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Understanding replication environments – a systems research approach to smart city replication of autonomous delivery robots

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Abstract

European policymakers chose the systematic funding of smart city initiatives to incentivize and accelerate innovation and sustainability transitions. To ensure these initiatives' broader effectiveness, smart city replication has been incorporated in funding calls for research projects as a policy instrument for innovation diffusion, information dissemination and mutual learning. With a growing theoretical and empirical base for these replication activities, there is an increased awareness that integrating and transferring new ideas and solutions into the urban context requires a holistic perspective and includes various endogenous and exogenous influencing factors. This article proposes a systemic view by presenting a method for analysing the replication environment for autonomous delivery robots based on a causal loop diagram. The method is applied conceptually to a district in Munich. The developed approach, which is called Replication Causal Loop Diagram, serves as an analytical tool to generate and provide relevant contextual knowledge and information about the replication environment to facilitate the operational planning and implementation of replicable initiatives, solutions, and practices. In further development steps and in particular settings, the approach can also be a valuable addition to the replication portfolio for stakeholder engagement and consensus building.

Keywords Smart city, Replication, Urban transport, Logistics, Last-mile delivery

1 Introduction

In April 2022, the European Commission announced its selection of 100 cities to become carbon neutral in 2030. The corresponding board members stated that the mission is to put cities into a *transformative* mindset by initiating replicable and scalable activities. Additionally,

the projects should also have an inspiring effect on other municipal decision-makers [1]. Urban transformation has been a key element in achieving decarbonization goals at the EU level. Due to their high density, cities are well suited to achieve sustainability goals through systemic changes based on technologies, new policies, and behavioral incentives [2]. Therefore, European smart city projects, activities and funding have been aligned with this objective. This means that new technologies should support the diffusion and adoption of system innovations in areas such as energy, transport, buildings, industry and agriculture [3].

In this context, smart city replication dedicated to transferring knowledge and technology has become part of the policy mix. Replication aims to efficiently and

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effectively use funding budgets and improve knowledge and technology management between project actors and cities, thus contributing to the sustainability strategy [4]. However, replication activities in European smart city projects have been repeatedly requested without precisely defining the replication concept [5, 6]. Like smart city research, this lack of conceptual and normative foundation has resulted in a multidisciplinary research field combining engineering and social science perspectives [7].

One of these perspectives that is relevant in this context is systems research. Systems research is dedicated to understanding systems in nature, society, engineering, and technology. From a systems research perspective, cities are complex adaptive systems. They are characterized by many components and their interactions, which can influence each other, adapt and learn [8]. Within urban studies, systems thinking has become a basic and integral requirement to strategically analyze and plan tomorrow's living and urban environments, develop urban infrastructures and sustain urban space. However, previous work on replication falls short in this regard and neglects systematic thinking within replication activities [9].

This paper addresses this gap in current academic literature, proposing an approach to assist smart city policymakers and practitioners in assessing and strategically planning replication activities. Autonomous (last-mile) delivery robots (ADRs) serve as an application case for this approach, demonstrating how systems research can support smart city replication. Transport is considered one of the most relevant smart city domains [10]. This work introduces a causal loop diagram (CLD) to systematically map the complexity of replicating ADRs in a mixed-use district in Munich, following the research question: To what extent can the replication of ADRs be supported with methods from systems research?

This study is structured as follows: Section 2 introduces the term smart city replication and presents the concept of ADRs from a smart city perspective. Section 3 explains the process and the methodology based on systems modeling. Section 4 visualizes the results of the CLD, illustrating the systemic connections and interdependences for replicating ADRs and discusses the implications of this approach for both research and practice. The concluding Sect. 5 summarizes the overall key findings and provides an outlook for future work.

2 Literature review

2.1 Smart city replication

In its literal sense, replication refers to making or doing something again in the same way as before [11]. Smart city replication is common in European smart city projects and relevant research activities. The aim is to facilitate the transfer of technology, experience, and

knowledge through different approaches and methods. Originally, European policymakers introduced the concept of replication more than a decade ago with the launch of the European Innovation Partnership on Smart Cities and Communities (EIP-SCC) to provide a strategic framework for implementation plans and funding programs [5, 12]. Back then, the European Commission referred to replication as something that should enable learning from projects and facilitate the full-scale deployment of solutions. A prerequisite of replication is the full commitment to collaboration and a willingness to share information and collect data among partners and stakeholders [12].

Replication efforts have been incorporated into smart city projects that have been initiated under the umbrella of the European Commission's funding program Horizon 2020 and Horizon Europe. Within this context, the idea is that the results from one pilot case are transported or copied to other geographic areas, albeit under possibly different boundary conditions [13]. These pilot cases, conceptualized as urban laboratories serving as testing grounds for changing urban systems, have originally been perceived as an efficient way to bring about change [6, 14]. Part of the replication principle is the assumption that the best solution does not have to be developed individually. The European understanding of smart urban development entails creating more socially inclusive and sustainable cities through efficiency improvements, potentially through the use of technology [15, 16]. Key barriers to implementing smart innovations are the availability of limited resources and the need to maintain or increase the quality of services to stay economically competitive while facing diverse challenges. In this context, the replication of proven solutions has been perceived as an approach to meet current urban challenges ranging from maintaining life quality to preventing social inequality through the use of pre-existing knowledge [17].

However, significant weaknesses have been revealed through scientific analysis and the application of the replication principle. Replication has been perceived as solutionist, technocratic, neoliberal and positivistic in its normative ideology and criticized for not adequately addressing urban complexity [4, 6, 18, 19]. This criticism was accompanied by a lack of results in transferring smart city initiatives among the project partners involved in the EIP-SCC [6, 14]. These limited outcomes of the replication results can be traced back to information and knowledge barriers, acceptance and implementation barriers [9].

Regardless of these shortcomings, a multidisciplinary field of research has emerged over the past few years to address the notion of smart city replication in a more nuanced way that has gone far beyond its original scope.

