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DOI
10.21606/drs.2022.323

Publication date
2022

Document Version
Final published version

Published in
Conference Proceedings DRS2022

Jun 25th, 9:00 AM

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Citation

Beldarrain, G.G., Carvajal Ortega, C.A., Baan, A., and Kim, E. (2022) Framing resilience in public transportation systems, inspired by biomimicry, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), *DRS2022: Bilbao*, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.323

DRS 2022
Bilbao 25th June — 3rd July

Framing resilience in public transportation systems, inspired by biomimicry

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doi.org/10.21606/drs.2022.323

Abstract: Resilience is a concept that describes the capability to be restored after unprecedented events, originally emerged from biology and human sciences. This paper aims to explore what a resilient public transportation system is and how nature's wisdom can be used as an inspiration for the creation of resilience in the area of mobility, by linking public transportation systems, biomimicry and resilience together. To this end, qualitative co-creative workshops were conducted with eleven domain experts from public transportation, biomimicry, and biology. The experts addressed several factors contributing to resilience in public transport that could be categorized into four aggregated dimensions: resilience through system organization, resilience through information management, resilience through operating performance, and resilience through subsystem integration. Finally, a conceptual wheel framework on factors of resilient public transportation systems is proposed, aiming to shed light on future public transport developments, where a systemic perspective is to be adopted.

Keywords: resilience; biomimicry; public transport

1. Introduction

Due to the increasing uncertainty and complexity of today's world (Bennett & Lemoine, 2014; Kim et al., 2018), cities' planning is gaining interest in tackling new challenges that affect their quality and performance, caused by current issues such as the outbreak of Covid-19, climate change (Hayes et al., 2019; Rueda, 2012) or increased social complexity (Helmrich et al., 2020). In this context, the resilience of transport infrastructure systems is a priority (Hayes et al., 2019) to ensure the wellbeing of the inhabitants within the ecosystem and the overall performance of the cities. In other words, enhancing resilience in public transportation, a subsystem in the city, may help cope with the more extensive ecosystem's increasing uncertainty and complexity.

Resilience is defined as the ability to "persist in the face of change, to continue to develop with ever-changing environments" (Folke, 2016, p. 2). This concept has been adopted in many disciplines, having different definitions and applications.

For instance, biology was one of the first disciplines to use this concept, conceiving resilience as an intrinsic characteristic of natural systems on multiple levels (Helmrich et al., 2020). In this discipline, it is defined as having the “ability to operate in constant flux, maintaining structure, function, identity, and feedback loop” (Helmrich et al., 2020, p. 2), being “characterized as the science of surprise” (Folke, 2016, p. 11), proper to dynamic systems.

However, this definition is far from those used in urbanism, construction, or engineering. In these other disciplines the concept of resilience implies rather the physical resistance against external and extraordinary events and the capability to recover efficiently (Sharifi & Yamagata, 2018) than the systemic approach conceived in biology, which also emphasizes ongoing adaptive capacity and flexibility of the systems and subsystems. Resilience has been explored in public transportation from the perspective of its infrastructure, but not from a systemic approach. Therefore, our goal is to dive deeper into these definitions in the review of prior work to explore the gaps in the implementation of resilience in the different levels of public transportation systems. Finally, we aim to analyse how those gaps can bring new insights to creating resilience in public transportation.

To implement the biological concept of resilience into public transportation systems, biomimicry has emerged as a logical element for our research, as Allam (2020) suggests that “perhaps the most interesting part with biomimicry is the possibilities of discovering and capitalizing on the capabilities of self-replicating, self-repairing, and self-assembling that are synonymous with most biological processes” (p. 29). Building on that rationale, we aim to use biomimicry to find the link and relations between public transportation systems, biology and resilience, concepts that will be further explored in the following sections.

The article will focus on ***Creating resilient public transportation systems inspired by biomimicry***. The sub-questions of our research statement are:

- How to frame the resilience concept in biology into public transportation systems?
- What elements or factors can be extracted from nature using biomimicry for creating resilient public transportation systems?

2. Prior work

Resilience is implemented in many fields, as explored by Ramezani and Camarinha-Matos (2020), but merely the concepts of resilience directly implicated in the public transportation field are taken into account in this research. To understand the nuances and differences in their level of applicability for the research statement, the different definitions of the terminology are explored (view Table 1).

Table 1. Resilience in different disciplines—its definitions & concepts in the second column and key references in the third column.

