15th Annual Conference on Systems Engineering Research
Disciplinary Convergence: Implications for Systems Engineering Research

Eds.: Azad M. Madni, Barry Boehm
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Redondo Beach, CA, March 23-25, 2017

A Smart Cities Decision Aid (SCDA) Framework

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Abstract

The potential benefits of Smart Cities (SC) technology solutions are appealing to municipalities looking to increase revenue. SC can drive revenue streams through cost reductions, and an increase in public perception that leads to population growth. However, realization of the potential benefits of a SC project is fraught with challenges for municipalities, due in part to the lack of a consistent and comprehensive methodology to evaluate project proposals. The Smart Cities Decision Aid (SCDA) framework proposes a new methodology for municipalities to pursue SC projects, in lieu of the current ad hoc process for project evaluation.

Keywords: smart cities, quality of life, internet of things, value driven design, model based systems engineering, model optimization

1. Introduction

Internet of Things (IoT) solutions rest on the extensive use of sensors. The deployment of IoT applications to make cities "smart" is no exception. Urban growth and infrastructure replacement cycles provide municipalities the opportunity to introduce new IoT technologies to replace aging and costly equipment not only for cost savings, but also to take advantage of improved quality of life for citizens with a concomitant increase in desirability and revenue for the city. The promised benefits are enticing, but the realization of those benefits is a challenge, due in part to the reality that the primary driver for design and implementation is a narrowly defined concept of cost. A deeper understanding of comparative costs and benefits is needed to facilitate successful deployment of Smart Cities (SC) IoT projects. Municipalities must target benefits that provide the highest return on investment (ROI) and be able to evaluate the technical solutions that most effectively enable these benefits. The proposed Smart Cities Decision Aid (SCDA) framework provides municipalities a tool to effectively pursue sensor deployments in lieu of the current ad hoc, cost-focused process.

In order to be able to more fully evaluate and manage the complexities of sensor applications in SC IoT projects, municipalities need a methodology that can support an analysis of alternatives and model interactions between alternatives in deployments. The methodology should not just model deployment costs, but also model how solutions impact perceived needs, culture, and quality of life for constituents of a municipality. These additional factors facilitate more comprehensive measures of effectiveness (MoE) for project proposals, providing a more complete cost evaluation than the current process of evaluating proposals based mainly on deployment cost. The new MoE should include reductions in societal costs, as well as other societal benefits achieved from deployment of technology solutions, to capture a more complete representation of overall utility.

The proposed SCDA framework offers a way for municipalities to consistently define objectives, constraints, and preferences for SC IoT projects, then translate those inputs to a common measure of utility for consistent and complete proposal comparison. The framework enables focused evaluation of feasible technology solutions that align with stated project goals through a model based relationship between cost, benefit, and utility. Additionally, the framework enables a more targeted and complete exploration into societal costs and benefits, as these elements are more difficult for municipalities to quantify and consequently are often overlooked in project decisions.

2. Literature Review

Much has been written about SC; what they are [1][2][3][4][5], methods to evaluate cities that are SC [6][7][8], as well as methods to design smarter projects [5]. There is literature available on how to implement specific technology solutions [9][10]. There are papers that present guidelines for smart growth and specialization projects such as the guide for the analysis of public investment projects [11], and a decision making support tool is in process for the Humble Lamppost large scale EU smart lighting solutions deployment [12], but there are no methods in the published literature for optimizing decisions to determine the most appropriate SC infrastructure projects for municipalities to pursue for the implementation of sensors, either for new design or retrofit to existing infrastructure in an IoT application.

3. Proposed Modeling Process for Project Evaluation

A new approach for decision making is needed to address challenges municipalities face in performing three critical tasks related to SC IoT projects:

- Understand preferences to focus research on target benefits and technical solutions.
- Limit model development scope to variables with most impact on project goals.
- Understand and quantify the full scope of costs and benefits for project proposals.

Each task should be designed and orchestrated to focus research efforts on IoT project elements that have the most impact on achieving project goals for the municipality. A major problem faced by municipalities is the overwhelming number of decisions involved in evaluating the technical solutions needed to fulfill the IoT-shaped project goals. By focusing design decisions on related variables that have the most impact on the final expected utility of a project, a municipality can concentrate limited resources on the elements that provide the most impact.