Even though European authorities emphasized the importance of replication, they were reluctant to share suitable strategies, methods, and tools. This left much room for interpretation and led to diverse approaches. This, in turn, resulted in a growing body of knowledge from different research disciplines and perspectives [5, 6].

The scientific discourse includes influences from urban studies, diffusion and innovation research, transition management, perspectives from management studies, and knowledge management [20, 21]. These viewpoints form a fundamental, albeit flexible, theoretical framework in the conceptual consideration of replication and the development of related approaches. In this way, it can be aligned with the perception of the smart city, which is considered a contextual interplay of technological innovation, as well as management, organizational, and policy innovation [22]. Therefore, replication activities draw on numerous methods, procedural models, and artifacts within this interdisciplinary research field. This wide scope and these considerable efforts in that field stress the scientific and societal demand for appropriate and consistent solutions.

Given the pressing need for comprehensive change in urban areas for better quality of life, sustainability and more resilient infrastructures and environments, the question of successful replication within and beyond the EU Policy Framework remains urgent. In this context, Smart city transitions can be considered a type of urban sustainability transition [23]. Bringing about or facilitating these transitions requires a holistic view from different research angles and the cooperation of different partners who contribute their skills, knowledge and resources. The insufficient results and findings from past activities and existing procedural models and frameworks indicate an increased need for research and the linking of different research areas. To contribute to a more holistic perspective of smart city replication the following paper introduces and discusses a systems research perspective.

2.2 Autonomous last-mile delivery robots in the Smart City

The present work picks up autonomous logistics for last-mile delivery as a case study for smart city replication. Sustainable urban transport is one of the most important issues for smart cities' economic and social development [10]. Many actors in urban transport management involved in policy design, planning and implementation are starting to look for alternative mobility concepts in forerunner cities [24]. One of the focal points that is in the spotlight of research and practice is urban freight delivery. Here, innovative concepts and solutions for last-mile delivery and logistics that rely on technological advancements are of growing interest [25, 26]. One of the

most prominent approaches is the integration of innovative vehicle concepts such as ADRs [27].

Connected and autonomous vehicles will change how people and goods move in the coming decades [28], in particular in urban environments [29–31]. While large-scale deployment of these solutions is still to come in European cities, there are many research and innovation activities related to the planning, piloting and diffusion of this technology, which makes ADRs an established part of numerous smart city projects and initiatives [30, 32–34]. For last-mile delivery, there is a large body of knowledge, based on models, simulations and case studies, suggesting that the technology will have a positive economic impact through increased efficiency and associated environmental benefits through resource savings [25, 31, 32, 35–38]. However, this can only happen if these solutions are embedded in the prevailing social, economic and institutional configurations of a city [39]. In context of smart city initiatives, such as in the field of transport and urban logistics, this requires the alignment and the contribution of different stakeholders from the public sector, industry, academia [40, 41] and civil society [42, 43]. These multi-helix innovation models describe how smart city projects benefit from multiple perspectives, backgrounds and organizational settings. However, reconciling the different interests and goals of these actors and resolving tensions caused by conflicting interests is crucial for the replication of smart city solutions [9, 21].

In the face of this challenge, ADRs are an appropriate subject for research at the intersection of private and public sector. While benefits are expected for logistics and service business models, there is also potential to reduce environmental impacts and contribute to public policy objectives. To achieve both, however, it will be necessary to successfully navigate conflicting priorities, accepting common trade-offs and compromises in terms of the degree of commercialisation, regulation, policy and a responsible approach to the allocation and use of public traffic space. [30, 31, 44]

3 Methods

This study develops a system research approach to support smart city replication of ADRs in Munich. The selected method in this study is a CLD from systems research. The CLD is an appropriate way to illustrate systemic thinking. It is a well-established method for identifying and analyzing causalities, interdependencies and connections in socio-technical systems. As a diagramming tool, CLDs are used to capture the structure of a complex system by visualizing its feedback loops and dynamic interactions of relevant variables [45, 46]. Therefore, its analytical features can be combined for further quantitative analyses and scenario simulations. However, the conceptual and analytical results, which qualitatively

reveal systemic connections and patterns, stand on their own [45]. In this respect, CLDs can also serve as a basis for further participatory forms of system dynamics, such as Group Model Building (GMB), which is used for group decision making, problem structuring and comparing contrasting perceptions in teams [47, 48]. In that way, the CLD is not limited to its function as analytical tool but serves as an artefact to contribute to consensus-building and acceptance.

Due to this methodical versatility a replication causal loop diagram (RCLD) is created to examine and discuss its potential for replication activities in smart city projects. In Sect. 4.2 the model is conceptually applied to a district as selected replication environment, where the replication of ADRs is analysed. The overall aim is to draw abstracted conclusions from this application regarding the suitability of systems research for overcoming existing replication problems in research and practice.

The Werksviertel-Mitte in Munich qualifies for the case study for evaluation purposes due to its size, location, and regulatory conditions. Part of the district’s strategy is to provide sustainable solutions for its 3,000 residents and approximately 7,000 workers within the district by 2030. One of the main attributes of the district is the interweaving of different spheres of life, such as living, working, and housing. Due to its heterogeneous stakeholder structure, which is marked by gastronomy, businesses, and residents, different needs arise regarding the requirements for ADRs.

The following steps were taken in the development of the RCLD, following the approach of Dhirasana [49]:

- Step 1: A systematic literature review on autonomous transport systems has been conducted to create a list

of variables. For this purpose, relevant publications have been selected based on search strings containing the following key words: *smart, city, urban, autonomous, transportation, logistics, vehicles, innovation, success factors, acceptance, last-mile*.

The search requests have been applied to the databases *Web of Science, Scopus, Semantic Scholar* and *Google Scholar*. The selection focused on European publications since 2018. Only European literature has been selected to allow comparison with the later district analysis in Munich. The focus on publications since 2018 ensures that the analysis reflects the latest developments in autonomous transport robotics and urban logistics. This timeframe is appropriate to capture the rapid technical, economic and political advances that influence the replication analysis. The sample selection is shown in Fig. 1.