Discipline	**Definitions & concepts**	**References**
Engineering	"Minimizing vulnerability to disasters by enhancing resistance and robustness of the physical infrastructure"	(Sharifi & Yamagata, 2018, p. 5)
Urbanism	"Ability [...] to continuously develop short-term coping and long-term adaptation strategies- [...] rapidly bounce back to baseline functioning, and more effectively adapt to disruptive events by bouncing forward to better system configurations"	(Sharifi & Yamagata, 2018, p. 6)
Biology	"Ability to operate in constant flux, maintaining structure, function, identity, and feedback loops"	(Helmrich et al., 2020, p. 2)
Transportation systems	Ability to prepare for, absorb, recover from, and adapt to disturbances	(Zhou, Wang, & Yang, 2019)

Based on these findings, we hypothesize that the biological definition of resilience may contrast with the definition applied in the other fields (e.g., urbanism and engineering), which is a gap that can be further taken as a research opportunity to explore possible applications in transportation systems to create a more holistic view of resilience within that transportation content. Various authors also present this gap as a future research topic: "Infrastructure designers, constructors and managers have made strong advances in hard engineering responses to climate risk, however, these tend to focus on stability and permanence, as opposed to ongoing adaptive capacity and flexibility" (Hayes et al., 2019, p. 679). While other fields focus on "resistance and robustness" against "disasters", "disruptive events" or "disturbances", in biology the "ability to operate in constant flux" should also be achieved under ordinary and ongoing conditions or contexts. This is where we also find extra deviance since the biology definition also includes the "feedback loops" concept, absent in urbanism and engineering. In our research, we frame resilient systems as follows: a resilient public transportation system should be able to continuously evolve through the iterative cycles based on feedback information, enhancing daily performance and operation, adapting to the unpredictable behaviour of citizens and other actors in the ecosystem, whilst having the capability of being restored in an efficient way.

3. Research design

3.1 Workshop design

To address the aim of this paper, co-creative workshop sessions were designed as a qualitative research method that involved different stakeholders with expertise in transportation, biomimicry and biology. This participant composition answers the need to introduce a biology concept (resilience) into the public transportation field, using a mindset or technique as a bridge-builder, which is biomimicry. From the discussion of various complementary perspectives, we aimed to understand the factors contributing to creating resilience in public transportation systems. The workshop design answered three subgoals:

- Understanding the internal and external influences in the current public transportation on a systemic level;
- Inspired by biomimicry, identifying what ecosystem features show resemblance in functionality that could be mimicked to create more resilient public transportation systems;
- Translating the insights from nature into factors which can serve as guidelines in a conceptual framework for creating resilient public transportation systems.

Biomimicry played a central role in the methodology. The tool has the potential to “enlarge the designer’s solution space” (Volstad & Boks, 2012, p. 199) as well as to enhance “cross-disciplinary thinking” (Nagel et al., 2017) and thus was chosen as appropriate for the co-creation sessions. Based on the framework by Chen et al. (2020), the technique was used for building up the workshop route. Furthermore, the problem-based approach was taken, which indicates that the design problem needs to be specified first (Kassem, 2018), so that biological analogies can be checked for identification, inquiry, and abstraction of the appropriate characteristics to mimic nature.

The activities were presented in the following order (see Figure 1):

1. Personal experience of the participants; the participants had to reflect on public transport and the influencing stakeholders and factors, based on their work or their experience as users;
2. Perceptions of the current public transportation system; identify and conclude in group the elements that make the current system less resilient;
3. Perception of future challenges for the public transportation system; the participants had to imagine the future based on group reflections;
4. Reflection about ecosystems in nature that show resemblance in functionality or structure with public transportation systems and that could be mimicked in;
5. Solving the challenges (from activity 3) by using biomimicry; the participants had to use the ecosystems (from activity 4) as an inspiration to propose possible solutions.

