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# Enhancing the Replication Potential of Smart Lighting Projects

**Madis Talmar *, A. Georges L. Romme and Rianne Valkenburg**

Department of Industrial Engineering & Innovation Sciences, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands; a.g.l.romme@tue.nl (A.G.L.R.); a.c.valkenburg@tue.nl (R.V.)
* Correspondence: m.talmar@tue.nl

**Abstract:** To address major threats to the sustainability and quality of life in urban settings, many municipalities have started exploring routes toward smarter cities to, for example, lower their energy consumption and carbon footprint. These explorations, in the form of living labs or other pilot projects, often suffer from major problems in scaling up the initial try-outs. In this study, we identify the mechanisms that facilitate the diffusion of smart city solutions, which are developed with public funds but typically lack dedicated resources to spur the diffusion of these solutions within the same municipality as well as toward other municipalities. We introduce the construct of *embedded replication potential*, defined as the capacity of an original project to be either scaled up locally or replicated elsewhere. Subsequently, empirical findings from a study of smart lighting projects in several municipalities in northwestern Europe serve to develop a checklist-based tool for assessing the embedded replication potential of an initial project. This tool can also be used to assess the replication potential of other smart city projects.

**Keywords:** smart city; living lab; smart lighting; sustainability; replication; replication potential; energy efficiency; social mechanism

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## 1. Introduction

Challenges such as climate change, resource scarcity, energy security and greenhouse gas emissions threaten the overall sustainability and quality of life in European cities [1]. To address these challenges, many cities have started exploring routes toward "smarter" cities that would, for example, lower their energy consumption and carbon footprint [2–4]. However, these exploratory exercises, in the form of living labs or other pilot projects, tend to have limited impact [5,6] because major problems arise in scaling up these initial tryouts [7,8]. In this study, we seek to develop an in-depth understanding of these barriers.

The empirical part of this study draws on a European project on developing and replicating Smart Lighting (SL) solutions. An SL solution is an integrated system for lighting, built up of both software and hardware components of different solution providers. The "smart" dimension of SL refers to interactive functions that utilize feedback from user inputs and integrated sensors to manipulate the produced light output and thus also eliminate the need for manual controls and switches [9]. Prior work in this area demonstrates that SL systems can provide overall savings of up to 80% compared to traditional streetlights [10,11]. Whereas SL can also be used within (private or public) buildings [9], we focus here on SL systems installed in public areas, such as streets and parks [11].

In this paper, we aim to identify the mechanisms that facilitate the spread of innovative SL (and more broadly smart city) solutions in public urban spaces. We define the capacity of an original project to be(come) either scaled up locally or replicated elsewhere as its *embedded replication potential*. In this respect, we seek to identify the managerial and socio-political factors that can increase the embedded replication potential of SL projects, focusing especially on the replication potential among small- and medium-sized municipalities in northwestern Europe. As such, we focus on the non-technical dimensions of enhancing the replication potential of SL systems, and also because an extensive body of knowledge about the technical aspects of these systems is already available [10,11].

In this article, we present the results of two cycles of research conducted to identify factors that can improve the replication potential of SL (pilot) projects. We first review various relevant branches of literature to infer a set of design principles for increasing the embedded replication capacity of SL projects. Subsequently, an empirical inquiry among potential follower municipalities and a range of technology suppliers and industry experts, in the context of a European SL project, serves to validate and extend these design principles. As a result of these two cycles of research, we construct a checklist-based tool for (self-)evaluating the embedded replication potential in initial (smart city) projects.

## 2. Theoretical Background

This section explores two relevant viewpoints on upscaling and replication. We draw on the field of transition studies, which seeks to understand the socio-technical aspects of upscaling an innovation. In addition, the field of management studies has a long tradition of analyzing the upscaling potential of novel innovations from organizational and market perspectives. These two perspectives are complementary in performing an analysis of the (embedded) replication potential of smart city solutions.

Before turning to these two perspectives, we first define upscaling and replication. *Upscaling* is typically defined as expanding, adapting and sustaining successful policies, programs or projects in different places to reach a greater number of people over time [12,13]. This definition assumes a spatial dimension, that is, "spatial scaling up refers to enlarging projects, practices, or programs geographically to reproduce the benefits from one locality in another. Reproducing a project that has worked in one district should bring similar benefits to the next district. However, there may also be important externalities that will not be achieved in full unless there is national or widespread ownership" [14] (p. 17).

Within this general framing, various types of upscaling can be identified: quantitative, functional, political and organizational upscaling [12]. Quantitative upscaling is the geographical spread of the innovation to reach more people in the same context [15]. This type of upscaling usually involves the replication of programs in nearby areas or expansion for reaching a larger number of people in the same area [16]. Functional upscaling refers to expanding the scope of the activity. Political upscaling is explained by expansion of the focus to widen the political process through which the projects operate, while organizational upscaling is about expanding the institutional base of implementing the intervention, which is achieved either by expanding the institution itself or by engaging other institutions [15].

Building on these conceptual distinctions, Kohl and Cooley [17] suggest that scale up, replication and spontaneous diffusion are three distinct concepts: they define upscaling as the expansion of a pilot within the environment that it was originally developed in; replication as the type of scaling that is done beyond the original environment (e.g., a pilot project or the organization(s) involved in the experiment); and spontaneous diffusion as the proliferation of positive outputs and practices on their own. Similarly, Pelling [18] defines replication as the horizontal reproduction of innovation through multiple small experiments; upscaling as the spread of the innovation experiment as it attracts more participants; and mainstreaming as the innovation turning into dominant policy and practice.

Despite these conceptual differences, *both* replication and upscaling are desirable targets for smart city projects. In the remainder of this paper, we draw on the concept of embedded replication potential as a property of (part of) an original project to be upscaled and/or replicated. In this respect, the term *replication* will be used as an inclusive construct, one that refers to both replication (in a strict sense) and upscaling.

### *2.1. Replication in Transition Studies*

The sustainability transitions (ST) literature suggests that a key element of upscaling potential is the design of the pilot stage [19,20]; that is, pilots should "be designed in such a way that they could be scaled up, if successful, and so that key factors which will be necessary for a scaling up decision (with what dimensions, with which approach, along which paths, etc.) are already explored during the pilot phase" [13] (p. 16). Smart city experiments especially appear to vary in their potential for upscaling. As such, experiments with a high level of local (e.g., neighborhood) specificity may be more difficult to replicate, compared to, for example, intelligent traffic systems that are inherently designed to be scaled up [7]. Thus, many smart city experiments are very context-specific, which itself makes the assessment of both the relevance and potential performance of the solution in other contexts difficult [21], and this consequently limits their broader implementation.

A key problem here is limited representativeness: that is, the design, conditions and results of pilot projects are often hardly applicable to new projects, and therefore the usefulness of pilot projects at other sites can be questioned [22]. Moreover, replication and social inclusion are strongly intertwined: a major deficiency in social inclusion (e.g., of citizens) can significantly hamper the replication potential, since the stakeholders at the new site may not recognize the features of the original solution [22].

### *2.2. Replication in Management Studies*

In the management literature, upscaling is about increasing the economic activity of a company. A pivotal notion here is the concept of economies of scale [23]. Achieving economies of scale creates an advantage by reducing the fixed costs per unit and also frequently the variable costs per unit. This is important because lower costs on the supply-side of a market tend to increase the overall adoption rate by demand-side agents [23].

When it comes to the economies of scale in smart city (e.g., SL) public infrastructure, an important factor is the level of customization required to satisfy the needs of specific municipalities. Here, the property of *fungibility* refers to a technological solution being re-deployable in more than just a single context [24]. Suppliers have a key interest in maximizing the fungibility of their offerings so that they can reach high economies of scale as soon as possible. Meanwhile, the supplier's incentive toward customization and fungibility can be counter balanced by the specific nature of experimental opportunities: for example, a national government may grant subsidies to municipalities, but only if their (smart city) solution involves a significant novelty which may, in turn, motivate suppliers to respond to a very specific market segment rather than the entire market for these solutions.

As a response to diversifying customer needs, supply-side offerings are increasingly integrated into modular systems [25]. One prominent way to exploit the benefits of modularity is to use it as a key design feature in a technological platform [26,27], making customization of individual components and subsystems less necessary. In turn, this allows component suppliers to further specialize and develop higher economies of scale, while spending few efforts in integration, which is (semi)automatically performed by the modular nature of the platform [28]. Upscaling can therefore be achieved by either individual organizations attempting to increase their own economies of scale or a network of organizations involved in a modular infrastructure. Both are relevant for analyzing the embedded replication potential of smart city projects.