- Step 2: 46 factors impacting the implementation and replication of ADRs have been identified within the literature (see Table 1. These factors are then divided into categories. The categories are inspired by the quadruple helix innovation model. In Table 2, the description of the categories is provided.
- To be able to evaluate the factors, it was partly necessary to adapt or supplement their formulation. Some of these factors, considered relevant in the literature review, were omitted from the pairwise evaluation of influencing factors in the context of replicating ADRs using the matrix because no correlations were present upon closer inspection. In addition, several factors were merged if their content and effects were sufficiently similar.
- Step 4: The matrix was used to identify direct and indirect influences on the replication of ADRs. The

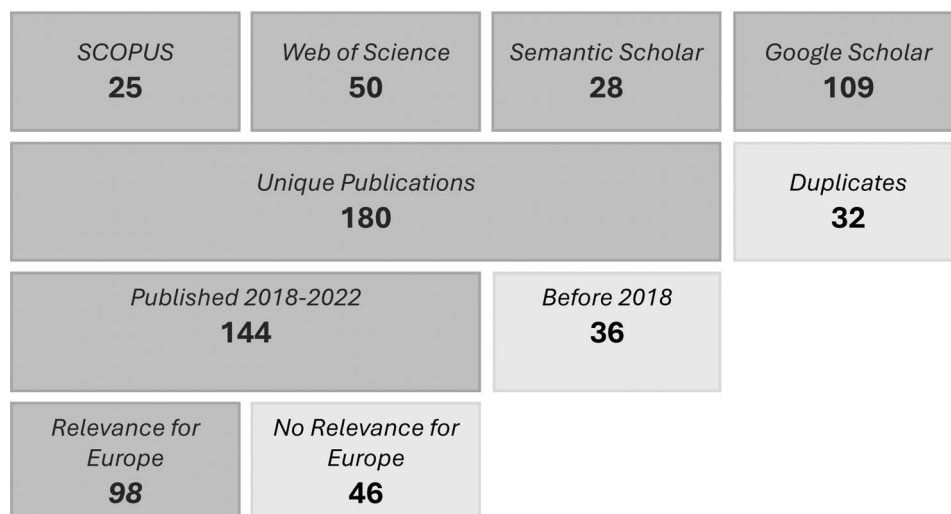


Fig. 1 Literature sample selection process

Table 1 Categorization of the influencing factors

Category	Influencing Factor	Description
Robotic Technology	Maximum Speed	Maximum speed achievable
	Maximum Delivery Size & Weight	Capacity for handling delivery size and weight
	Operating Range	Maximum distance on a single charge
	Cybersecurity	Protecting robots from cyber threats
	Smart Routing Management	Optimized and adaptive routing for efficiency
	Human-Robot Interaction	Usability and user-friendliness in interaction
	Noise Pollution	Sound levels produced during operation
	Implemented Safety Requirements	Adherence to road safety standards
	Functional Interoperability	Technical & communication standards
	Versatility and Modifiability	Adaptability for different operational contexts
	Space Requirement	Physical dimensions (maneuverability & storage)
	Energy Consumption	Energy requirements for robot operations
Society	Societal Need	Public interest and need for the service
	Usage Price	Affordability of using the service
	Marketing, Communication and Prevention	Awareness and prevention campaigns for public safety
	Technology Acceptance	Public willingness to adopt new technology
	Testing in an Urban Context	Real-world testing before full deployment
	User Satisfaction	End-user contentment with service performance
	Data Protection	Ensuring protection of personal data
	Verbal & Physical Abuse of the Robots	Preventing verbal or physical abuse of robots
	Societal Trends	e.g. Environmental awareness, sharing economy
	Country/Culture Specific Differences	Variations in language, regulations, societal behavior, and cultural attitudes towards technology in different countries or regions
Economy	Stakeholder Involvement	Engaging stakeholders throughout the process
	Willingness of the Partners	Willingness of partners to collaborate
	Location Factor	Advantage through innovation showcase
	Digital Services and Technologies	Collection, preparation, and use of data
	Acquisition, Operating and Repairing Costs	Maintenance, repair, and acquisition costs
Politics and Legislation	Political Readiness & Willingness	Recognition of potential by policymakers
	Legal and Regulatory Basis	Liability, time windows, etc.
	Public Funding	Availability of subsidies and grants
Environment	Political Restrictions	Regulations on the deployment of ADRs
	Availability and Expansion of Physical Infrastructure	Availability of roads, buildings, and pathways
	Availability and Expansion of Digital Infrastructure	Availability of networks, real-time data, etc.
	Topography	City layout, size, and terrain characteristics
	Climate and Weather Conditions	Weather suitability for operations
	Population Density	Urban density affecting delivery efficiency
	Traffic Volume	Congestion levels in urban areas
	Traffic Safety	Measures to ensure safe operation
	Space Requirement	Storage, parking, and loading needs
	Charging Infrastructure Available	Availability of charging stations
Charging Infrastructure Expansion	Expansion/Improvement of charging stations	
Replication	CO2 Level in City	Pressing need due to local air pollution
	Replication of Solution	Core System Node [45]

resulting RCLD was generated using the VENSIM software version 9.3.0. In several phases, different layers were developed, and the interrelationships and dependencies of the influencing factors were extracted. The findings are presented in Chapter 4.1.

- Step 5: The RCLD is applied to the replication environment. In this paper, the approach is

illustrated using the Werksviertel-Mitte district of Munich as a conceptual application (see Chapter 4.2).