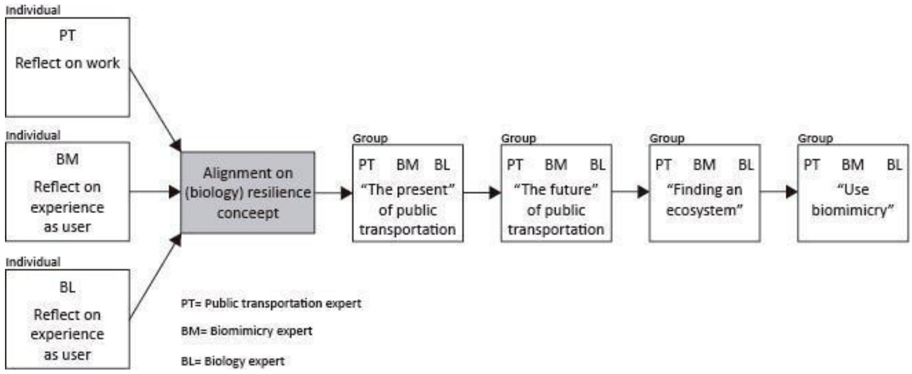

Figure 1. Workshop route

3.2 Data collection and analysis

A criterion-based participant selection (Patton, 2014) was used to select the sample. The main selection criteria for recruitment were the candidates' expertise. The participant had to be involved in one or multiple relevant research fields (public transportation, biomimicry, and biology). For the biomimicry and biology experts, it was necessary that they had knowledge concerning natural ecosystems. Other participant characteristics (e.g., age) were not considered as relevant criteria. Around 70 experts were contacted, out of which there was a 42.8% of response rate and 15.7% of participation. No incentive was provided for participation in our research. A total of eleven participants from industry and academia took part, who reported having expertise within one of the required areas. The participants were evenly distributed through the workshops based on their expertise; see characteristics in Table 2.

Table 2. Summary of workshop participants

Participant ID	**Expertise**	**Experience years**	**Workshop session**	**Type of expert**
P1	Public transportation	(+)15	A	Academic
P2	Biomimicry	(+)8	A	Academic/Practitioner
P3	Biology	(+)25	A	Practitioner
P4	Public transportation	(+)15	B	Practitioner
P5	Biomimicry	(+)20	B	Practitioner
P6	Biology	(+)1	B	Academic
P7	Public transportation	(+)5	C	Academic
P8	Biomimicry	(+)1	C	Practitioner
P9	Biology	(+)20	C	Practitioner
P10	Biomimicry	(+)4	D	Practitioner
P11	Biology	(+)2	D	Practitioner

Note that 12 participants were recruited at first, but 11 participated in the end, meaning that one of the workshops (D) was conducted with two experts only (with biomimicry and biology profiles).

Four iterations of the designed 1.5 hour-long-workshop were hosted. The raw data sets gathered from the workshops in the formats of audio, observations and Miro-boards were all transcribed and later analysed using NVivo and descriptive coding (Saldaña, 2013). The coding process was done using the last three activities of the workshops, since those three steps were designed to generate conclusions through the discussions among the participants; these sections compose around 55% of the data gathered. For the analysis of the dataset, we used a Grounded Theory-enlightened approach (Gioia, Corley, & Hamilton, 2013). Previous research using co-creative workshops as a research method (Madaio et al., 2020; Pradhan et al., 2020) has also implemented this data analysis method.

The data from each workshop was analysed and coded by two coders, who then discussed and selected the final codes together, having the research question as an analysis filter. This coding process produced 80 codes. Those 80 factors contributing to resilience were clustered using thematic analysis, generating 9 themes and 4 aggregated dimensions. For the clustering process, patterns were identified among the codes by forming groups of 6 to 15 codes; the themes present the overarching ideas of those patterns. The aggregated dimensions were conceived similarly.

4. Results

The experts discussed different perspectives, expressing their experiences, concerns about the present, visions of the future with its challenges, and got inspired by nature on how to tackle these concerns and challenges naturally, to achieve resilient public transportation systems.

The co-creation workshops unfolded smoothly. Participants (mainly of a non-designer profile) needed some time to understand the initial mindset that the biomimicry approach and the creative facilitation required, such as postponing judgment and divergent thinking (Heijne & van der Meer, 2019). Nevertheless, when participants were asked to look into nature to find similarities with the topic of discussion, many insights were brought and rich discussions were obtained, in an atmosphere where everyone added to the previously mentioned ideas. We could therefore conclude that the workshop route was successful in creating a creative environment.

Those insights were used to answer the research statement, “creating resilient public transportation systems inspired by biomimicry”, as well as the sub-questions, 1) How to frame the resilience concept in biology into public transportation systems? and 2) What elements or factors can be extracted from nature using biomimicry for creating resilient public transportation systems?

4.1 Themes and aggregated dimensions

Below the themes and the aggregated dimensions identified are presented, beginning with a short summary for each of them:

Features of the **system organization** were suggested, for the control and management of a resilient public transportation system, including policy-making and decentralized systems.