### *2.3. Decision Criteria for Adoption by Municipalities*

A rather unique aspect of smart city projects is the institutional logic of the adopting customer: while smart city applications are predominantly used by citizens, their adoption is decided by municipal bodies acting as gatekeepers. In this respect, the policy analysis framework of Loomis and Helfand [29] suggests that public decision making is done by measuring and evaluating a proposed innovation along six (categories of) criteria:

- *Social and cultural acceptability*—the extent to which the innovation resonates with the aesthetical appeal and current values of civil society and, therefore, does not invite possible opposition. In the case of SL applications that often are geographically bounded (e.g., at the neighborhood or street level), an important dimension of acceptability is the direct perception of the application by local inhabitants, also including possible concerns about privacy, data management and other back-end aspects of urban installations.

- *Economic efficiency*—the extent to which the innovation produces sufficient (monetary and non-monetary) benefits for the municipality over its costs. In an efficiency analysis, a comparison can be made with the internal features of the project (e.g., by calculating the monetary payback time). However, an important point of comparison also involves measuring the proposed innovation against the status quo and/or alternative interventions.
- *Distributional equity*—the extent to which the innovation could disturb the prevailing distributional balance in the (respective neighborhood of the) municipality and, therefore, produce winners/losers. Innovations associated with a rise of inequality in living standards may especially be viewed as problematic and give rise to public discontent.
- *Operational practicality*—the extent to which the innovation can be embedded within the current municipal administration, and, therefore, is administratively more or less feasible. In the case of SL projects, this may, for example, imply that the total number of non-integrated applications needs to be severely restricted.
- *Legality*—the extent to which the innovation would conflict with present laws and regulations. For SL applications in particular, this criterion concerns procurement regulations, privacy regulations and operational safety regulations.
- *Inherent uncertainty*—the extent to which it is uncertain whether the innovation will create the assumed benefits against the expected costs. Inherent uncertainty, therefore, refers to the level of confidence that municipal staff and other stakeholders have regarding the evaluations on each of the previous five criteria [29].

## 3. Methods

The aim of this study is to design strategies and processes by which one can ensure that an (e.g., SL) project is already embedded with future replication potential in the design phase. This is a major challenge because replication can provide significant additional resources as well as economies of scale, which reduce the costs and risks of SL applications for all major stakeholders. In view of the design-oriented nature of this challenge, we adopted a design science approach. *Design science* serves to create prescriptive evidence-based knowledge [30]. It entails employing (theoretical) knowledge and methods to create situations that yet do not exist or, alternatively, change existing situations into more desirable ones [31,32].

In a general sense, design science seeks to connect relevant research outcomes (e.g., from social science research) to the implementation of associated knowledge in practice, so that knowledge flows between these two often disconnected domains are significantly improved. Design scientists seek to improve these knowledge flows with a two-stage approach, involving the development of *design principles* as guidelines for designing real-world interventions that apply to a broader class of similar situations/problems and the development of *design solutions* as context-specific guidelines/tools/artifacts which can assist practitioners in applying the underlying knowledge to their own challenges [32,33].

By applying a design science approach, the first aim of this study is to determine the underlying factors and mechanisms that contribute to replication processes, which themselves have roots in different fields of research [21,34]. As such, composing an initial set of design principles (or design propositions) for designing a successful replication process requires reviews of various distinct literatures. These initial principles are specifically formulated for the replication of (public) SL solutions developed in original projects and transferred to subsequent (follower) projects. This is the first cycle in this study.

In the second cycle, we explore and scrutinize the empirical applicability of the theoretical knowledge obtained by drawing from both the demand and the supply sides of the public lighting market. Here, we focus on empirical work within and outside a specific project consortium (set up to develop and replicate smart lighting solutions in several

European cities) to identify the extent to which the design principles developed in the first cycle hold up against data collected from various stakeholders involved.

Finally, we synthesize the findings of both cycles in the form of a tool for measuring the embedded replication potential arising from a given smart lighting project. Appendix A provides a detailed overview of the methods for collecting and analyzing data in both research cycles.

## 4. First Cycle: Design Principles for Embedded Replication Potential

This section summarizes the outcomes of the first cycle in this study, resulting in the creation of an initial set of design principles. From an extensive literature review, we derived 11 principles that each prescribe conditions that can be embedded in a new SL project to enhance its potential for replication. Whereas replication assumes certain conditions on both the demand and supply side of the market, it is ultimately decided by demand-side (non)adoption decisions; we therefore linked each of the conditions with the six decision criteria identified earlier: social and cultural acceptability, economic efficiency, distributional equity, operational practicality, legality and reducing inherent uncertainty [29].

### *4.1. Aligning System Value to Demand-Side Priorities*

New innovative products often require substantial (upfront) investments by adopters to achieve major gains such as improved energy efficiency or enhanced quality of life. As such investments are often associated with high costs, the decision to allocate resources may involve numerous factors that can hinder the adoption decision. A crucial element in various models that explain new technology adoption is adopter perceptions [35–37]. The *perceived usefulness* here is the subjective expectation of adopters that the application of the technology would help them achieve a certain goal; a technological solution is therefore more viable if the adopters have a positive perception of the usefulness of the offering, which means it matches their expectations. In other words, the adopter's intention to employ a technology is directly affected by its perceived usefulness [36,38].

The most common goals of municipalities in adopting new technologies are increased economic efficiency, reduced carbon footprint, enhanced public safety and improved social and cultural cohesion of neighborhoods [29,39]. In the context of a smart city proposition, this means that if this proposition helps municipalities achieve these generic goals (shared by many municipalities), the solution is more likely to be adopted and replicated. This implies the following design principle (DP):

**DP 1:** The more the municipality recognizes the immediate value arising from the properties of smart city (e.g., SL) solutions in terms of its current priorities and goals, the more likely it is to consider and adopt these solutions.

### *4.2. Involving Citizens in Solution Developing and Diversifying the Offering*

There is a growing interest in interactive innovation processes that take into account multi-actor networks [37,40], especially those actively including end users [8,41–43]. User involvement may take varying forms, based on the extent to which the users can take an active role and can influence decisions on the development work [42,44,45]. For smart city projects, this implies that active engagement of citizens can guide the innovation process toward better outcomes that address their needs, enhance their satisfaction level and encourage further adoption [8,46,47].

A key objective of smart city projects is improving the quality of life and creating a sustainable urban environment [48], but many projects lack an underlying strategy for the meaningful involvement of citizens [44,49–52]. The active involvement of citizens helps to develop a clearer understanding of the local context, including major problems, needs and requirements [53,54]. Theories of user-centric innovation suggest that the efficacy of user involvement largely depends on the scope and intensity of the interaction with users [55,56], which in turn largely depends on the resources that users contribute [57] as well as the appropriateness of the interaction tools used [58]. The interaction with the users should therefore include a variety of relevant techniques as well as direct interaction, to go beyond a superficial needs assessment by also identifying tacit needs [59,60].

Some SL contexts, such as pedestrian crossings, are more mainstream because they are rather common across many municipalities; consequently, the SL industry is likely to have already developed viable solutions. However, in other contexts, such as public parks, the needs of local users need to be scrutinized in depth; by means of need-based segmentation, the (municipal) market for SL solutions can then be divided into smaller categories of potential users sharing similar needs [61,62], to which SL offerings can be customized [63]. Active participation by citizens also helps ensure the social and cultural fit of the solution to their context [61,64,65] and thereby safeguards distributional equity [29]. We outline these findings in the following design principles:

**DP 2:** As the needs of end-users are becoming more complex and diverse, offering a broad range of citizens the opportunity to get involved in implementing smart city (e.g., SL) applications will enrich the knowledge inputs for solution development, which serves to create viable solutions that address actual user needs while safeguarding social acceptance and distributional equity.

**DP 3:** The identification of context-specific user needs enables smart city solution suppliers to distinguish their solutions from those of competitors, enabling replication in municipalities that are facing similar use contexts—in addition to generic contexts found in many or all municipalities (which are already being addressed by these suppliers).

### *4.3. Using Boundary Objects to Enable Knowledge Sharing*

A key challenge in smart city projects is that they inherently involve highly diverse actors, representing different backgrounds and institutional settings. More specifically, people with highly different backgrounds often do not have enough common "language" to effectively engage in conversations about collaboration [66]. In this respect, three types of knowledge boundaries have been identified in innovation processes: syntactic, semantic and pragmatic boundaries [67]. *Syntactic* boundaries arise from the various parties not sharing the same format (syntax) to express themselves. For example, citizens express themselves primarily in an ad hoc and verbal manner, while suppliers communicate mostly in a structured written form.