Step 3: The 46 variables identified in the previous process were arranged into a matrix (46 × 46). Both inhibiting (antiproportional) and reinforcing (proportional)

Table 2 Categorization of the influencing factors

Category	Description
Robotic Technology	Factors influencing the technical aspects of ADRs, such as functional requirements and features
Economy	Economic factors refer to aspects regarding profitability, value proposition and the underlying business model
Politics and Legislation	Influences in this category set the framework for the introduction and replication of ADRs including operations and planning.
Society	Factors include aspects such as the user acceptance and handling of delivery robots as well as their respective use
Environment	The environment refers to urban conditions, topographical features, and infrastructural availability and needs

Table 3 Final selection of influencing factors in each category

Category	Influencing factors
Robotic Technology	Maximum Delivery Size and Weight; Maximum Speed; Robot Size; Operating Range; Power Demand; Noise Generation; Cybersecurity; Implemented Safety Requirements; Smart Routing Management; Distinctive Human-Robot Interaction; Functional Interoperability; Versatility and Modifiability; Space Requirement
Economy	Stakeholder Involvement throughout the Process; Willingness of the Partners; Location Factor; Digital Services and Technologies; Data Management; Acquisition, Operating and Repairing Costs
Politics and Legislation	Political Readiness and Willingness; Legal and Regulatory Basis; Public Funding
Society	Societal Trends; Societal Need; Marketing, Communication and Prevention; Technology Acceptance; User Satisfaction; Data Protection; Verbal and Physical Abuse of the Robots; Testing in an Urban Context; Usage Price
Environment	Availability and Expansion of Physical Infrastructure; Availability and Expansion of Digital Infrastructure; Favorable Topography; Favorable Climate and Weather Conditions; Population Density; Traffic Volume; Traffic Safety

influences were identified for the analysis. They were marked with +1 or -1. Factors that had no influence were marked with 0 (Fig. 2). The influences are assessed by the research team in a workshop.

Ultimately, a total of 38 relevant factors were identified (Table 3). Most of them behave proportionally and only a few antiproportional, which is indicated in the RCLD by a dashed line and a negative sign. The factors and their

interrelationships were visualized in the RCLD and are

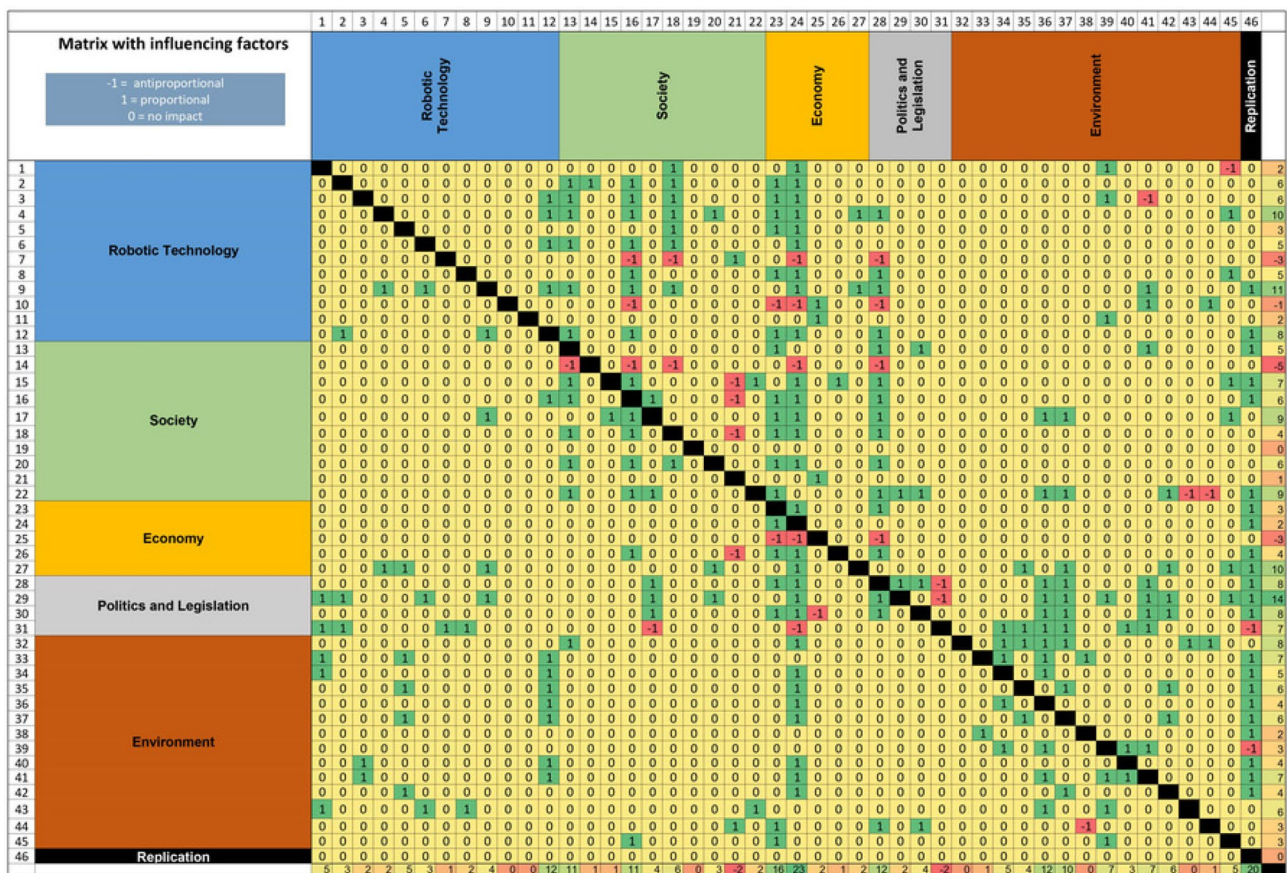


Fig. 2 Cross-evaluation matrix for replication influencing factors

colored according to their category.

4 Results

4.1 Evaluation of the replication causal loop diagram

Only three of the thirteen factors from the **Robotic Technology** category are considered direct influences. Meeting the requirements for the factors *versatility and easy modifiability* along with the *functional interoperability* of the ADRs ensure that the use of the ADRs is possible in a wide range of applications and facilitates replication in another context or another city. These two factors also have a proportional effect on the *willingness of partners*. *Space requirement* for the ADRs' storage, parking, loading and driving has an anti-proportional impact on replication. Thereby it is influenced by further technological factors.