This approach offers a more quantifiable way to evaluate solutions that are more aligned with preferences and project goals, because the impact of the design on project goals is more fully understood.

3.1. Process Flow

The functional flow presented as Figure 1 is a model of the SCDA framework.

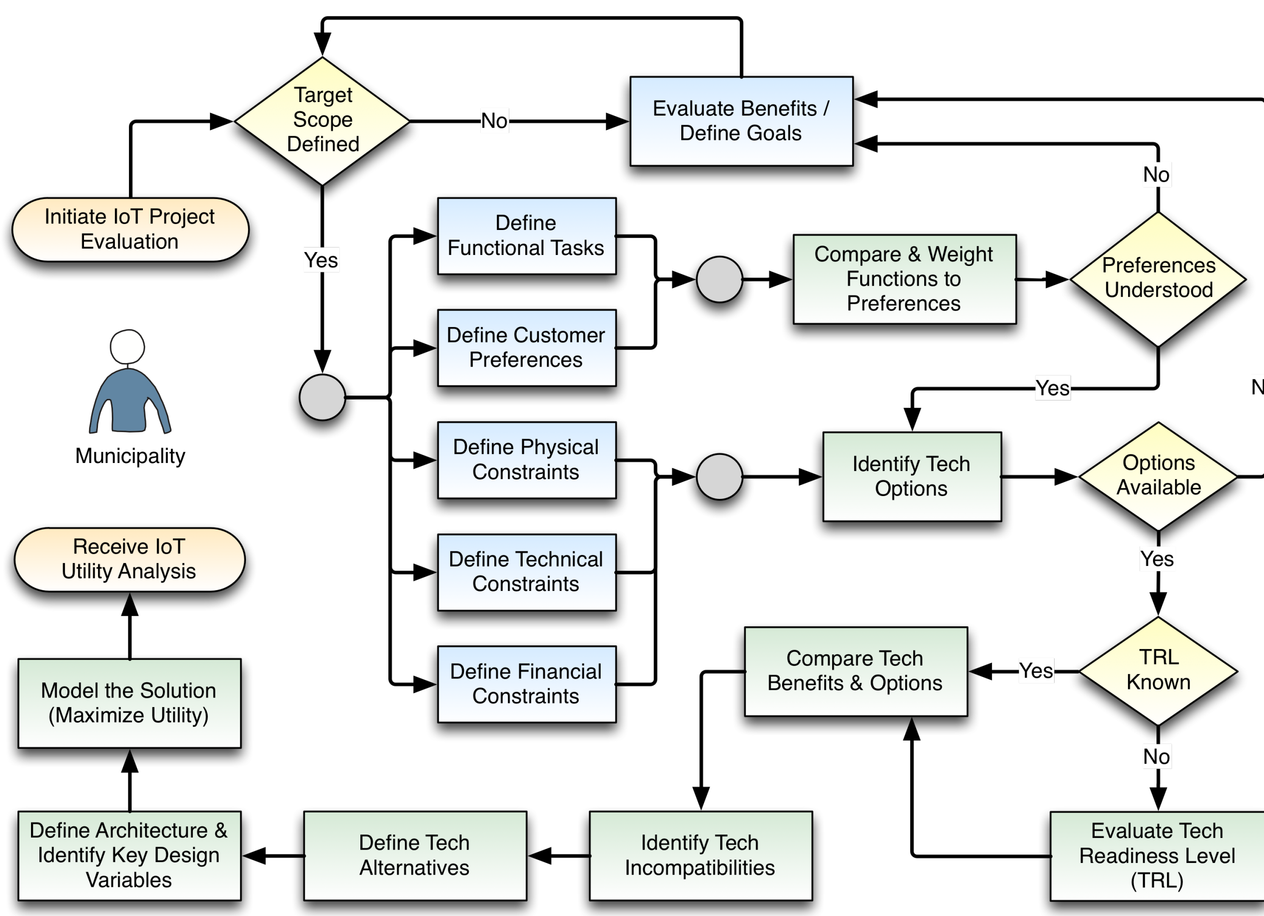

Fig. 1. SCDA Functional Flow

Prior to evaluation of any technical solutions, it is imperative to understand the objectives, constraints, and preferences of the municipality. This information is utilized to identify possible target benefits that are best aligned to produce the desired goals for the IoT project. Once the target benefits are identified, the challenges involved with achieving those benefits are derived from similar reference projects and expanded into possible technology solutions to meet the desired goals.