*Semantic* boundaries arise when different parties do not share a similar meaning about objects in a project [67,68]. For example, a citizen living in a particular urban site might look at this site as a bundle of aspects, such as memories of the past, daily physical interactions and personal quality of life. However, municipality representatives primarily associate this site with certain statistics (e.g., crime rate, average population age), and potential SL suppliers assess the same site in terms of the revenue potential arising from the number of light poles and other technical artifacts. These semantic boundaries are difficult to overcome, since they are strongly rooted in personal backgrounds and (e.g., job) roles [63]. Nevertheless, to successfully develop a SL project, all these perspectives need to be acknowledged and incorporated.

Finally, a *pragmatic* boundary arises when people do not share an understanding of the consequences of various interdependent artifacts [67]. For example, a citizen might not realize the technical and cost consequences of demanding a specific additional functionality from an SL artifact.

To overcome these three boundaries, all stakeholders involved have to adopt a "broader" perspective. However, many stakeholders may not be able to invest sufficient resources (e.g., time) to become familiar with the worldview of others. As such, innovation scholars have demonstrated that knowledge sharing and collaboration benefit from so-called *boundary objects* [66,69], involving abstract or physical artifacts with the capacity to bridge perceptual and practical differences among diverse actors and thereby promote cooperation [70], while still being pliable enough to accommodate and retain heterogeneous goals and points of view [65]. Boundary objects may include models, graphs, visual representations, tools and conceptual frameworks that enable different stakeholders of the project to express themselves, but also to translate their knowledge into formats that other stakeholders understand. Especially for SL applications, visual representations and narratives of use cases may serve as boundary objects [70].

Furthermore, boundary objects have been found to be particularly effective in facilitating innovation activities when several objects are used in parallel, providing a "boundary infrastructure" [69,71]. As such, an SL or another smart city project could produce a combination of boundary objects, such as area maps (of the existing infrastructure), visual representations and narratives of use cases, and a roadmap for the project. Such a boundary infrastructure can facilitate applications for initial projects in pioneering municipalities as well as support the transfer of key findings to replicating municipalities. In sum:

**DP 4:** Using a combination of boundary objects that facilitate the interaction among different project stakeholders improves the effectiveness and efficiency of knowledge transfer between parties representing different backgrounds and interests, and therefore improves the value potential of the original application as well as the likelihood of replication by new adopters.

### *4.4. Transaction Cost Reduction for Municipalities*

Transaction costs involve all the expenses incurred in organizing an economic exchange in excess of the costs of the goods themselves [72]. There are three categories of transaction costs: search and information costs before the transaction, costs associated with negotiating the details of the transaction and costs associated with policing and enforcement of the transaction [73]. In this respect, whenever many relevant details about an upcoming transaction are not known yet, one can assume that the transaction and its follow-up will incur some or all of these costs [72,73], especially when there is a substantial asymmetry in knowledge and other resources between the transacting parties [74,75].

For example, municipalities exploring the adoption of SL solutions will face substantial search and information costs, given the complexity of (e.g., the specifications of) these solutions and the relatively low level of expertise that municipal staff have in this area (compared to SL suppliers). Consequently, an SL solution is more likely to be adopted by small- or medium-sized municipalities (which, by definition, are resource-constrained) when the associated transaction costs are relatively low. These transaction costs can be minimized by, for example, bundling technological artifacts into seamless solutions, which reduces the total number of transactions required; demonstrating the results achieved in previous implementations of the system, which reduces uncertainty about potential outcomes; having municipalities that previously implemented the solution produce detailed letters of reference about their experiences with the implementation process, which increases the solution's legitimacy and reduces concerns about any enforcement issues [76]; and independent experts validating the costs and benefits of the solution for implementation in a municipality, which reduces information and negotiation costs [24,76,77]. Thus:

**DP 5:** The more suppliers deliberately reduce the transaction costs of a (e.g., SL) solution offered to a small- or medium-sized municipality, the more convenient and less costly it is for this municipality to adopt such a solution.

### *4.5. Two-Sided Economies of Scale*

Firms accomplishing larger quantities of sales compared to their competitors have lower average unit costs that enable them to lower prices and consequently enhance their competitiveness [78]. This effect is stronger if the fixed costs are large relative to the variable costs. Accordingly, the prospect of future economies of scale is a key driver of product development and pilot projects [21]. Furthermore, a pilot project that validates the initial expectation of high sales volumes creates strong incentives for the firm to sustain its involvement and raise additional resources for scaling up its operations [79].

This concept of supply-side economies of scale has been extended and reinforced by the idea that the value of an offering increases in the case of demand-side economies of scale [80]. For example, an SL system drawing on artificial intelligence algorithms can increase safety on the streets (while keeping costs under control), but the more widely this system is implemented—within the same city, other cities, the same country, and so forth—the higher the value perceived by most citizens, especially those that commute a lot across neighborhoods, cities, etcetera. Correspondingly, SL suppliers already have an incentive to create a large (potential) user base in the initial phases of development. A large user base will, over time, also create demand for complementary products and services [24]. For instance, the increasing usage of SL applications may require more sensory capabilities, therefore creating demand for new types of sensors.

Consequently, increasing economies of scale on both the supply and demand side of the market reinforce the creation of value for both sides and support further replication efforts [78]. Furthermore, in addition to improving the overall economic efficiency of SL installations, a larger installed base of variations of the same solution in any given municipality also improves the operational efficiency if the control and maintenance of all installations is set up as a shared operation. In sum, this implies:

**DP 6:** The more demand is expected by existing and new (e.g., SL) suppliers, the more likely they are to contribute to the proposed solution. With more demand, these suppliers can accomplish higher economies of scale.

**DP 7:** Municipalities are more likely to adopt and replicate an SL solution if it exploits demand-side economies of scale in further developing the solution toward higher levels of value for existing and new adopters (i.e., the municipality as buyer-adopter and citizens as user-adopters).

### *4.6. Fungibility of Innovative Components*

To create value for citizens and society at large, smart city solutions have to incorporate a wide range of product and services that span the various layers of lighting systems (i.e., infrastructure, devices, ICT and services) as well as create meaningful applications [48,81]. In this sense, an SL solution involves an ecosystem of products and services centered around connectivity. Such an ecosystem provides value if its products and services are properly integrated and governed from an operational point of view [82]. The governance approach can involve a modular architecture [24] or regulating the alignment of various modules by way of given (technological/communication) standards [25].

The downside of the steep integration of products into a larger ecosystem is that it may require major investments by suppliers to adjust their products/services to comply with the overall system requirements. With such investments, suppliers always incur opportunity costs, that is, they potentially cut themselves off from alternative ways of customizing their product/service for competing systems (e.g., implemented by other municipalities). Therefore, the ideal contribution by a supplier to a larger (e.g., SL) ecosystem is one where little or no adjustments have to be made. This property of a product/service is its *fungibility*, that is, its re-deployability to similar contexts without any (substantial) additional investments [24]:

**DP 8:** Suppliers of system components are more likely to support the replication of the entire (e.g., SL) system if no or hardly any customization is needed, that is, their components are re-deployable without (substantial) additional investments.

### *4.7. Including an Intermediary*

One key challenge in replicating SL projects in other urban settings (in the same or another municipality) is that some or all implementation roles are fulfilled by different parties [21]. This exchange of partners creates an additional problem around knowledge transfer, since some of the knowledge obtained in the initial project(s) may not be sufficiently codified (e.g., in manuals) or not be codifiable at all. The latter tacit knowledge often is critical for successful replication efforts [77].

In this respect, replication efforts can be reinforced by including an intermediary organization [83] in the consortium. Such an intermediary, for example, gathers insights from individual projects and disseminates knowledge and network contacts to new initiatives. Intermediaries are often non-profit organizations that employ professional staff operating in multiple cities and countries and across different projects [83,84]. As such, an intermediary may be well positioned to (help) assemble local consortia by connecting interested parties to each other and to previous projects. In sum:

**DP 9:** To improve knowledge transfer in the process of replication, both the original and subsequent (e.g., SL) projects will benefit from including an intermediary organization in the consortium, which serves to gather and disseminate knowledge and develop relevant network connections between the various projects.