Out of the six factors in the **Economy** category, all are direct factors, except *acquisition, operating and repairing costs*. The *costs* mainly affect the willingness of the politics and partners as well as the *location factor* (anti-proportional effect). The stakeholder involvement throughout the process has a great and diverse impact. The *availability of digital services and technologies such as platforms, IoT devices and AI*, as well as the *data management* factor, not only have a direct impact but also influence the functional interoperability and the location factor. In this context, the factor data management includes the direct use of data, their collection, processing, and public provision.

All three factors from **Politics and Legislation** are among the direct factors. *Political readiness and willingness, public funding* and *legal and regulatory basis* are highly interdependent and have a proportional effect, for example, on the expansion of digital and physical infrastructure including the aspect of charging infrastructure.

In the category **Society**, nine factors were considered, of which four are classified as direct influencing factors. Without *societal need*, replication is unnecessary. However, a high societal need in combination with an increase in various *societal trends*, such as environmental awareness, individualization, the willingness to share resources (Sharing Economy) and further changes in consumer behavior, have a proportional effect on many other factors and show therefore relevance. The importance of *marketing, communication and prevention* and *technology acceptance* will be discussed in detail.

Four of the seven factors in the category **Environment** directly influence replication. *Availability and expansion of digital and physical infrastructure* including charging infrastructure as well as *favorable topography, climate and weather conditions* partly influence each other but have no additional influence on factors of different categories.

The development of the RCLD ensures a more elaborate examination of the topic. It provides a good basis for learning and decision-making by providing an overview of correlations and connections. Nevertheless, the method has its pitfalls, as the visual representation of the RCLD can quickly become incomprehensible if too many influencing factors and relationships are included. This is why the research team made a prior selection to visualize the RCLD. Therefore, Fig. 3 only shows the factors that directly influence replication and how they are interrelated.

Indirect factors that are not shown are mainly from the **Robotic Technology** category (see Table 3). These technological aspects mainly influence *technology acceptance* and *willingness of partners and politics*. In the **Society** category, *testing in an urban context, data protection, user satisfaction* and *verbal and physical abuse of the robots* indirectly influence the replication. From a financial point of view *usage price* (**Society**) as well as *acquisition, operating and repairing costs* (**Economy**) need to be mentioned. Factors of the category **Environment** that have an indirect influence are *population density, traffic volume* and *traffic safety*. All of them primarily affect the *societal need* as well as *political readiness and willingness*.

One factor that can be highlighted is *technology acceptance*, as it was mentioned particularly frequently in the literature review [50–52]. Accordingly, technology acceptance is emphasized in the visualization of the RCLD. Based on the diagram, five factors have a direct and proportional influence on *technology acceptance*. In addition, the research team identified the relevance of providing information via appropriate communication channels for different stakeholder groups as further factors. High technology acceptance leads to fewer societal concerns and facilitates replication through faster diffusion and adoption.

Technology acceptance is part of a reinforcing loop: Increased technology acceptance can be achieved with successful marketing, communication or prevention strategies that will lead to more commitment of partners and policymakers. Such a trend increases the chances of public funding and a conducive legal and regulatory basis. As soon as there are beneficial framework conditions and available funds, digital services can be further developed and established. The availability of elaborated digital services allows a more versatile use and increases technology acceptance. This acceptance loop is visualized in Fig. 4 and includes some more user-side factors derived from the literature research.

4.2 Conceptual application of approach

With the designed methodology and the developed RCLD, ADRs can be systemically investigated and evaluated in the defined research area in the