- **Policy making:** Participants identified that public transportation is a public service and it concerns the shared responsibility of different stakeholders, including public entities, private companies, and citizens. These stakeholders must cooperate in order to strive for a resilient system. Moreover, P4 raised “survival of the fittest”; according to the concept, companies that are not flexible enough to adapt to different conditions or policies will not survive in the system. Sustainability emerged as another relevant factor to achieve resilience in the public transportation context. P11 stated, “sustainability… of course, it’s a governmental issue”, suggesting that sustainability in the public transportation context should also be addressed through policy making. With policies aiming for resilience, cities’ stakeholders that comply with those will merely be part of the system.
- **Decentralized system:** By identifying travel areas that are crowded or, on the contrary, underused, the public transportation system can respond to it. P4 phrased this process as analysing the “migration circle”, where he referred to birds as a metaphor for the (daily) public transport circle of people going to work and coming back. Other participants also referred to this as identifying “patterns of travellers”.
  To respond to the uneven demand of travel areas and aim for a decentralized system, the importance of spreading out the population and promoting concentration in different urban areas, emerged in the discussion. Furthermore, a decentralized system allows “shorter links” between origin and destinations, thus leading to route optimization. Moreover, P2 stated that decentralized systems could respond to a smaller area of disturbance quicker.

Operating performance is the second aggregated dimension, where the robustness of the system and efficiency for regulating and accounting for performance of the system emerged as relevant concepts.

- **Robustness of the system:** The system's robustness relates to reliability and the condition of its infrastructure. To strive for resilient public transportation, P4 mentions that the safety of the system is an essential factor to decrease possible disruptions (e.g., accidents). Moreover, he speaks of a robust infrastructure that is “weatherproof all year round”, to optimally perform and make the system more reliable. Another key factor that was identified during two of the workshops was reliability. It was addressed as inspiration when discussing a water ecosystem as “a stream of movement”. It being constant, leads to robustness. P11 mentioned “different needs day and night”, suggesting that adaptations to different needs in different moments can strengthen the robustness of the system.

- **Efficiency:** A key potential for creating resilient public transportation systems is "using energy efficiently" to move in space (P2). This was linked to nature in general and that there is no waste in natural ecosystems.
  To create efficiency within a system, diversity in systems was suggested as designing a system for multiple species, different purposes, or multiple types of trips (P7).
  In three workshops, the concept of timing was mentioned by the participants. This was linked to efficiency, which is maximized when the system is "on the move all the time" (P4). On the contrary to being continuously on the move, the Swiss train system was brought to the discussion, which builds in "stationing buffers" and therefore, the trains are "always on time". Thus, a difference in perception of the relationship between timing and efficiency was identified.

Information management emerged as the third aggregated dimension, where constant feedback, demand sensitivity, adaptability and flexibility in dynamic situations referred to receiving information, translating it into data, and taking action accordingly in the public transportation system.

- **Constant feedback:** By monitoring public transport, user movements and the station areas, input is gathered which can consequently be instrumental for constant feedback. Intelligence and data are suggested as useful tools. P2 and P10 considered that the optimization of routes could be enabled through feedback loops and communication between elements in public transportation, similar to how ants create optimal routes to food sources by giving feedback to each other.
  Moreover, constant feedback can also be beneficial for users when interpreted as signals in the surroundings (e.g., inside the stations); ant colonies were mentioned reiteratively, explaining that they leave "a chemical trail that signals where to go." P5 adds to that notion, suggesting "clues in nature" can help a species find out where to go.
- **Adaptability & flexibility in dynamic situations:** A key challenge for the current public transportation systems, as stated by P1, is their inflexibility; this makes it slow to react and adapt to changes and to improve the adaptability and flexibility of the system as a whole. An example a participant brought that does not support this flexibility in the current infrastructure is guided lanes: "then you have an obstruction, and the system is getting into problems". Besides, to make it flexible, the system has to be adaptable to "different weather conditions, different economic situations, different client wishes" (P4). Constant feedback, enabled by the information gathered and used in the form of data, can potentially contribute to making the system more flexible and adaptable to the dynamism of a transport system.

Moreover, flexibility limits the impact of disruptions and thus aims for a resilient public transportation system. It was also mentioned that by ensuring geographical accessibility, crowdedness can be mitigated.
Apart from that, public transport systems should also acknowledge their "different layers" and "depths" concerning flexibility and adaptability. This notion was raised when taking inspiration from the oceans: "the different layers in the ocean have different depths". This can be translated into "diversified schedules" to match everyone's desired traveling time (P10).