### *4.8. Integration by Strong Leader (with Commercial Interests)*

The implementation of SL and other sustainable technologies increasingly draws on platforms in which value creation is distributed across a (growing) network of organizations, also known as (innovation) ecosystems [82,85]. In view of the need to integrate several parallel value chains into a shared proposition, the governance of such an ecosystem is rather challenging. This challenge is best addressed by a leading firm [82] that orchestrates the ecosystem by determining what value is being co-created, in what way and for whom, as well as the various roles played by other stakeholders in the ecosystem [86,87].

The existence of a strong leader enables ecosystem members to move toward a shared vision, to align their investments and to develop mutually supportive roles in the future value constellation [82,86]. Given the highly uncertain outcomes of the ecosystem [86], the leader has the rather difficult task of attracting sufficient support and resource commitments from other suppliers and complementors [88,89]. The leader also has to mobilize all participants around a strong vision of implementing and scaling up the developed solutions [12]. In an ideal situation, this vision is created at an early (pilot) stage [13,88].

In this respect, a strong and compelling vision can reduce uncertainty, ease coordination and empower the leading firm to engage and mobilize all other contributors required [90], especially in the context of scaling up the (e.g., SL) ecosystem's proposition [88]. In sum:

**DP 10:** Efforts to accomplish and replicate SL installations are more likely to succeed when there is a strong vision driving the project as well as a key orchestrator (preferably a company) that makes every effort to commit the other parties to that vision.

### *4.9. Designing Replication Coordination into the Project*

A final challenge in replicating (e.g., smart city) innovations is that, once a pilot project nears completion, its momentum tends to slow down; as a result, various participants have little motivation to pursue replication elsewhere, even if the solution appears to be highly appropriate for replication. This problem partially arises from how the principal–agent relationship between the (public) funding body and the consortium is structured [91]. Publicly funded projects typically measure the impact of the innovative solution within the (funded) project duration itself, rather than beyond it, which potentially incentivizes consortia to focus on immediate implementation instead of long-term impact.

Furthermore, Hartman and Linn [13] demonstrate that, where commercial firms have a market incentive for replication, not-for-profit and public organizations tend to move from one new idea to the next, rather than making a substantial effort to replicate successful pilot projects. This problem is reinforced in that some participants involved (e.g., intermediaries) are forced to stop engaging with (replicating) the project when their expenses are no longer covered by public bodies; as a result, the transaction costs for municipalities seeking to replicate the solution tend to rise, because part of the knowledge as well as network ties are lost. One way to avoid a loss of momentum is to plan for significant efforts in coordinating replication activities in the original project [13,91]. In sum:

**DP 11:** Replication of an original (e.g., SL pilot) project is more likely to occur if it includes structural activities in coordinating replication efforts at the interface of suppliers and potential adopters (i.e., municipalities).

## 5. Second Cycle: Main Findings

In this section, we test the empirical applicability of the design principles developed in Section 4 by studying both the demand and the supply side of the smart lighting market. This empirical work was conducted in the context of a large research program on SL in various cities in northwestern Europe. The data collected via interviews and workshops serve to identify the extent to which the design principles developed in the first cycle can be (further) empirically validated. We discuss the results obtained from the perspective of the demand and supply side in the remainder of this section.

### *5.1. Findings from Researching the Demand Side*

#### 5.1.1. Aligning System Value with Demand-Side Priorities

A key finding from the interviews and workshops conducted in municipalities is that aligning the value of the (proposed) SL system to the current priorities of municipalities may be even more important than anticipated in Section 4. First, in view of the limitations on municipal budgets, adopting an SL solution can be very desirable in terms of the long-term structural decrease in the urban lighting infrastructure. Lighting is one of the largest energy cost items for most municipalities, and therefore the reduction in energy consumption via the lighting infrastructure is a top priority for municipalities. One representative of a potential follower municipality: “We’ve got to target to reduce energy consumption and the reason for doing that is that the cost of energy is going up and the budget is going down” (municipality #D). Similarly, another municipal staff member noted that “the ambition is ultimately to save money. If you are saving energy, you are saving money, so it has to be money” (municipality #B).

Second, energy efficiency and reduction in the environmental footprint are also high priorities at higher levels of (e.g., national) government, which means that municipalities can obtain new resources for investing in these priorities. For example, a representative of a French municipality observed that “we are labelled by the French state and the regional council as a demonstrator city in the 3rd industrial revolution, which means energy transition. This gives us money to showcase the solutions for energy saving and $CO_2$ reduction” (municipality #C). Another interviewee said that the UK government has created a special funding stream for lighting projects that can earn themselves back within 7 years: “ . . . in the UK a funding stream is offered by the central government, which is what we use to retrofit the lighting; if you can produce a saving within 7 years, then they will fund you” (municipality #B). This suggests that support schemes in various countries can be tuned to measure the ultimate outcomes of SL installations, which constitutes a higher-level performance indicator than activity-based subsidies.

Third, with municipalities being increasingly scrutinized by their own residents, the legitimate use of public funds (for non-marginal changes) can be a high priority as well. Thus, for higher impact, it may be worthwhile to connect SL to other important municipal goals, such as safety or employment: “We really have to involve different stakeholders like the police and others because, if you don’t, the first request is they want more lighting because they think it’s safer. If you involve such stakeholders in the whole thinking process, it is going to help” (municipality #B). Furthermore, another representative added: “It’s a more coherent action. We have to work together with other involved stakeholders and say that everything is important, so let’s look at global lighting that contributes toward all our goals. This way the decisions we take are more legitimate and are more likely to be accepted” (municipality #C). As such, citizens may become sort of gatekeepers for accomplishing innovations that also have impact on other municipal goals (i.e., reduction in emissions and cost): “One thing is the perceptions about the system, so we’ve solved the problems not only for the municipality but also for the citizens themselves, so the citizens say yes that's now better, and on the other hand are we reaching our goals on emission and energy saving? If their answer is yes, then I think we should just go for it and replace every light bulb in the city" (municipality #F).

Moreover, the priorities and objectives set at the municipality level appear to further trickle down to specific expectations of lighting solutions. For example: "I think the ambition for [the city] is certainly to have the right lighting but when it's not required, when people aren't using it just bring it back to the minimum, that's when there are savings for us" (municipality #B); "purchasing standard solutions that are available in the market is a very good idea because the price and maintenance costs are very important for us" (municipality #B); "our ambition is a safe and accessible living environment; there are new needs for living" (municipality #I). In addition, several municipalities expect major opportunities for more sophisticated (i.e., smart) lighting solutions to transcend their existing public lighting infrastructure and generate cost savings in other budgets of the municipality: "For every Christmas we do all the infrastructure like the banners and anything like that, so what we're looking at is using the projector, so we have the snowflakes, we have a day in [the city] for races. Every time it costs a lot of money, but with a good lighting system that can support this, we can save a lot of money on this" (municipality #B).

Overall, two overarching goals appear to be shared by most, if not all, municipalities: reducing the environmental impact and decreasing the costs spent on energy usage and public lighting infrastructure. The following quote best illustrates this: "To transfer this to us as a follower city or even to extend it to any other European city, it is very important to answer these questions: for one, do the citizens actually feel a difference and accept it; second, can we save money; and three, can we reduce emissions?" (municipality #F). These overarching goals are not only useful for accomplishing any SL solution but can also be conceived as critical adoption factors. There appears to be a critical mass of municipalities (in northwestern Europe) where the replication of pioneering SL projects could take place, for example, to attract people to certain parts of the city (e.g., waterfront) with lighting ambiance, supporting commercial areas, public safety and festive celebrations.

#### 5.1.2. Involving Citizens and Using Boundary Objects

The workshop data demonstrate that citizen involvement in rethinking SL solutions was more problematic than originally assumed. Many municipal staff members appear to focus on obtaining a minimum (threshold) level of stakeholder acceptance. For instance: "they think there are going to be small steps, but at the end it's going to be a big change in their personal life so their acceptance is very important" (municipality #F); "if we tell the residents that we are going to lower the lights they will really think something and express their opinions ... if we don't tell anything they wouldn't even notice. So probably it's better not to tell too much to the residents" (municipality #H); "we want to learn how to work together with the users and other stakeholders like shop owners; sometimes it is very difficult to communicate with them and there is a conflict of interest" (municipality #C).

