and access standards is that they allow for the development and use of data management, visualization, analysis, and quality control tools across members of a community. This can be especially true when using official standards, which may lend themselves to larger communities of interest. Having access to these common data management tools can drastically reduce the cost of developing your own sensor network. Additionally, contributing standards-based data management tools that you have developed to a broader community helps to build and sustain that community, which helps ensure the sustainability of your project (i.e. you won't be going it alone), and helps to ensure that sensor network data management systems evolve in ways that align with the strategic interests of your sensor network.

Next, you will need to consider how the data management solution provides data integrity guarantees for both data in motion (i.e. when being transmitted) and data at rest (i.e. when being stored). Data integrity is especially important for data that will be submitted to regulators, and for data that may be subject to evidentiary requirements of civil or criminal legal proceedings. The key question to ask in these cases is: does your data management solution allow data chain of custody and integrity to be verified by a third party?

2.9.1 Summary of Key Considerations

A. What are the best practices in industry for the type of data you're collecting?
B. Do you plan to use the data from the sensor network for regulatory purposes? If so, identify the accuracy, calibration, validation, or other quality assurance/control standards or protocols required by regulatory agencies to whom you will submit the data.
C. Are there data representation (i.e. serialization formats) and access (i.e. application programming interfaces; APIs) standards that you can take advantage of as part of the data management hardware/software solution you plan to use?
D. Are the standards for real time streaming formats the same as the batch download formats?
E. Contributing standards-based data management tools that you have developed to a broader community can help build and sustain that community and your project's sustainability.
F. How does the data management solution provide data integrity guarantees for both data in motion (i.e. when being transmitted) and data at rest (i.e. when being stored)?
G. For data to be used for regulatory or legal purposes, does your data management solution allow data chain of custody and integrity to be verified by a third party?
H. What features do the standards you adopt need to support to address your vision for future deployments?
I. Are the data standards comprehensive enough to become a policy to ensure interoperability for future projects?
J. If creating a data standard policy, is it written to allow superseding technologies to be deployed?

2.10 Data Validation

Data validation is a critical step to ensure usable data for your identified use cases or applications for sensor measurements. Lower-cost sensors can be affected by a wide range of variables including power for connectivity and communication, orientation of the sensor, temperature, and installation issues such as a loose wire. A method will need to be planned for how you will validate data initially as well as

measure and maintain data validity over time. Data validation may need to occur seasonally as other environmental variables change.

To help decide the level of validation required, you can consider the level of resistance that may occur to the decisions that are based off the data. Similar to data standards, if the data is to be used for regulatory or legal purposes, a strict level of data validation will be required and there are standard procedures you can refer to develop your methods. Community engagement strategies may also be able to help inform you of what the community would look for to understand and trust the data measurements are valid.

Leveraging relationships with research/university partners, other local or state agencies, and/or private partners to provide resources such as higher cost instruments and other sets of data may be needed for validating certain kinds of sensors such as low-cost air quality sensors. Comparing sensors to the existing forms of measurement, for example a traffic camera compared to inductive-loop counts, can be a helpful method of validation and address a common question you may get from other practitioners and the community.

If working with a private company providing the sensors, figure out a plan during contracting to make sure you have all the data needed to conduct ground-truth or validation studies on your own. For example, if using video cameras and machine learning algorithms for pedestrian, traffic, and bicycle counts and the company is not providing any type of validation or error information then you need to make sure you have access to some of the actual images with the ability to overlay the counting/detection zones on the images. Validation projects can be useful applied research projects for students as well as the data users and sensor device developers.

Planning data validation alongside data standards can also help tackle issues such as addressing drift and accuracy in sensor measurements and supporting data integrity throughout the life cycle of the data and sensors. When planning these methods, think ahead about methods of how to correct data after data validation tests are applied and what other proofs will be required for the data users and community to return the system to an operating level of trust.

2.10.1 Summary of Key Considerations

A. How will you validate the data initially, and how will you measure and maintain data validity over time?
B. What level of validation is required based on the level of resistance the decisions that are based off the data will face?
C. How will you manage situations where the data is proved to be unreliable, what proofs will be required to return the system to an operating level of trust?
D. How can you leverage relationships with research/university partners, other local or state agencies, and/or private partners to help provide data and other needed resources for validating the sensors?