Instead of allowing the latest technology solutions to dictate goals of the project, the SCDA approach narrows the scope of possible technology solutions, which need to be evaluated. Systems engineering processes can then be applied on a narrower subset of technology solutions, therefore reducing the project scope and increasing the probability that the final solution aligns with stated project goals.

After identifying possible technology solutions in line with municipality goals, deeper analysis of technology solutions is performed through Model Based Systems Engineering. Exploration into benefits achieved and challenges presented by a technology solution provides data to understand the most impactful elements on project goals. To increase the opportunities for success, a project should focus on technology solutions and challenges that have the most impact on achieving the defined target benefits of the municipality. The SCDA framework provides municipalities a methodology to create more properly focused and complete models to increase the opportunity of successful SC IoT project deployments.

3.2. Layered Model Approach

Model Based Systems Engineering is a powerful process for evaluating technical solutions, but expanding the scope of models to include every design variable of a system can quickly overwhelm the usefulness of any modeling effort. The increased scope drives up complexity and cost exponentially, while simultaneously reducing the usefulness any information derived.

The SCDA approach defines MoE for models, based on identified target benefits and challenges, using a common measure of utility. This common measure of utility is expressed in financial terms, so a municipality can quickly understand and maximize the expected utility of a technical solution.

The SCDA framework is based upon an adapted version of Hazelrigg's Rational Design Framework [13], presented by Lee and Paredis as a Value-driven Design Framework [14]. Initial efforts to focus technology solutions around the objectives, constraints, and preferences of the municipality serve as inputs to models. The models are organized as layers, with each layer optimized individually, and the results of inner layers feed into the optimization of outer layers. This layered approach allows smaller, more focused models of specific solutions to aggregate into larger models that include more complex configurations and combinations of specific technical solutions in a large project deployment. Figure 2 presents the SCDA model layers with specific applied systems engineering methodologies.