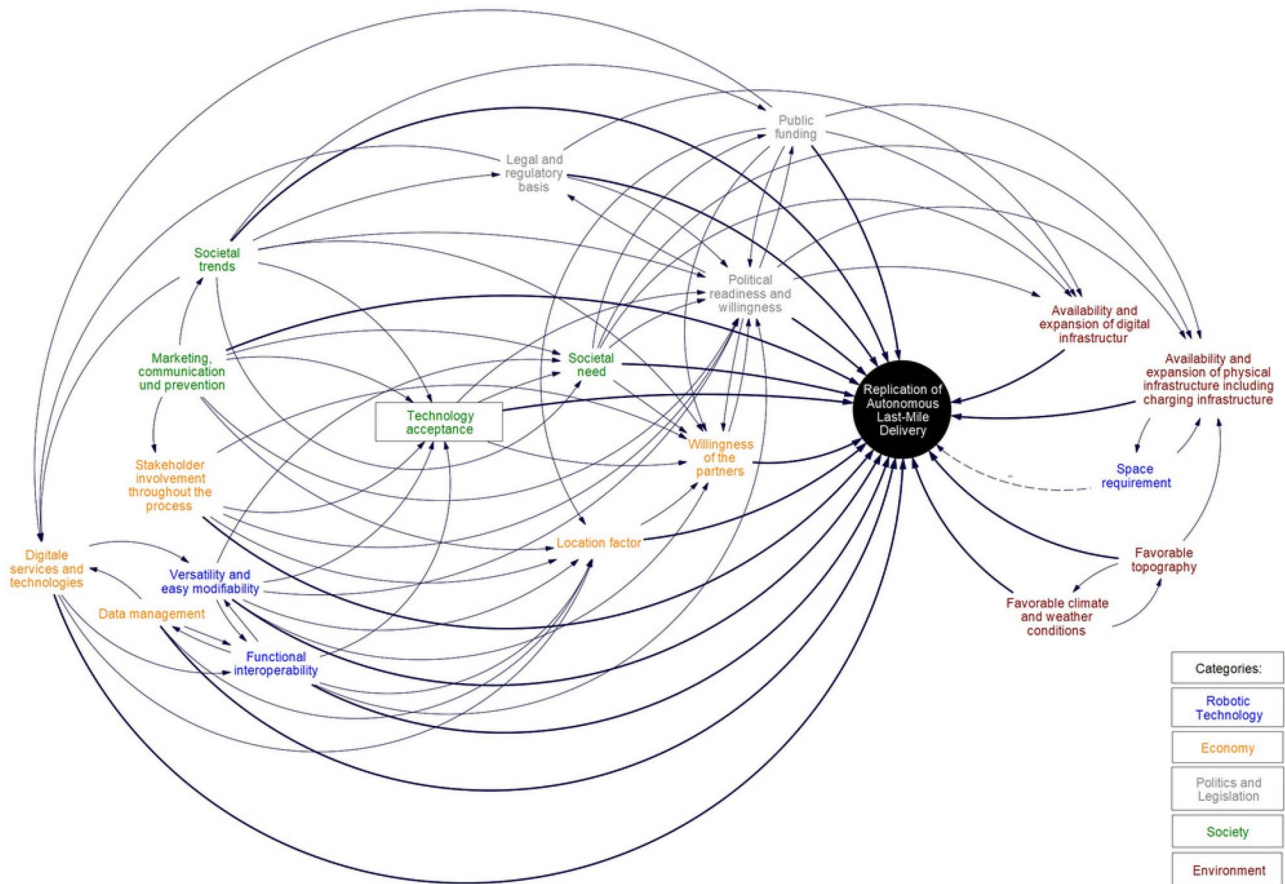


Fig. 3 RCLD for autonomous delivery robots

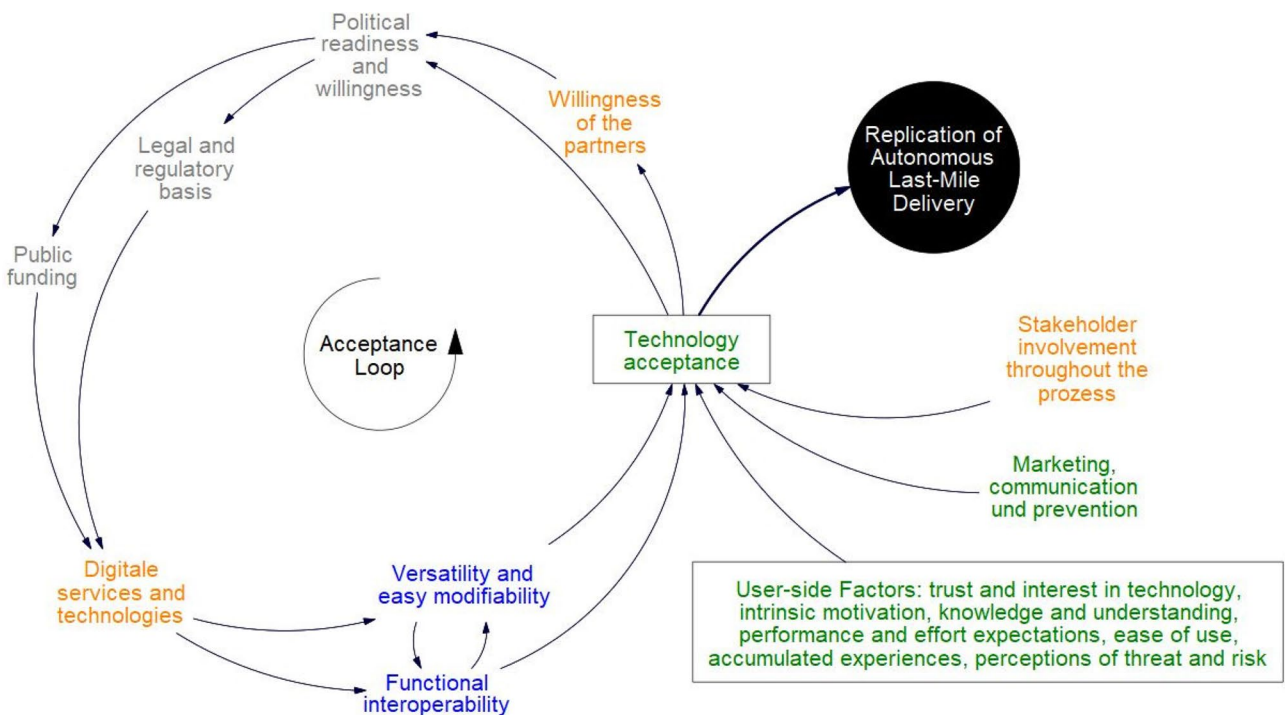


Fig. 4 Technology acceptance loop of the RCLD

Werksviertel-Mitte in Munich. In the following, the direct factors influencing replication are concisely described based on the current status in the Werksviertel-Mitte. Subsequently, corresponding recommendations for action are derived.