2.11 Data Integration

A pitfall for many smart community projects, data integration if not properly planned for can cause cost overruns, reduced usability, delayed return on investment (ROI) and even complete failure of a project. Integration of a new data source into existing or externally scoped systems is a complex process. While immense value can be obtained from a well-integrated system, special care must be taken at the planning stage to ensure success.

During the planning process for your project, be sure to spend adequate resources scoping the data integration requirements. Ensure you know the exact level of integration and specific value streams the stakeholders are looking to unlock through these integrations.

Ensure all platforms that you will be integrating have the required features and APIs to successfully integrate into the final solution. Be sure you are connecting your integrations team with respective vendor technology teams so that you get beyond a sales executive saying yes to everything.

Some sensor platforms are better suited for specific types of integrations than others. If your value proposal has a real-time component to it, you may need to select a sensor platform that can support that requirement, based on its integration capability rather than its sensing domain performance.

2.11.1 Summary of Key Considerations

A. Who will own the process of integrating data for the final application?
    a. Does the responsible party have the required legal agreements in place to access all the data required?
    b. Will the city retain access to all data for future integrations?
    c. Do you have an agreed upon technical plan created with the vendor engineering teams before making the investment?
B. Who owns the operation of the sensor platform?
    a. Is it compatible with systems already in place in your civic technology infrastructure?
    b. Do you need a new platform, or can existing platforms be used to provide the solution?
C. Do all relevant city agencies understand the application requirements and the data integration process?
    a. Are there missed opportunities to address secondary issues by adding minimal additional integrations?

2.12 Funding

Project funding can be a daunting challenge, especially when deploying a new or unproven technology. There are many ways to fund a smart city sensor network. The right funding mechanism for your project will be determined by many external factors. This section will help you understand some of those factors, and the key questions you can ask to understand the right funding model in your community.

Public-Private-Partnerships (PPPs) are a popular model for sensor network deployments. However, much of this document warns of the importance of maintaining control of the collected data and its derived value in the public realm. Balancing this concern for privacy with a PPP deployment can be challenging, and the success will most likely rest on the sensitivity of the specific data you're addressing.

Wrapping sensor networks into larger infrastructure projects is another common tool for funding projects. These can be highly effective, representing not just a strong ROI, but actually reducing the capital outlay cost of the total infrastructure project by using a sensor network to maximize its efficiency from day one. Care should be taken to communicate exactly how the sensor network benefits the community and the project. Infrastructure projects are large and complex, and often subject to delays and cost overruns. Without a strong understanding within the community of the value the sensor network provides, it will be all too easy to cut from the project when difficulties arise.

Standalone projects are certainly possible, and if the public awareness of the problem to be solved is great enough, can be the easiest to generate support for. Successful projects will likely address an immediate need with an immediate solution, and a project narrative that citizens can clearly understand.

Pilot projects can often be easier to get off the ground than fully scoped solutions. However special care should be taken that resources are budgeted to communicate the success of the pilot to help build support for the larger funding required for full deployment. Ideally budget will also be allocated to support some amount of pivoting of approach in case assumptions made in the pilot proposal are proven false during the course of the pilot.

For any of the above funding formats, you will still need to have a thorough understanding of your network's business model; including the costs of ongoing operations, maintenance (replacement, upgrades), and lifecycle costs. While a sensor network that generates income for the city is a great asset, it's not required or desirable in all situations. The goal is to create a sensor network that delivers more value than the resources it consumes. That value can spread across multiple departments and services, and documenting that value is one of the key reasons to engage as many stakeholders as possible.

As you begin to develop a budget for your project, reducing the cost of operation and deployment is critical. While grant funding can be an appropriate source of capital costs, the operation and maintenance needs are what the community will be living with on an ongoing basis. Ensuring sustainability will require true operationalization of the resulting services and data delivered by the network, ideally from multiple stakeholders.

2.12.1 Summary of Key Considerations

A. What funding model is most compatible with the primary use cases?
    a. P3's may be appropriate for some networks and not for others, based on security, privacy and other public responsibilities
    b. Is the project ROI driven, or based on political priorities?
    c. If ROI driven, does the network need to be revenue positive on its own, or can the value be delivered through other channels?
B. Have you engaged other city agencies to determine additional value streams that can be generated by the network?
    a. Are those value streams compatible from a security, privacy and technology standpoint with your primary use case?
C. If pursuing grants to start a project, are you engaging the public and other agencies early to ensure sustainability and adoption beyond the grant-funded scope?
    a. What are the ongoing operations costs that need to be offset after the grant term?