Likewise, municipal representatives acknowledged ample opportunities to collaborate with business owners; for instance: "we'll be talking with them to develop the proposals ... Also, how to communicate with all these stakeholders is important" (municipality #D); "I think we can ask about issues from the people themselves because when you have some regional arguments in different parts of the city it's the people there who best know what's going on specifically" (municipality #F). However, the resources and capabilities of the municipalities appear to be an important limiting factor, since several municipalities had major difficulties in facilitating the meaningful inclusion of residents. Our earlier argument about use cases serving as boundary objects is also relevant here: "But I think if we have some sort of solutions to show them [referring to the ones developed within the project], they're able to tell if this fits with their particular situation" (municipality #F). Similarly, another representative from the same municipality talked about an interest-based (as opposed to geographical) clustering of resident involvement targeting, for example, "cyclists to ask them what the problems are and what the situation is, because we're thinking about how improve the streets themselves, but it might be an additional part of the solution to help them feel safer by giving them a better lighting situation."

Overall, our data suggest a growing number of municipalities appreciate the potential of an active dialogue with residents as an important driver of adopting SL. In particular, the various follower-city workshops demonstrated that the involved municipalities benefit a lot from being presented a documentary package that includes artifacts such as use cases, possible implementation considerations, system design elements and procurement guidelines developed in comparable municipalities elsewhere. These various items, collectively referred to here as boundary objects, appear to serve as knowledge carriers between locations as well as focal points for conversations on adoption. A testament to the efficacy of such boundary objects is that the follower-city representatives became fully engaged in exploring how use cases developed elsewhere could be implemented in their own city.

#### 5.1.3. Transaction Cost Reduction and Links between Applications

As noted in Section 4, municipalities often make ambitious plans for SL applications, although it may be difficult to accomplish these plans without a systematic approach to transferring knowledge and technology from elsewhere. Beyond original SL projects, a key reason appears to be the lack of adjustments in the sales process of SL suppliers which would make adoption by municipalities more convenient. In this respect, our data suggest that the current SL market is characterized by arm's length transactions, rather than synergistic (long-term) approaches in which suppliers and buyers together build long-term relationships for mutual value creation. This market structure results in rather high transaction costs associated with adopting SL solutions; for example: "we've been thinking about doing something with the lighting here for about one year, but we don't find any answers and nobody can help us; the firms that came here to [the city] come to sell something, not to give advice" (municipality #C). A similar knowledge asymmetry was indicated by two other municipalities: "How easy was it for them [i.e., other cities that already implemented SL] to produce the designs? Were they straightforward? And did they have problems actually procuring it? How was the experience in finding the partner suppliers? Were the components available and easily accessible in the market? This is actually one of our questions/problems, how we're going to buy them. How we design it, how we purchase it, and then how we install it. They're all going to be big problems for us" (municipality #D); "we need to know the costs-benefit of the system to know which system is the most appropriate for us" (municipality #E).

Other categories of transaction costs raise issues for municipalities as well. For example, municipalities are facing substantial uncertainty about the future implications of adoption choices: "the other problem is that when we have acquired the new system, the developer adapts it to our requirements and obviously they want to pay the minimum, then it's transferred to us; we have to ensure the quality of the infrastructure and its efficiency" (municipality #B); "we want to sit with the designer to see what you can do more, especially in the shopping street ... but that's what [the grid operator] does not want to do. They only want to look at the excel file and say we have this and that and we put this on the street" (municipality #G).

Meanwhile, the municipal staff of three follower cities referred to the original project as a catalyst for transaction cost reductions. For example: "because we all have these EU regulations regarding procurement, we can look at how they [referring to original implementation cities] did it and go for the same or similar solution to give it a try; or maybe we have on one street a mixture of different solutions to test which one works, but at the end of the day we need to comply with the regulations" (municipality #F). Indeed, according to both municipalities and suppliers (discussed later), the rigidity in the procurement process appears to be holding projects back from creating new value constellations. Accordingly, learning about how other municipalities have been able to navigate the procurement process may help to reduce the transaction costs.

#### 5.1.4. Developing New Value Models at the Interface of Supply and Demand

A related finding that was not part of the design principles in Section 4 is that the fundamentally different institutional logics of demand-side and supply-side actors tend to significantly undermine progress. As mentioned in Section 4, municipalities have been developing higher ambitions regarding the functionalities of SL solutions and related services, such as: "It should be used as a platform for interactive form of advertising as well, and different things like that to generate additional revenue" (municipality #B). Especially important here is that SL systems should be open for new functionalities (potentially from other suppliers) that are not yet on the market: "if we are going to change infrastructure, it should support future needs if they are going to be added later . . . so, the system should offer some sort of ability to add other components later and it should also be compatible with a wide range of off-the-shelf components" (municipality #F); "if we are in the transition to 5G, then it's like we're now spending a lot of money and in a few years, it might not be relevant anymore; so, it should also be open to future adjustments" (municipality #E). Furthermore, one municipal representative argued that cost savings, as an important purpose of SL implementation, may be undermined if many ancillary purposes are added: "As an authority, we do not have to do that. What we have to do is go to the standard. Now obviously to do all this nice stuff, it does cost additional money. Because you got additional lighting services, which you don't necessarily have to do, costs could rise as a result" (municipality #B).

As is also evident from our interviews with suppliers (see 5.2), municipalities often find it difficult to adopt an SL system that enables higher value services alongside the structural openness of the system. A supplier commented on this as follows: "Business models are changing now. When we talk about smart lighting, normally these installations are for the government. Maybe that's not necessary anymore, maybe we as a company can say we do it for you. You don't have to pay anything for the maintenance or the structures, but we earn our money from the sensors and the cameras and that's our profit. With that profit we'll maintain your lights. You only pay for your light and we build everything" (informant #8). New business models for SL are also envisioned by municipalities: "If there is a co-investment model, to benefit both private and public it's a sort of double win, isn't it? For example, if you get the local businesses to invest and then you get sensors to give them data on when visitors come and where do they go they are interested, and certainly if you're doing that you can also set the public lighting to suit the amount of the people there, so save money for the municipality" (municipality #B).

However, there is a high level of uncertainty about whether new value models will work in practice and about how to invest in ways that enable these models to come alive. Municipalities appear to procure predominantly from system integrators, who are perceived as relatively conservative companies (e.g., by informant #1) that strongly prefer to supply particular types of SL installations, rather than installations with open-ended functional specifications. Municipalities also prefer to avoid handing over the control of infrastructure (incl. data) to residents or suppliers: "Our preference is that we would have control over the lights in the streets so that we can light the street; if there is additional light from the shops, that's fine, we can always talk to them and say, if you need a little bit of extra light, that's fine; if you don't, you can dim it down, or take it down all together. But we don't want to be dependent on them" (municipality #E). Overall, it is a major challenge for municipalities to consider and embrace new value models.

#### 5.1.5. Procuring Standard Solutions

As previously indicated, municipalities tend to prefer standardized SL products, which are perceived as beneficial for at least two reasons. The first reason is costs: "purchasing standard solutions that are available in the market is a very good idea because for us the price and maintenance costs are very important" (municipality #B). With higher economies of scale, standard products typically outcompete fully customized units, even if the integration of the standard product is somewhat customized for a specific municipality.

The second major reason for preferring standardized products is the expectation of future compatibility and interoperability, in both replacing these units and adding further functionalities. For example: "I suppose the other thing is we're looking for complementary functions. For example, we could put in noise sensors, purely as a monitoring tool for environmental noise and opposed to other uses, the other aspect would be the air quality; we're very limited in terms of what we now have in [the city]. Using the lighting platform for doing this, would be a great idea" (municipality #E). One municipality decided to limit the total number of models in use within the city: "we do everything with eight very standard lighting units. Standardized units are very important for us because it is much cheaper if they need replacement and maintenance and also more devices are compatible with them; it's very difficult when you have to maintain the LED lights if you have many different models, especially not standard models, also because of the drivers and all that stuff. So, maintenance is a lot easier if you have a few standard models" (municipality #B).

### *5.2. Findings from Researching the Supply Side*

#### 5.2.1. Aligning to Major Goals of Municipalities

The findings with regard to what makes SL offerings attractive for municipalities, reported in Section 5.1.1, can be triangulated with the data collected from the suppliers. That is, the suppliers emphasize that satisfying major goals and priorities of municipalities is an important driver of SL proposition development. For example, suppliers commented on the importance of reducing energy costs and $CO_2$ emissions: "I think this is the reason that the cities do all this, and that opens the door for us. So, if you can't save energy costs with this system, you can't any longer sell it" (informant #12); "all clients always talk about the European Union, and $CO_2$ is one of the targets that all companies have to look into because that's what the clients want; so we have to be able to solve their $CO_2$ problem" (informant #10). In targeting these goals, the basic proposition of LED lighting as a replacement for existing technologies appears to enable the realization of both major goals mentioned: "Especially LED lighting is the main driver for government to start replacing public lighting, because with that they can reduce the power usage and also reach the sustainability goals that government needs to achieve" (informant #3).