- *Functional Interoperability:* ADRs are only used in the considered district now but may be used in urban areas later. Conventional robots in Werksviertel-Mitte can meet requirements without specific features.
- *Versatility and Modifiability:* A conventional robot can be used for this particular use case. The terrain is relatively simple, but robots should have the ability to be used in various ways. This is due to the wide range of companies and service providers in the Werksviertel-Mitte and the district's different functions (working, living, and hospitality). As a result, there is a possibility for more flexible and demanding applications for autonomous modes of transport, such as food, medicine, and goods.
- *Space Requirement:* The Werksviertel-Mitte area has a dense concentration of buildings. While the district is not yet fully developed, ongoing construction projects in the planning phase could accommodate the future needs of ADRs. Pedestrian areas offer suitable locations for robot operations, but it is important to incorporate warehouses and parking spaces into future planning cycles. However, there is a potential for conflicts among various road users such as cars, delivery vehicles, bicycles, and pedestrians on the main traffic routes.
- *Societal need:* The optimization of supply chains by ADRs would be suitable within the neighborhood, e.g., due to the short distances. The use of technology could contribute to greater efficiency and increased connectivity of services in the district. Since there are no residential units in the neighborhood yet, the current use of ADRs would be exclusively by local businesses and service providers.
- *Marketing, Communication and Prevention:* The district takes on the role of an experimental environment for sustainable and innovative urban development, including areas such as mobility and logistics. Therefore, introducing ADRs fits the established image and external perception quite well. The use case represents a novelty that tenants and visitors of the Werksviertel-Mitte would expect and appreciate. However, regarding external visitors, additional education campaigns and signage would be needed to increase neighborhood safety.
- *Technology Acceptance:* Werksviertel-Mitte in Munich has a progressive approach to new technologies and innovations, making it an ideal location for utilizing robots. It also offers test/model status, which boosts visibility for businesses and their partners. Successful integration and individual benefits are crucial for user acceptance.
- *Societal trends:* Werksviertel-Mitte aims for sustainable logistics and mobility through sharing concepts and eco-friendly practices. ADRs can reduce emissions and replace larger non-electric vehicles, but alignment with existing supply chains and consumption patterns is crucial.
- *Willingness of the partners:* Local stakeholders consider it important to be pioneers and contribute to the ongoing growth of the district. Several local food services are affiliated with a shared corporate entity, resulting in fewer objective conflicts. However, there are also independent restaurants and bars located in Werksviertel-Mitte.
- *Location factor:* Having innovative solutions exclusively available gives the district a competitive edge. As a result, the introduction of ADRs increases the appeal of the area.
- *Stakeholder involvement:* The responsible district operators support the introduction of ADRs. The stakeholder management and involvement comprise the technology providers, participating gastronomy businesses, the district operators, and scientific monitoring. In addition, public municipal authorities have to be involved to clarify legal boundary conditions.
- *Data management:* Given that the Werksviertel-Mitte is under private ownership, the collection and evaluation of data should be possible. Due to the many existing corporates among the partners within the corporate family on-site, advantages can be seen in data collection and exchange. Fleet management and operation require solutions and expertise from external partners.
- *Digital services and technologies:* At present, there is no supporting infrastructure in the area of IoT and artificial intelligence that could serve as a foundation for the operation of the delivery fleet. Currently, there are no digital platforms to capture the data. The entire infrastructure for data management needs to be developed.
- *Political readiness and willingness:* Since the Werksviertel-Mitte is privately owned, the implementation projects are not solely dependent on political processes and official procedures. Nevertheless, the intensive cooperation with political decision-makers is essential. A perception of the Werksviertel-Mitte at the political level as a living lab and an urban testing environment can help facilitate the implementation of the project.

- *Legal and regulatory basis:* The transportation infrastructure in the ADRs area of operation primarily consists of private land with some public access, which makes it easier to introduce autonomous vehicles. Nevertheless, certain regulatory concerns need to be resolved through close collaboration with the local authorities.
- *Public funding:* The implementation of ADRs has significant political implications, with potential funding opportunities available at the European or national level. However, the current model does not prioritize public funding.
- *Favorable topography:* Topographically, the neighbourhood is ideal for introducing ADRs. The terrain is flat and there are no major obstacles or challenging conditions. However, there are stairs in some places that would need to be overcome.
- *Availability and expansion of digital infrastructure:* There is access to public WIFI, and plans to establish sensor technology and other digital infrastructure in the future. Depending on the selected robot technology, a 5G campus network may be considered as a reliable option to operate the fleet.
- *Favorable climate and weather conditions:* Munich and its corresponding city district experience relatively stable weather conditions, without any extreme events expected. However, heavy rain, icy conditions, or snow may affect operations. The use of canopies can help alleviate any weather-related operational constraints.

Reviewing the current situation in the Werksviertel-Mitte, for some factors, there are very favorable framework conditions in the district that will facilitate the replication of ADRs. What is also conducive for replication is that the district is privately owned, which means that innovation projects are, at least to some extent, independent of the general political landscape. Still, the coordination and stakeholder management for planning and implementation of the projects with the owners and local service providers can be demanding. Further infrastructural requirements needed to implement the ADRs can still be incorporated into the construction plans on the site, as the neighborhood is not yet fully developed. By thinking with innovative technologies at an early stage, the local economy can also benefit in the future since these investments create competitive advantages at the local scale and positive marketing effects (location factor). In addition, some replication factors are facilitated by the presence of a family of businesses. For example, a local marketing agency could cover communication, awareness-raising, and educational measures for new technologies. In addition, the social structures in the district, with its first-mover mentality, promote a high level

of acceptance of innovative technologies. Still, for external visitors, appropriate marketing measures would be necessary.

Stakeholder management and placemaking are integral parts of the Werksviertel-Mitte concept, so many residents and businesses are willing to support future-oriented projects. However, an early inquiry into the commitment of potential partners and stakeholders would be helpful to ensure the individual participation of the companies and service providers. The collection, processing and use of appropriate data to support the delivery services also seems advantageous due to the proximity of the stakeholders. However, it is important to define the handling of the collected data in the context of anonymity and data protection.

However, besides the improvements already explained, there are some key challenges to replicating ADRs. These include, for example, analyzing the overall demand for delivery services. Since no residential units are in the neighborhood, ADRs would currently be used exclusively by local businesses and service providers. Furthermore, it is important to include the testing of ADRs as early as possible in further neighborhood planning. For example, the early presence of the charging and digital infrastructure can already significantly influence the test phase of the robots. Above all, the digital infrastructure proves to be particularly important for digital services and technologies. Further recommendations for action arise in regulations and legislation and concerning public funding. The regulatory restrictions should be analyzed and clarified for corresponding use cases to implement convenient delivery services. Likewise, corresponding funding calls should be analyzed. An important focus within the funding programs can be on the replication of those projects.

A replication strategy could focus on establishing regulatory sandboxes to facilitate implementation. Emphasis can be put on the early integration of infrastructure, such as charging stations and digital networks, alongside active stakeholder engagement. Pilot programs and living labs can refine operations, supported by marketing campaigns to accelerate the technology acceptance of the solution.

4.3 Discussion and limitations

The RCLD maps the replication environment. From a macro perspective, the direct and indirect effects of replication become visible. The results show that the replication of ADRs is generally less of a technological issue since only three of the 13 technological factors have a direct impact. Instead, the implementation is highly dependent on the social and economic viability of the overall concept. The analysis in the Werksviertel-Mitte illustrates how the application of the RCLD can be

translated into measures for action (e.g. early stakeholder involvement, screening for funding opportunities) and an assessment of the relevant boundary conditions to consider. Still, the RCLD development and analysis remains a participatory and normative task when it comes to selecting appropriate variables. While too little data limits the validity, too many influencing factors complicate the usability and interpretability of the model.