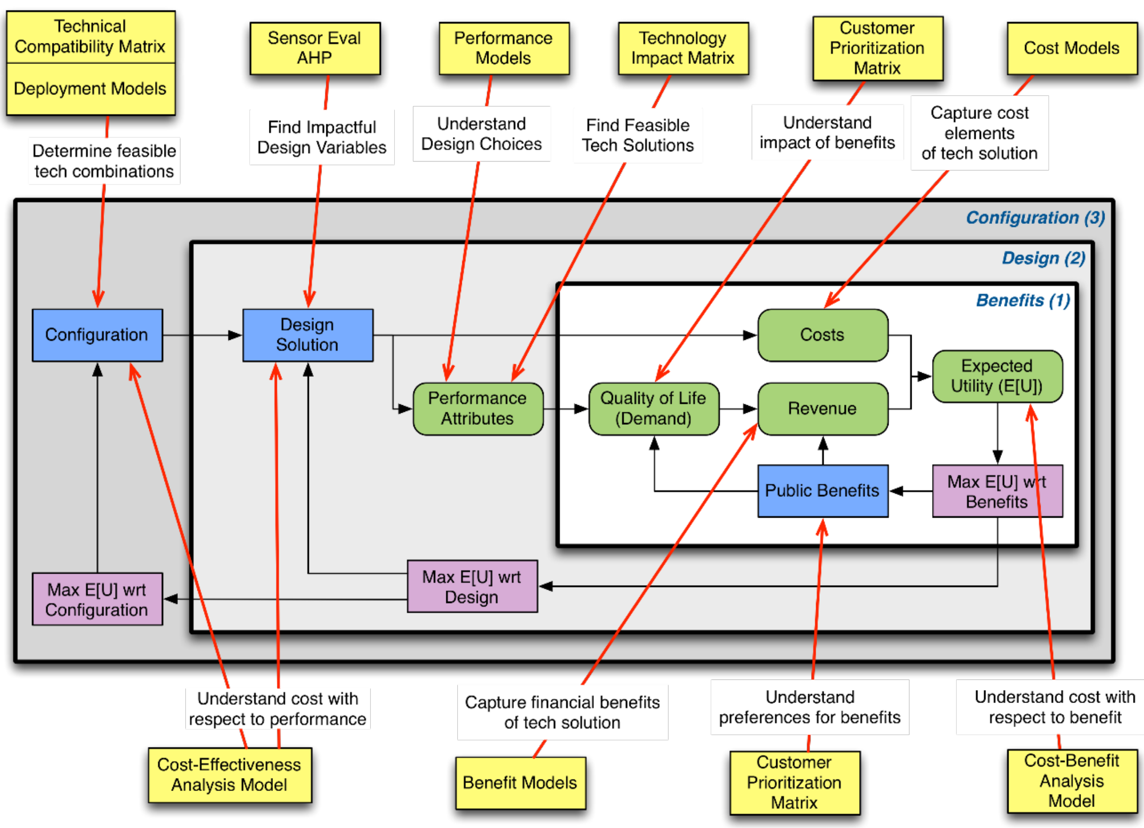

Fig. 2. SCDA Model Layers

The separation of complex logic into smaller components is not a new concept to software development, but it is a novel approach for modeling SC IoT projects. Each layer of the model is designed and validated separately, which provides a tremendous reduction in complexity as compared to modeling the entire solution monolithically.

The Benefits layer utilizes the previously identified target benefits and associated challenges, outside of influence from any specific technical solutions. The purpose of this modeling layer is to fully understand the range of costs and benefits associated with achieving a specific benefit offered by an IoT solution. The current societal and municipality costs are compared to the proposed benefits of the new solution to understand what level of performance is needed to optimize the expected utility from a specific benefit. The Benefit layer aligns with the objectives, constraints, and preferences of a municipality to provide a quantifiable way to optimize expected utility from a specific benefit offered by the concept of a particular IoT solution. This optimization process allows municipalities to rationally determine which target benefits best align with project goals and provide the maximum expected utility.

After target benefits are identified in the Benefits layer of the model, the Design layer is utilized to understand the technical solutions that support achieving the target benefits. Specific technical solutions are evaluated with cost-effectiveness models to understand the cost required to meet a desired level of performance. While the Benefits layer of the model is optimized based on the cost-benefit analysis of specific target benefits, the Design layer of the model is optimized based on the ability of a specific design to meet the performance requirements of the target benefits analyzed in the inner Benefits layer of the model. This approach allows a more complete understanding of the costs to achieve a performance target defined by the Benefits layer, which creates a feedback loop for more complete evaluation of proposed target benefits.

The Configuration layer aggregates multiple target benefits, and multiple technical designs aimed at supporting those target benefits, into an aggregated deployment configuration. Models of the Configuration layer explore the deployment densities, technology combinations, and configurations of different technology solutions to optimize overall expected utility for the project. Without this layered approach, a full evaluation of benefits aligned to preferences, technical solutions aligned to benefits, and configurations aligned to technical solutions would not be feasible for a municipality. The complexity of creating a monolithic model to capture and coordinate many different modeling aspects could possibly overwhelm a municipality and lead to project decisions misaligned with project goals, therefore putting project success at risk.