The suppliers also observed that municipality goals may extend beyond energy and $CO_2$ reduction. That is, our data suggest an ongoing shift toward adding value to basic public lighting installations; for example: "We are now in a rapidly changing environment for smart cities in general and smart lighting particularly. As things are changing so fast, more and more clients ask for not only lighting but complementary things. So, when they are spending a lot of money to change the lights, if they have a little bit more money or any ambition other than energy, they often like to have a little bit more than just that. So, this becomes a very important thing for us too as a selling point" (informant #9); "in the future, smart cities are bigger than only the lighting; I think it's smart for us to look into what's the real problem, and what we can advise and what we can innovate for this problem. Then, I think we've got the best-selling point there" (informant #10).

Conversely, at least four suppliers interviewed appear to believe that maintenance costs are not a major concern in municipalities. Here, the viewpoints of municipalities and suppliers diverge somewhat, which may be mainly due to the suppliers' short-term focus on arm's length transactions (see Section 5.1.3).

#### 5.2.2. Supply-Side Economies of Scale

Of course, suppliers greatly value economies of scale. However, SL suppliers understand that economies of scale can often not be accomplished in the short run. One informant argued that the lighting industry is not yet at a stage in which significant economies of scale can be realized, due to the diversity of projects: "We're at a point in time that many things are not clear in the industry yet and public lighting products are sometimes very context specific; so, it [economies of scale] is certainly a consideration but it's now very difficult to achieve" (informant #9); "sometimes we make decisions that go against economies of scale; for example, we did a project in Rotterdam; its sea port facilities are very special and you only find it in that place; so, we sometimes accept these special situations, also to learn more" (informant #8).

SL suppliers also expect this context specificity to be a key characteristic of their market, one that is going to increase rather than decrease: "We're generally moving toward more customization and context-specific requirements. So, yes. I agree that it's nice to have a few [standardized offerings] and just do the same thing over and over again, but I can hardly imagine it's truly possible" (informant #11). As such, customization and market segmentation may constitute trends that inhibit efforts to accomplish major economies of scale. Meanwhile, our interviews with the three largest suppliers suggest they, unlike their smaller counterparts, have a relatively stable portfolio of offerings with substantial economies of scale—especially regarding various generic elements of (customized) SL installations: "Especially from our point of view, we'll not modify the product for each individual need of the customer because it will be too expensive; however, looking at the questions that we often get about our lighting management system, customers increasingly want to have a personal modified dashboard for example. Simply stated, this is not an attractive revenue model for us, so we try to use a more generic user interface as much as possible" (informant #1).

Overall, opportunities for higher economies of scale are likely to attract suppliers, but the public lighting market is still far from being commoditized. Moreover, we expect that many suppliers are willing and able to adjust their offerings to local conditions.

#### 5.2.3. Standardization and Affiliating with Major Platforms

Many SL suppliers seek to make a bigger impact and scale up their novel SL lighting applications by affiliating their products or services with specific standards and/or technological platforms. The benefit of this approach is twofold. First, it appears to reduce the anxiety in municipalities about becoming locked into a technological solution that may become obsolete and no longer enable future extensions. As such, suppliers acknowledge the promising role of a standardized SL platform for municipality-oriented offerings (as opposed to ad-hoc integrations), one that would modulate their (existing) products/services for interoperability and also promote the development of new products and services that operate within that modular structure: "I think this [referring to interoperability] is at this moment a problem. We all want to innovate new solutions, but all the customers now say we already have this or that system, how is it possible that we can still use them if we buy your stuff. So, when it's an important buying decision for them, it naturally becomes an important consideration also for us" (informant #10).

Second, the need to affiliate with a technological platform will limit adoption to municipalities whose lighting installations align with this platform but can also boost suppliers' opportunities for carrying their products to the market. This effect is likely to increase in the future as "smart lighting is only a part of the smart city and we're certainly moving toward smart cities, so it's important to already look at the possibility of different systems working together. Especially when I'm thinking about data, they should be able to talk to each other and work with each other" (informant #8). Nevertheless, suppliers tend to assume that the future market situation will be characterized by more than just one major platform: "Standards now make it easier also for other companies to look at it, what's happening there [in an existing platform-based solution] and make a platform of their own" (informant #6); "eventually, I don't think there will be one standard, but I also don't think there will be 5 or 10 standards. So, I think two or three will become the dominant technologies which will cover say 80% or 90% market. And then the remaining 10% will be shared by niche players, which will always come to something unique for military applications or unique applications but until that time" (informant #7). This especially involves the so-called middleware layer that is at the heart of any modular architecture and coordinates the various products and services (provided by different suppliers): "So, that is let's say the holy grail in most of the projects—the middle layer that connects everything.

That is, the layer that can collect the inputs from all the system components and generate outputs to the system components. You can put intelligence in different parts of the system, but this middleware layer is more suitable for the coordinating function" (informant #2).

Moreover, until several of these platforms are developed and brought to the market, suppliers will need to adapt and customize their solutions to the needs of each municipality: "we also connect to asset management system of the cities that keep track of where the trees, are where the roads are, where the park benches are, then with specific lamp information to be extended to whether to synchronize that or not on a higher level" (informant #5).

#### 5.2.4. Developing Use Cases and Involving Residents in Project Development

The involvement of citizens and other residents (e.g., shop owners) in developing use cases is a topic on which opinions somewhat diverge between supply-side informants. Some informants (#8, #11, #12) considered the engagement of end users as a key task for the municipality and, therefore, outside the responsibility of the suppliers: "It's not always possible to involve the actual end-users. What we can do is to involve for example the city representatives but having the actual end-users especially in the public lighting is not really feasible. So, as a partner we ask the municipal administration what do you need, what is your problem? I don't have to and can't speak to all end users; the city has to make the decisions" (informant #8). Several informants also expressed the shortcomings of municipalities in this area: "If possible, yes [talking about added value services for residents], but I think the cities are now mostly thinking about just LEDs. If they can use [smart lighting systems] to improve livability, then why not, but I don't think that's what the cities are thinking about yet. If possible, maybe in 10 years" (informant #12); "the municipality needs a totally different mindset of working to identify what they really want for citizens. This is different from what they used to do with public lighting, and they can't do it behind the desk and probably not the same people in the municipality can do it. But they have to know how to talk and listen to citizens and how to define use cases. . . . My personal experience with municipalities is that they see the promise of smart lighting, however, like [city name] they want to make a jump from conventional lighting infrastructure in one go toward a fully smart lighting system that can do everything. However, they don't have really clearly defined use cases" (informant #1). This reflection also underlines the observation in Section 5.1 regarding the strong desire of many municipalities to roll out new lighting infrastructure in a short period, rather than do so in an incremental manner.

Suppliers emphasize the pivotal role of use cases and seek to support and direct municipalities in this area: "We define the quality as satisfying (and to which degree satisfying) the desires of the customers but here it's interesting to define who's your customer. I think you have to understand the city to sell your products. But, on the other hand, you need to make the citizens happy, so it's a complicated issue when you think how to satisfy your clients because you first need to define who your client is. The companies need to understand this and convince the municipalities that the involvement of the real end-users is important" (informant #12). As such, interactions with residents provide an opportunity for suppliers to generate higher value as well as increase the acceptance rates among residents: "In terms of organizational things, to involve people in the lighting for their public space is an opportunity for all these spaces but even more so when lighting gets changeable, responsive. I mean then lighting gets more attention as well. For now, lighting is something that is just there but then it becomes really something, it becomes an actor in a sense. And so, involving the people in the creation process, in the design process of such systems I think works very well" (informant #2).

#### 5.2.5. Developing New Value Models

Some suppliers acknowledge the huge potential of new value models that go beyond the municipality simply buying and paying for lighting solutions. The predominant adoption model is currently, however, the latter one: "I think this [referring to new value models] is a very important thing, but at this moment very few people think about it, so it's also less of a concern for us. Now the buyers usually have a budget that's either a subsidy or whatever, they want to buy a solution and they do. I think in the long-term it becomes more important, but now not many people think about it" (informant #11); "I think the cities have a budget, which has to be adopted by the political parties and if they agree, you have the budget and then I don't think you should bother yourself with the revenue models to overcome investment barriers. It's more for a private party, not a city, I think" (informant #12).