The approach presented offers a specific and exemplary approach to integrating systems thinking and systems research methods into replication activities. The RCLD is an appropriate way to illustrate this. As a well-established method, it offers several pathways. RCLDs can be used as preliminary work for further quantitative analysis and simulation [46]. However, they also represent independent conceptual and analytical results that reveal systemic connections and patterns [49]. This is in line with current research that calls for quantitative and qualitative methods to systematically investigate and understand the contextual attributes and processes that facilitate the replication and scaling of smart city initiatives [53].

So far, methodical contributions in the field of replication mainly follow three strategic directions: (1) *Development*: Methods are used to analyse, plan and thus increase the replication potential [21, 54, 55]. This means that replication is taken into account during the development and piloting, so that a solution is planned and designed at an early stage in such a way that it is prepared for later replication (e.g. use of standards [56]). (2) *Context*: Emphasis is placed on analysing and identifying contextual information that can facilitate the identification and integration of an existing solution [33, 54, 57]. (3) *Embedding*: A specific solution is analysed for suitability and compatibility in a defined replication environment and its implementation is facilitated [33, 54, 58]. In addition to the analytical steps, these *Embedding* methods already support the implementation, for example in terms of stakeholder involvement and technical and operational planning.

According to this conceptualisation, the proposed approach serves the third direction, at least if the generated knowledge, the resulting RCLD artefact and the development process is equally integrated into replication activities. These mostly qualitative data can form the basis for further interpretative and participative steps such as GMB [9]. From this perspective, the model presented can be seen as a *concept model*, the result of an expert-led modelling process at an early stage, which is further developed with client or stakeholder groups [59, 60].

In this regard, Talmar et al. [21] introduce the concept of the *boundary object* to replication research. Boundary objects consist of models, graphs, visual representations, tools and other conceptual approaches to mediate

between stakeholders and facilitate the communication of knowledge in diverse stakeholder environments [61]. Given that compatibility for participative formats and its visual development and result, RCLDs can serve as such a boundary object or could contribute to a set of boundary objects in a replication process to provide knowledge but also to activate stakeholders. Engagement and collaboration are essential enablers in replication activities [53].

There is to mention that this approach comes with several limitations. The model development focuses on conceptual work, where the research team particularly emphasized an extensive literature review and initial model development. The conceptual application shows the transferred and contextualized findings. However, a broader empirical base including decision-makers and stakeholders in the application of the model would be beneficial to learn about different participatory approaches in the model development and analysis following the principles of GMB.

Another aspect that is not sufficiently considered in the present procedure is the adoption and acceptance of the discussed delivery solutions at the citizen level. Since it is up to municipal bodies to decide about the implementation of smart city initiatives, they act as gatekeepers for applications predominantly used by citizens [21, 62]. Therefore, it is crucial to how a smart city project is perceived and adopted by the urban community. The findings in this work prove this by highlighting the role of technology acceptance in the case of ADRs. To address the citizen perspective appropriately a complementary micro perspective is needed. From the perspective of systems research, simulation approaches such as agent-based modeling are suitable methods for analyzing diffusion and adoption processes. Both approaches can be used in combination. The RCLD describes the world in which the citizens and other agents act and move [46].

5 Conclusion

The idea of benefiting from each other through mutual learning and knowledge sharing seems plausible. Therefore, the motivation to strive for efficient and successful replication strategies in smart city projects is understandable. However, the tangible effects of this effort remain elusive. Numerous projects and attempts with varying approaches and activities revealed the obstacles and challenges of the replication concept. In other words: More replication led to more knowledge about the corresponding shortcomings of replication efforts.

For policymakers, researchers, and urban technology providers, shaping cities through replication comprises understanding influencing factors, dependencies, and causalities to derive strategies and action plans in normative consensus-building processes. In doing so, they

remain capable of acting under uncertain environmental conditions. This is where this work comes in.

The overall premise of the paper is to complement the replication research perspective by opening a discussion on the benefits and potential of systems research when it comes to replicating smart city solutions. Admittedly, the method used provides only a glimpse of what systems research is about and could potentially contribute to the overall research question. Still, a possible way how the question can be approached is shown. In most cases, replication fails not because of a lack of knowledge, but because of an implementation and operationalization deficit. Contextualizing knowledge is a key to putting things into practice. Corresponding methods, such as the one introduced, bridge this gap by providing orientation and mediating between stakeholders, experts, and decision-makers. In other words: Replication does not happen automatically, but requires dedicated activities [63]. And these activities can benefit from systemic thinking and acting.

Although this work is approached from a smart city perspective, its ideas and findings could also be applied and further discussed in the related fields of city logistics and urban freight. Consensus-building and the development of common goals and perspectives are seen as most relevant success factors for upscaling and replication of city logistics solutions [33]. At the same time the cross-sector collaboration along the helix innovation model is perceived as substantial limiting factor and barrier [64–66]. This also applies to effective mechanisms for knowledge sharing and dissemination as well as approaches to align goals, priorities and interests within stakeholder groups in the urban freight system [66]. But the reverse is also true: smart city replication can benefit from abstracting and integrating lessons from scaling research, relevant policy reports and innovation initiatives in the logistics field. Replication, as shown here, is fundamentally a systemic challenge. Recognizing this opens pathways for cross-field learning and more effective urban innovation at scale.

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Author contributions

Patrick Ruess: Conceptualized and designed the study, provided substantial contributions to the interpretation of results, critically reviewed the manuscript, provided guidance throughout the manuscript development process, provided expertise in the field of smart city replication. Svenja Weber: Contributed to the study design, conducted literature review, provided a first draft of manuscript, assisted with data analysis, and critically revised the manuscript. Sina Rzesznizek: Performed data collection and modeling, conducted literature review, and provided substantial contributions to the interpretation of results.

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Competing interests

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