2.12.2 Case Study: Lincoln Nebraska Small Cell Deployment

The City of Lincoln was faced with a familiar challenge to most communities in this era. With multiple wireless carriers pushing to deploy their modern small cell services within the public realm, how could the City ensure that these deployments delivered maximum value for the public, and not just each carrier's subscribers? By crafting legislation that required the permitted carriers to take on operations and maintenance costs of the public assets they were utilizing, as well as deploying communications and infrastructure for city services at no cost, the city ensured that these assets were a benefit to all citizens of Lincoln, not just the users of the carrier networks.

Learn more about this approach and find links to samples contracts, drawings of agreed on pole designs, and more at Community Broadband Networks, posted on February 1, 2017: https://muninetworks.org/content/small-cells-yield-big-results-lincoln-community-broadband-bits-podcast-238

2.13 Sensor End of Life Considerations

Lifecycle management and planning will be a key component of a successful sensor deployment, and will need special attention during the procurement process detailed in 2.6. Unlike many public realm assets, sensors, their associated infrastructure and communications hardware as well as the software systems that integrate with them are evolving rapidly. While a typical asset like a light pole or street sign may expect lifecycles measured in decades, many of these systems will not be relevant technologies within 5-7 years. It's important to understand this reality of working on the bleeding edge of technology, and the implications for deployment and planning that these much shorter lifecycles have.

Budgeting for replacement of components in your original project scoping is a key step in effective lifecycle management for a sensor network. You need to understand the direct hardware costs associated with replacing a failed component, as well as the indirect costs, such as labor, mounting materials, calibration, or any external services required to restore the system functionality after a component failure. Understanding the Mean Time Between Failures (MTBF) for the various components of the system will help you accurately model the replacement costs over the planned lifetime of the system. A detailed deployment plan will help you understand the indirect costs of installation, and eventual deinstallation at the project's end.

Aside from budgetary concerns with lifecycle management, environmental impact is an important consideration that will vary with the type of sensors deployed. Some sensors that collect physical samples will even obtain enough of the targeted pollutant that they will require special disposal considerations at end-of-life. Many sensors are made with rare earth materials that should be responsibly recycled, but may require special processes. Understanding and making provisions for those processes should be undertaken at the beginning of the project, while all the necessary stakeholders and expertise are engaged.

2.13.1 Summary of Key Considerations

A. What are the reasonable expectations for the lifetime of your sensors?
    a. What critical services will be relying on your sensor network, and how will you manage the transition to the next generation of technology at end-of-life?
B. What costs are associated with replacing a sensor, outside of the hardware itself?

    a. How will you fund the selection process for the next generation of sensors at the end of your project's lifecycle?

C. How will you ensure data integrity as you replace hardware?
    a. Are there standards for the type of sensor you are selecting that will give you confidence you can find an equivalent sensor after the original design is end-of-life?
    b. What mechanisms does your network have for managing records of sensor replacement, calibration and other integrity affecting lifecycle events?

3 Conclusions

The compiled information in this document strives to provide a robust orientation for those tasked with assessing, planning or deploying advanced distributed sensor networks in communities. Twelve project stages for a distributed sensor network were identified through two facilitated workshops in Washington, DC and Portland, OR as part of the NIST GCTC program. The discussion of key considerations for each project stage help to identify common issues and lessons learned from existing projects while challenging the reader to discover the critical aspects of their project through coordinated effort with the appropriate stakeholders, and with full appreciation for the cultural, technical and resource constraints of their community.

A recurring theme throughout this document is the absolute dependency on good communication with stakeholders, and a realistic view of the limitations in expertise and resources within that group that you should seek to augment for maximum efficacy. As the available technologies and community needs evolve, we hope that keeping this theme in mind while addressing the various considerations identified here will help support successful planning and implementation of sensor networks.

References

1. Williams, R., Vasu Kilaru, E. Snyder, A. Kaufman, T. Dye, A. Rutter, A. Russell, AND H. Hafner. Air Sensor Guidebook. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/159 (NTIS PB2015-100610), 2014 https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=277996

2. Array of Things Civic Engagement Report, A summary of Public Feedback & the Civic Engagement Process. Prepared by Smart Chicago Collaborative and the Urban Center for Computation and Data (Computation Institute at the University of Chicago and Argonne National Laboratory). Available online at: https://arrayofthings.github.io/engagement-report.html