Nonetheless, some other suppliers believe they need to help municipalities think about new value models: "This is probably the first thing we think of. We need to make it possible for our customers to buy our products and if we can help them with innovative business models, we have to do it" (informant #8). The following supplier thinks it should orchestrate the development of a new value model, one in which "you don't have to pay anything for the maintenance or the structures, but we earn our money from the sensors and the cameras and that's our profit. With that profit we'll maintain your lights. You only pay for your light and we build everything. So, we can tell them you don't have to look into maintenance anymore" (informant #9). Here, a long-term perspective is offered by informant #3: "What you see is that in the coming twenty years you'll see a lot of innovation coming with integration with other domains and that's something municipalities cannot handle, because the knowledge is not in-house and they don't have the budget to acquire the knowledge in-house. So, what needs to be done is to start cooperating with the market." However, this may imply the need to develop new capabilities inside municipalities, as commented by informant #7: "If we can find a way to monetize the non-financial into some form of financial benefit then it is part of the equation. $CO_2$ is not a part of the financial equation, so therefore that's a tough one, otherwise yes—cities will go for the lowest hanging fruit and lowest risk. And of course, the guy that is retiring doesn't want to take any risk, so it [referring to possible interactions] will require four years and he doesn't want to have complaints from the citizens."

Overall, these findings suggest that SL projects in municipalities will increasingly feature additional value elements as well as initiatives to develop new value models. However, it is unclear which party should take the lead in the latter area. A group of collaborating municipalities appears best positioned to do so, but may lack the relevant capabilities and resources. Suppliers can be encouraged to take the lead, but only if they work with municipalities that are open to novel value models (including novel procurement approaches).

#### 5.2.6. Developing a Common Vision

Finally, developing a common vision among municipalities and suppliers is considered to be critical for future commercial success: "I think it's very important to work with the customers that are reliable and also have a good understanding of the issues and are willing to work together to address those issues. I think this is a very important thing ... but, again, it's a very difficult" (informant #11): "it is very important to have a shared vision to formulate sound value propositions to our customers; our partners should also have same interests" (informant #7). Collectively envisioning the future is also important for any initiatives to establish standards and/or modulate supply-side products and services by means of a shared platform. In this sense, suppliers appear to be well prepared to contribute to collective sensemaking and visioning at the interface of original SL projects and follower-city projects.

### *5.3. Summary*

Overall, the empirical data presented in this section can be summarized as follows. On the demand side (of municipalities), our results underline the importance of:

- aligning system values with demand-side priorities;
- involving citizens and using boundary objects;

- transaction cost reduction and links between applications;
- developing new value models at the interface of supply and demand; and
- procuring standard solutions.

At the supply side, our data suggest the following activities are critical:

- aligning with major goals of municipalities;
- supply-side economies of scale;
- standardization and affiliating with major platforms;
- developing use cases and involving residents in project development;
- developing new value models; and
- developing a common vision.

## 6. Replication Checklist for Smart Lighting Applications

In this section, we integrate the findings reported in Sections 4 and 5 to design a tool for assessing and measuring the embedding replication potential of SL projects in small- and medium-sized municipalities. The checklist-based tool presented in Figure 1 involves 14 activities and strategies that appear to be critical for original application projects seeking to improve their embedded replication potential.

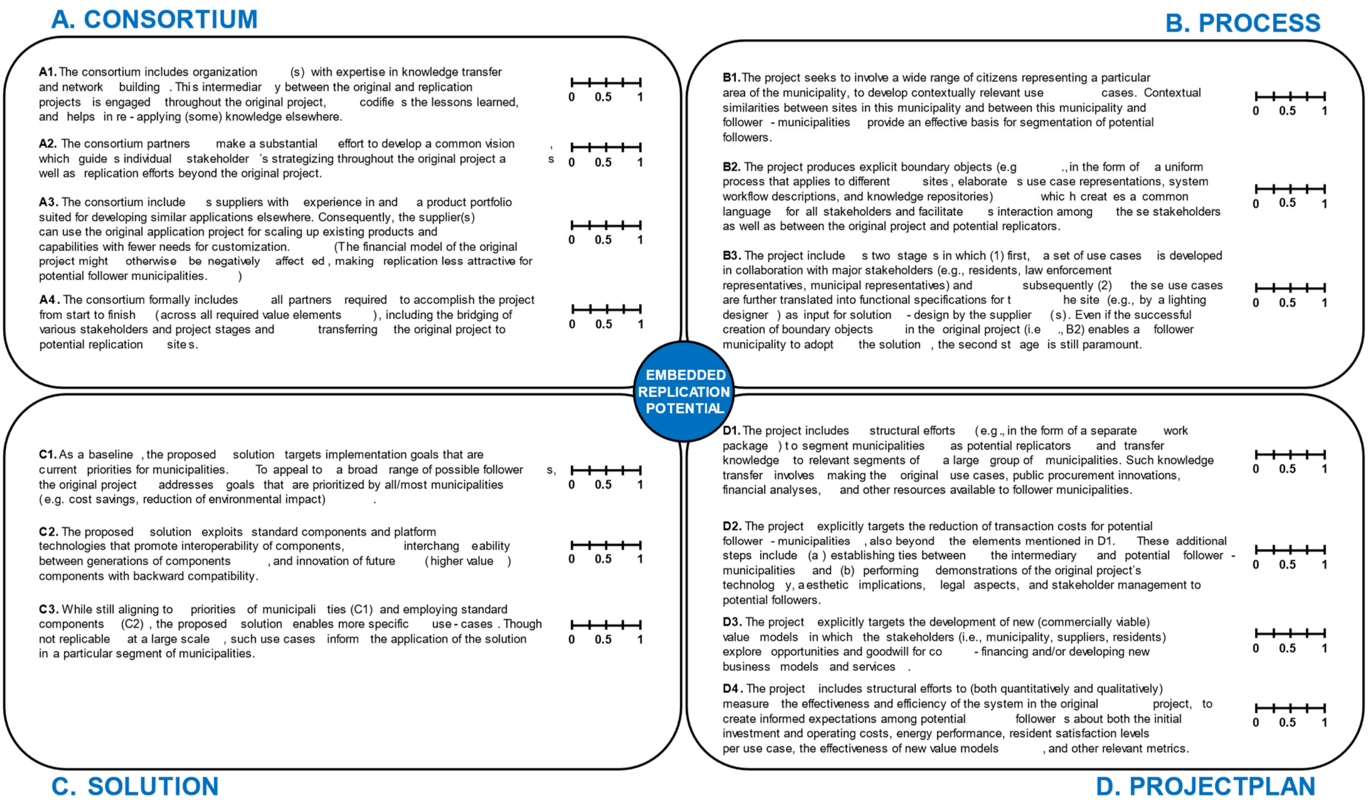


**Figure 1.** A checklist-based tool for embedded replication potential in original application projects.

These 14 checklist items were developed by synthesizing the findings from Sections 4 and 5. Design principles (DPs) 9, 10 and 11 described in Section 4 were combined with the findings in Section 5 about developing new value models (Sections 5.1.4 and 5.2.5) and developing a common vision (Section 5.2.6) to formulate four key guidelines for composing and shaping the consortium: items A1 to A4 in Figure 1. Similarly, propositions DP2 and DP4 were adapted in view of our findings on involving citizens and boundary objects (Section 5.1.2) and developing use cases and involving residents in project development (Section 5.2.4) to formulate three key process-related activities (B1 to B3) in the tool. The remaining design principles were validated and adapted in view of other findings reported in Section 5 to formulate activities C1 to C3 and D1 to D4 in the checklist.

To facilitate the usage of the checklist, the 14 activities and strategies are categorized in four key boxes: (A) consortium, (B) process, (C) solution and (D) project plan. As such, the various activities and strategies outlined in Figure 1 span both the project preparation phase (e.g., consortium partner selection and work package development) and the project execution phase, including activities that can be incorporated into ongoing projects (e.g., the creation of boundary objects). Each of the 14 items on this checklist can be rated on a scale from 0 (i.e., "not incorporated at all") to 1 (i.e., "fully incorporated").