4. Model Details of Proposed Approach

4.1. Deriving Total Cost

Total Sensor Cost is determined by relating annual operational costs to an *Equivalent Annual Cost*. This is multiplied by the sensor's expected lifetime and combined with one-time total lifecycle costs. These calculations should include weightings to account for uncertainties and risk.

$$Sensor_{Cost} = Cost_{\text{lifecycle}} + Cost_{EAC}$$

Societal Costs affected by sensor installations should be identified. These may include such factors as legal personnel, lost productivity, insurance costs, personal injury, emergency response station density, taxes, property prices, privacy, traffic or healthcare. If gunshot detectors are shown to reduce crime, then it is logical to assume that other societal costs related to crime will also be reduced. This difference in the new societal costs from an established baseline is what the SCDA program refers to as the *Societal Benefit*. A reduction in societal costs from a technology deployment will be characterized as a benefit to a municipality in the overall project evaluation.

$$SocietyBenefit = \sum^{i} (SociertyCost_{Baseline})_i - (SocietyCost_{Improved})_i$$

The proposed modeling method results in higher financial returns on SC sensor installations than the immediate ROI would indicate. Sensors are used to positively affect a community's health in a variety of ways. To realize the total effect of a large sensor installation, the *Total Cost* is determined by summing the *Sensor Cost* and the *Society Benefit.*

$$TotalCost = Sensor_{Cost} + \ SocietyBenefit$$

By searching for the lowest *Total Cost*, the modeler can determine which solution, if any, is most cost effective. This process also exposes additional benefits that can help justify a new project. In one example, the SCDA team found that a gunshot detection system would cost \$3.2M to install and \$3.4M annually to maintain. Even with this considerable cost, it was possible for the municipality to save \$56M per annum. The additional revenue associated with the system was realized not only through cost reductions associated with fewer crimes and less demand for emergency healthcare, but also through an increase in the public perception of safety, which logically will lead to population growth and increased tourism.

The Cost-Benefit Analysis (CBA) model pulls together the previous cost and benefit models into one final evaluation of total utility as the benefit of various technology solutions in financial terms. Within the context of a specific target SC use case, the modeled utility can be optimized in the Benefit layer to understand which related benefits provide the most utility for a municipality. The utility can also be optimized at the Design layer, to understand how different design variables impact the performance as well as the cost of a technology solution, which ultimately impacts overall utility.

It is possible to perform a CBA on each technology solution, or to abstract to an outer model layer and perform a CBA on a combination of technology solutions working in concert in a solution configuration. Different configurations of technologies and deployment options may yield different overall utilities based on the technology interactions and compatibilities.

Optimizations at the Benefit, Design, and Configuration model layers are performed through simulations that explore a trade space and account for uncertainty elements in various models. The optimized solution is then evaluated to understand the overall utility gained, which provides the overall benefit a municipality will receive for the project with respect the cost to achieve that project. Maximizing for overall utility will allow the municipality to identify the best project option(s) to select.

Several software products are available to develop supporting models and execute simulations. In a reference project the SCDA team used Phoenix Integration's ModelCenter optimizing algorithm to converge on an optimal solution by seeking the minimum *Total Cost* for the proposed sensor configuration being evaluated. ModelCenter returned an exact number of gunshot detectors, cameras, RFID sensors, and LEDs to optimize utility. These values represent the point where additional sensors are not worth the additional cost. While additional gunshot detectors per block may marginally reduce crime, *Society Benefit* integrated with *Sensor Cost* can show the diminishing returns economically. The final numbers were then compared to third party data for validation of the proposed solution.

4.2. Quantify Public Perception

4.2.1. Concept

Since consumers are the constituents of a municipality, the demand for living and working in the municipality is related to public perception. Several groups [15][16][17] have made attempts to define a qualitative measure for public perception. In some instances, the describing term utilized is "Livability Index" and in others the term "Quality of Life" is preferred. For the scope of this discussion, the term Quality of Life (QoL) is used to refer to a quantitative measure of public perception.

In general terms, QoL is derived from a set of influencing factors, each defined by calculation criteria. The influencing factors, or measures, are aggregated into specific indices relating to different facets of public life. Finally, the separate indices are aggregated into a total QoL index, which provides a quantifiable way to understand and represent public perception. This measure can then be evaluated to understand impacts specific SC projects will have on public perception, with the ultimate goal of providing a more understanding of the total benefits derived from a SC project.