- **Demand sensitivity:** To take action according to the data received, a key challenge identified by participants is that the system has to understand and respond to the demand. By monitoring public transport and identifying crowded areas, P7 stated a need for "demand-responsive infrastructure" or, as P5 phrased it, "flexible on demand". Another public transport expert raised a similar notion: "flexibly align your supply with demand".
Influencing the behaviour of travellers or postponing peak hour is also suggested. P4 indicates: "it helps spread the users, it's a system as a whole more resilient because you avoid the peaks. And the peaks are where things break down." This can be supported by offering flexible pricing or offering more services on board at a certain hour.

The last aggregated dimension is **subsystem integration**, composed of diverse functionalities and travel means, and cooperation and integration between subsystems. It was suggested that keeping the independence within the different subsystems but complementing each other's function and backing up each other when disruptions happen is key to creating resilient public transportation systems.

- **Diversity of functionalities and travel means:** Participants from all four workshops raised the key consideration of diversity of functionalities and travel means. Concerning "diversity of travel means", P8 mentioned: "We can travel by air, we can travel underground, we can travel by water, and we can travel by roads. And by train, so the means indeed". He suggested the concept of "having different purposes mix".
When discussing the ant colonies during one of the workshops, a participant spoke of flexibility as a consequence of the diversity of choice (P3): ants have choices where to go, and this allows for flexibility. Moreover, P11 raised the key potential of combining different kinds of public transport as a challenge for the future of public transport. Later he refers to the notion of diversity in general for him as "quality of ecosystems in the context of resilience".
- **Cooperation and integration between subsystems:** Valuable for creating resilient public transportation systems, participants spoke of scheme and stakeholder adaption in the second workshop. For example, P4 states, "if … schools would start at 10 o'clock in the morning, instead of at eight, it would

make a major difference, then you wouldn't have a peak hour at all, at least not in public transport."
P3 and P1 also noted the importance of cooperation. Subsystems should not be dependent on each other but yet, cooperative and integrative. P5 later refers to this examination as a "symbiotic relationship" as "they're using opportunities that are already there, energy that's already being expended."
As a goal, P2 phrased it as an integrated seamless system, and mentioned the criticality of distributed risk and collaboration between public and private.

4.2 Framing resilience and its factors within the public transportation systems

As a manner to bring the revealed findings together, a conceptual framework on factors for resilient public transportation systems is proposed (see Figure 2)—Its schematical shape and structure are grounded in the framework priorly suggested by Sharifi and Yamagata (2017), which comprises factors and themes that assess urban resilience.

The framework is visualized in the form of a wheel that reads from its centre to the outside. The first, the inner ring, represents the metaphors in which we compare the aggregated dimensions with various elements from living beings. Metaphors were an addition by the authors as a manner to better express the information, while nonetheless expressing the integration of the different aggregate dimensions and their co-dependency. The second ring links those metaphoric terms with more technical titles of the aggregated dimensions. Finally, the outer ring reflects the factors or themes that can be found under those bigger clusters.

Figure 2. A Wheel Framework "Factors of resilient public transportation systems"

The metaphors that were chosen, compare the way a living being functions with how a resilient public transportation system would work, to understand and explain better the quadrants of the framework:

- Resilience through system organization is referred to as the "Brain". As this dimension concerns resilience through a core organizational part of public transportation, this factor should be central, connected to all stakeholders that are part of the system and manage the system as a whole.
- To achieve resilience through information management, it is critical to process information and manage the system. This is similar to the function of the "Sensory nervous system".
- Resilience through operating performance relates to the state or quality of the public transportation system, both on a system-infrastructure level

(robustness) and a functioning level (efficiency). This is similar to living organisms, where their body condition and performance are connected. The body condition can be measured through biomarkers that change according to its state; related to this, public transportation systems' performance can be measured by diverse indicators such as delays, occupancy level or station buffers. Thus, the metaphor used is "Body condition".

- To achieve resilience through subsystem organization, it is suggested that the system is composed of multiple subsystems that work independently but in an integrated way. They support each other when unbalanced situations or disruptions happen. When this occurs, they offer multiple travel means and multiple functionalities options. These act as independent subsystems, but also interact in an integrated way to offer multiple functionalities, similar to biological "Organs".

5. Discussion

The resilience of public transport systems is a priority for the future development and performance of the cities (Hayes et al., 2019) challenging not only policy makers, but also private organisations and citizens. The framing of resilience that has been proposed in this paper contributes to going beyond the infrastructure-focus taken until now within the transportation systems. The main contributions that we achieve from this research are:

Resilience as a multi-factor concept - It arose that resilience is a concept that groups many factors and themes. Within those factors, we found various concepts (for instance, efficiency) that were prior considered as external to the resilience scope, and this research is now embedding them within the systemic approach to resilience in public transportation systems.