We alpha-tested the tool in the consortium in which our study was conducted. This initial test demonstrated that the tool serves to assess the design of a (proposed or ongoing) project; it also appears to facilitate discussions about the scope of the project. Moreover, the tool can be deliberately used as a self-assessment instrument when the project owner and its stakeholders evaluate the incorporation of replication-enhancing strategies into the current state of the project. The outcomes of multiple users assessing a single project may not only facilitate discussions about the project's design but also help monitor the project's progress at a later stage. In any case, the tool serves to prevent some activities and strategies that would be completely neglected.

The tool may have a significant impact in scrutinizing consortia-based applications for (publicly funded) new SL projects. Indeed, gaining followers is key to the success of any original application project—from both an energy-saving and an environmental impact point of view.

## 7. Conclusions

The main purpose of this paper is to identify factors that can improve the embedded replication potential of SL projects. We first inferred a set of 11 design principles from a range of literatures. Subsequently, we adapted and validated this initial set of design principles and added several new insights based on an empirical study of potential follower municipalities as well as technology suppliers and industry experts. These two cycles of research together informed the development of a checklist-based tool for (self)assessing the embedded replication potential in an SL or any other smart city project.

A key limitation of this study is that the empirical work was conducted in several countries in northwestern Europe. Our findings may therefore be biased toward this specific institutional setting. In this setting, for example, energy companies play a limited role in replicating SL projects across municipalities and regions. In other institutional settings, however, energy companies may play a more pivotal role. Another limitation is that the empirical part of this study only draws on qualitative data (analysis). Future work in this area should therefore adopt methods such as controlled experiments and simulation models to develop a more robust body of knowledge on the replication potential of SL and other smart city solutions.

Our study makes two contributions to the literature. First, we developed the construct of *embedded replication potential*, that is, the capacity of an original application project to be either scaled up locally or replicated elsewhere. This construct extends earlier work on smart cities, calling for explicit replication strategies that are multidirectional, iterative and democratic in nature [8]. The theoretical construct of embedded replication potential may inform future work on applying SL or other smart city technologies. This new construct also serves to extend the existing literature on smart cities (incl. smart lighting), which primarily focuses on technical requirements and solutions [4,10,11,92,93].

Second, we developed a *tool* for assessing the embedded replication potential of a project, also in response to observations that SL projects suffer from too much ad hoc knowledge development, in which extant knowledge is transferred in highly ineffective ways between various sites—if at all [5–7]. In this respect, a substantial part of the tool described in the previous section deliberately serves to strengthen ties between the original and replication projects. As such, the developed tool can support project managers and their stakeholders to better understand the conditions required for building stronger ties with potential replicators.

Finally, the construct of embedded replication potential and the tool for measuring it may appeal to public funding agencies as a valuable approach for estimating the impact potential of any sustainability project in an urban context. This approach may work both ways. First, funding agencies can request substantial efforts in embedding replication potential in project proposals, especially those aiming to develop and apply novel technologies in use cases; this would make it easier to transfer the technology to other sites. Second, project managers that seek funding for replication activities need to engage in substantial efforts to identify previous projects and their outcomes, to subsequently transfer (some of) that knowledge to reduce the transaction costs of the replication project envisioned. Either way, the tool developed in this paper may inspire funding agencies and project owners to enhance the replication potential of their (funded) projects and thus make our cities more sustainable.

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## Appendix A. Research Methods

This appendix outlines the research methods adopted in the two main cycles of this study. Within the first cycle, the first step was to define the contextual setting and acquire a clear understanding of the problem by means of a literature review and field observations. This also involved an extensive desk review of previous SL projects and their (self)evaluations of replication potential. Subsequently, we defined the theoretical framework and an appropriate research method for the study. As a result, we adopted a design science approach (see Section 3), with its starting point being the existing body of knowledge on the replication potential of technological solutions. Consequently, we conducted a literature synthesis in which several branches of the literature on organization studies and transition studies were integrated into a set of design propositions [32,33] for embedding the potential for upscaling/replication in any new public SL project.

In the second research cycle, we focused on empirical work within a particular project consortium, involving the development and implementation of SL solutions in four small- and medium-sized cities in northwestern Europe. As the first step in this cycle, we identified and selected the key stakeholders around each implementation location. Furthermore, we sought to uncover the interests and needs of additional small- and medium-sized municipalities in northwestern Europe, as possible adopters of solutions generated within the main project. With that step, we attempted to validate the design principles developed in the first research cycle on the demand side of the market. These cities were in different stages of development and had different levels of ambitions with respect to SL and other smart city solutions. Moreover, we maintained a certain level of diversity in terms of the type of cities and their geographical location (within northwestern Europe) to capture key differences arising from specific technical, regulatory, economic, societal and ethical conditions.

As is evident in the design principles presented in the main article, there is strong support for the assumption that replication to a large extent depends on the convergence of both supply-side and demand-side actors toward a collective approach to SL projects. Therefore, alongside the workshops with follower cities, we focused on supply-side actors by actively engaging fifteen experts and company representatives from the SL industry in validating the design principles developed in the first research cycle. The involved parties included representatives of all four layers of an SL system: infrastructure, devices, ICT and services [48].

*Appendix A.1. Methods for First Research Cycle*

The first part of this study draws on an extensive review of various relevant literatures on replication (broadly defined), especially relevant studies in the field of organization studies and transition studies. Due to the dispersed nature of the literature on replication, we decided that reviewing every publication about this topic would not be efficient and therefore adopted a semi-structured review method aimed at including the most influential works from relevant research streams [94]. To find relevant studies in the Scopus and Web of Science databases, the following keywords were selected in view of the research topic and the several publications initially reviewed: upscaling, replication, ecosystem, consortia, innovation ecosystem, innovation platform and new product development. The main inclusion criterion for filtering the identified papers was their applicability to the context of SL products and services. From the studies initially identified, we continued by using snowballing, that is, using the reference lists of relevant papers to identify additional publications [95]. Overall, 54 studies were selected and included in the literature review to build a theoretical base for developing design principles (in Section 4).

*Appendix A.2. Methods for Second Research Cycle*

In the second cycle of this study, we focused on empirical work within and outside the project consortium to identify the extent to which the design principles developed in the first cycle would hold up in the face of data on both the supply-side and demand-side stakeholders. As a first step in this cycle, we identified and selected a substantial number of stakeholders at each location of the main project. At each of these locations, data on stakeholder needs and requirements were collected by means of a series of physical workshops held with residents at each location. Subsequently, eight SL use cases were developed for implementation within the consortium and then tested for replication potential in nine follower cities. In the same period, we also conducted interviews with supply-side representatives and industry experts to evaluate the preliminary design propositions (developed in the first cycle) from an industrial perspective.

Following the development of the use cases, we invited nine other cities in northwestern Europe to join as potential replication locations (referred to as "follower cities"). The municipal representatives of these cities decided to join the project to closely follow and monitor the implementation (processes) of the use cases in the pilot areas of the original partners/municipalities in the project. As such, the original SL project followed the initial design principles developed in the first research cycle, such as deliberately bringing potential follower cities into the SL project as early as possible, using boundary objects to facilitate knowledge transfer between leader and follower municipalities, and seeking to support replication of the use cases developed earlier. Multiple representatives of each potential follower city joined multi-hour workshops at each location to identify which use cases would be relevant and appropriate for being replicated and implemented in their city. Each follower municipality consequently selected two application sites in their own city, which were thought to be most relevant and attractive for implementing SL. These application sites were discussed in more detail, adding additional requirements (to be considered during the development of the SL solution).

For the data collection among supply-side actors, we used the set of design principles defined in Section 4 to compose a set of interview questions that address the current state of the SL market, the decision-making heuristics of suppliers and the current connections between suppliers and municipalities. We conducted a total of 15 interviews and workshops with SL suppliers and experts to obtain their input.

The follower-city workshops and interviews with suppliers served as the main means of validating the design principles developed in the first cycle. For that purpose, all interviews and workshops were fully recorded, transcribed and coded by means of qualitative data coding [96], including data reduction to structure and filter the raw data; displaying data to provide an organized and compressed assembly of the data, which enables the researchers to draw initial conclusions; and drawing final conclusions by synthesizing observations and interpretations. More specifically, we applied a two-step data coding procedure. In the first step, we used a provisional coding approach [96] based on the findings from the first research cycle in which the initial design principles for embedded replication potential were formulated. Accordingly, we started with a list of codes corresponding to the main constructs used in these design principles. Additional codes were added to reflect novel insights arising from the analysis of the transcripts of the workshops and interviews. The second step involved axial coding [96], in which we created themes related to the underlying mechanisms of replication and identified various relationships among those themes.

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