4.2.2. Process

The objective of the proposed process is to understand the Benefits, Design, and Configuration model layers to derive an optimal utility and identify a preferred project proposal. The solution that provides optimal utility may not always maximize the possible benefits, due to constraints and cost-effectiveness targets. The optimal solution may not require maximum performance from a technical solution, as the cost to achieve that higher level of performance incurs diminishing returns. The balance point between the cost-benefit and cost-effectiveness models identifies the target level of performance and cost for a technology solution to optimize overall utility from the solution. This target level of benefits to achieve optimal utility is referred to as the benefit scaler in the SCDA framework.

The concept of a range of possible benefits can be modeled using distributions. The SCDA framework utilizes public opinion, derived through various channels, to identify a prior belief as to how a SC technology solution will impact public perception for a particular use case. The benefit scaler provides an opportunity to update this prior belief, and further refine our analytical model representing public perception derived from the benefits incurred from the solution. By providing a scaled level of benefits, the SCDA framework can proportionally scale the public perception that could be derived from the maximum benefit of a technology solution. This scaling provides a consistent methodology to adjust and align the calculations used to calculate QoL with the technology solution selected based on the proposal that maximizes utility.

4.2.3. Continuing Research

A quantitative measure to evaluate the impact of SC projects on public perception is an extremely important component for a complete representation of costs and benefits for project proposals. While the introduction of a notional QoL index is helpful in improving the models used for project evaluation, a more valuable measure would be a direct financial measure. A financial measure could be combined with *Total Cost*. The addition of the QoL measure into the total costs equation would increase the ability of municipalities to more easily understand the impact of public perception in financial terms.

Research from Albouy and Lue [18] suggests that it is feasible to understand QoL measures in financial terms, through the willingness to incur higher costs of living for a higher QoL measure. The challenge to this research is that the definition of public perception is very dependent on preferences, and therefore very localized to groups with similar preferences. The research performed by the SCDA team found that correlations between the cost of housing and a QoL index can be strongly correlated in controlled groups, but the strength of the correlation breaks down with larger sample populations.

One unique approach to this localization problem is provided by the Georgia Tech Center for Geographic Information Systems (CGIS) in the "Atlanta's Neighborhood Quality of Life Project" [16]. This project utilizes Neighborhood Planning Units (NPU) as a way to group different sections of Atlanta residents in ways that are more aligned with preferences than legal borders. The project also evaluates socioeconomic factors of unemployment, education, poverty, and income to further identify populations that may be more aligned with QoL preferences and decisions. By using a localized approach and aggregating sections of a population that share common preferences it becomes more feasible to translate a QoL index into a direct financial measure.

Further research into the data and process used to calculate QoL indices is warranted to allow tighter integration of QoL measures into the total cost representation proposed by the SCDA framework. The ability to merge these concepts will provide municipalities with another directly comparable measure to assist in evaluation of SC project proposals.

5. Conclusion

The SCDA framework presents a methodology for municipalities to evaluate potential large scale SC IoT sensor deployments based on optimized utility. A consistent process for identification and focused evaluation of technical elements that are most aligned to preferences is a key benefit of the SCDA framework. The layered model approach allows for a more integrated and comprehensive evaluation, while at the same time reducing complexity and focusing on the elements with the greatest impact on project success. The SCDA framework integrates societal costs and benefits in a quantifiable way in contrast to standard deployment costs. This more complete representation of costs and benefits is critical to fully understand the expected utility, and eventually the attractiveness, of a proposed SC IoT project. To proceed, further research into understanding how QoL indices represent public perception, and how SC projects influence public perception can be explored. The addition of QoL measures in financial terms will provide even more information to assist municipalities in making sound, consistent, and comprehensive decisions in SC IoT project realizations.

Acknowledgements

(*) This article summarizes a Capstone project, centered on the City of Atlanta's Smart Pole Initiative, realized under the direction of Dr. Margaret Loper, Chief Technologist of the Georgia Tech Center for the Development and Application of Internet of Things Technologies (CDAIT), within the Professional Master's Degree in Applied Systems Engineering (PMASE) program at Georgia Tech. The full graduate team participating in the Capstone project included: Christopher Byrd, Ryan O'Keefe, Cheryl Emerson, Bryan Ripple, Brett Thompson, David Kundinger, and Toshir Livingston.

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