A systemic entity is achieved - Beyond the focus on physical attributes in the literature, the factors for resilience expand their definitions to non-material explanations as well. For example, the participants used the term 'robustness' to refer to a broader entity that also contains systemic characteristics like reliability, safety, or constant behaviour.

Besides, a multi-stakeholder context is revealed, and the relationships among the different actors that belong to the system are critical. Resilience is not merely the responsibility of one stakeholder, but as a result of the interactions, the sum of responsibilities lies with all the stakeholders, on a macro level (government) as well as the individual (citizens) (Snel et al., 2019).

Related to this, the public transportation system is suggested to be composed of multiple subsystems that should work independently but in an integrated, cooperative way. The relationships among public and private organisms could be reorganised according to these ideas, in favour of the resilience of the system they all belong to. This causes implications in policy making, which in addition is identified as a factor of a resilient system in our framework. Our framework is coherent with Helmrich et al. (2020a), which suggests that resilience in this type of system complexities can only be achieved through an approach that recognizes deep uncertainty and the interrelatedness of components.

Interrelations with emerging concepts - The research suggests that concepts like smartness and efficiency are factors for achieving resilience, suggesting possible perspectives for the future, where data-driven cities (Arafah & Winarso, 2017) can help to deal with uncertainty and continuous changing conditions in an efficient way, when embedded in a public transportation system conceived from the resilience perspective. The possibility of integrating emerging ways of transportation like shared mobility and MaaS into public transportation systems (Becker et al., 2020), aiming at an increase in system efficiency, whilst keeping it as an independent stakeholder or subsystem also arises. The results of this study lay the groundwork for creating resilience in public transportation systems.

The systemic perspective proposed in the paper is considered a relevant step in the application of resilience in a broader, multi-stakeholder and multi-layered context. Public operators, policy makers, private organisations and users, can benefit from the framework proposed, and apply the factors to their future contributions on resilience. With the framework, designers (and other stakeholders) will be able to assess what resilience factors are missing or underperforming in a transportation system, as well as to design actions that act upon one or various factors or aggregated dimensions, which propose directions for contributing to the resilience of public transportation systems.

Before, research was limited in this area, as the traditional view on engineering resilience was exclusively focused on improving the physical characteristics of the transportation systems to withstand the impacts of occasional threats. Besides, the approaches to resilience in previous work were addressed on bigger (urban planning, cities planning) or smaller scales (infrastructure, engineering, specific transportation means) than the one proposed in this paper.

Beyond the results found, the current paper demonstrates how design can bring different perspectives and fields together; it is a transversal tool, with the capability to take inspiration and learn from diverse sources, abstract the characteristics found, and adapt them the problem or needs of interest. This makes it especially powerful in the resolution of complex, systemic issues for sustainability-oriented innovation development (Buhl et al., 2019).

6. Limitations and future research

The research has some limitations; there was a gender gap among the participants, as 90% of them were male. Additionally, not all the participants are located in the same country; as public transport systems may differ from country to country, this might make it difficult to create a common understanding among participants. It is proposed as the next step for research to validate and iterate on the framework conceived in this paper, having two main questions for further validation: (1) is there any hierarchy that the factors should have? and (2) are there any additional factors missing in the proposed framework?

7. Conclusion

The multidisciplinary co-creative workshops conducted in this research expanded our understanding on the notion of 'resilience' in public transportation systems. Current challenges emerged, that transportation systems need to face, and inspiration was taken from nature to see how those challenges are solved in existing ecosystems. Employing a biomimicry inspired approach, it was possible to identify the different factors that contribute to resilience in public transportation systems, grouped and presented in the framework.

The wheel framework, depicting the "factors of resilient public transportation systems", presents resilience as a multi-factors concept, that goes beyond its traditional infrastructure-focus and understands its implications in a broader, multi-stakeholders' system. This work is proposed as an initial ground for future approaches and research in public transportation from a systemic perspective, where we aim to lay the groundwork for creating resiliency in public transportation systems.

The framework allows for the integration of emerging concepts in transportation and cities planning. Overall, the transversality of design is emphasized, as well as its ability to bring multidisciplinary perspectives together to solve complex, systemic challenges, thus implications for practice include a potential guidance for planners, designers, engineers and politicians to approach problems from a systemic perspective, taking into account the subsystems and different actors embedded in it.

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