IMPROVING URBAN INFRASTRUCTURES RESILIENCE USING CONCEPTUAL MODELS: APPLICATION OF THE “BEHIND THE BARRIERS” MODEL TO THE FLOODING OF A RAIL TRANSPORT SYSTEM

Michaël Gonzva[1,2] and Bruno Barroca[2]
[1] SYSTRA, Innovation Department, 72 rue Henry Farman, 75015 Paris, France
[1] mgonzva@systra.com
[2] Paris-Est University, Lab’Urba Laboratory (“Génie Urbain” Department), Marne-la-Vallée, France
[2] bruno.barroca@u-pem.fr

Abstract

The vulnerability of guided transport systems facing natural hazards is a burning issue for the urban risks management. In this context, several conceptual models of resilience are elaborated for presenting the various possible resilience strategies applied to urban technical systems. One of this resilience conceptual model is the “Behind the Barriers” model based on the identification of four complementary types of resilience: (i) cognitive resilience; (ii) functional resilience; (iii) correlative resilience; (iv) organizational resilience. The purpose of this paper is to offer an application of this model to a specific urban technical system, a public guided transport system, facing a particular risk, a flood hazard. The paper is focused on a past incident on a French Intercity railway line impacted by a river flooding, in 2013. The level of resilience of this transportation line is assessed using the model both as an evaluation and action grid.

1 INTRODUCTION

Several facts and figures reveal the vulnerability of rail network systems facing different natural events, on an international scale. This vulnerability can easily be highlighted through the costs and the repair times of weather-related incidents. In 2006, for example, a 100-year flood event due to the rise of the Morava River occurred at the border of Austria and Slovakia. The flood affected an important line of the Austrian Federal Railways between Vienna and the Czech Republic along a section of around 10 km causing repair costs of more than EUR 41.4 million and a complete shutdown of passenger and freight operations for several months [Moran et al., 2010b, Kellerman et al., 2015]. Sandy storm in New-York in 2012 caused damages estimated at US$ 5 billion only for the metro and associated infrastructures [HCFDC, 2013]. As an overall picture at European scale, the research project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) showed that in terms of the cost assessment, floods caused more than EUR 103 million in damages to railway lines. This value can be compared with the damages on railway lines due to storm, about EUR 0.07 million, and due to snow and low temperatures, about EUR 0.04 million [Enei *et al.*, 2011]. Therefore, the rail transport systems are indubitably vulnerable to many natural hazards and especially to flood events that imply extensive and expensive damages.

Furthermore, the modern cities are dependent on technical systems, considering them as critical infrastructures to ensure their functioning: transportation networks, electricity network, drinking water network, etc. Reducing the vulnerability of modern cities against natural hazards involves improving the resilience of these critical infrastructures, such as transport systems. For this purpose, examining the resilience of rail transport systems appears necessary to increase resilience at urban scale.

2 CONTEXT OF THE STUDY

In this dual context of need for mobility and natural hazards intensification, developing resilience-oriented approaches for analyzing critical infrastructures is became the new parading for the urban risk management since over the last decade. Numerous resilience conceptual models can be identified in the international scientific literature for analyzing urban technical systems facing natural hazards. These models can be classified into 3 main categories [Gonzva 2017]:

- Models aiming at building metrics for assessing resilience through criteria, indicators or required capacities;
- Models consisting in defining a comprehensive framework for shaping the concept of resilience into

several complementary dimensions;
- Models characterizing resilience as a set of successive steps for any analysis.

Several pioneering and dominant models can be highlighted. Firstly, the 4R's Resilience Framework developed by [Bruneau et al. 2003], as a model based on metrics. This model divides resilience into 4 performance criteria:

- Robustness: the ability of elements to withstand a given level of stress or demand without suffering degradation or loss of function;
- Redundancy: the extent to which elements exist that are substitutable, meaning capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality;
- Resourcefulness: the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element;
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

This approach is based on a measurable quantity which varies with time and is defined as the infrastructure's quality of service. This quantity can range from 0% to 100%, where 100% means no degradation in service and 0% means no service is available. Thus, measures dedicated to increasing the resilience of a system aim at improving the system's performance and/or decreasing the time to full recovery [Tierney & Bruneau 2007]. Many models have been developed as a spin-off from the 4R's Resilience Framework, in keeping with the idea of resilience quantification based on the robustness, redundancy, resourcefulness and rapidity [Chang & Shinozuka 2004; D'Lima & Medda 2015; Cimellaro *et al*. 2010).

Secondly, the City Resilient Framework (CRF) initiated and developed by [ARUP 2014] and the Rockefeller Foundation can dually act as a comprehensive framework and a model based on indicators. Indeed, according to the CRF, the urban resilience is based on the resilience of the urban systems characterized by 7 qualities:

- Reflective: reflective systems have mechanisms to continuously evolve, examine and systematically learn from their past experiences and will modify standards or norms;
- Robust: robust systems include well-conceived, constructed and managed physical assets, so that they can withstand the impacts of hazard events without significant damage or loss of function;
- Redundant: redundancy refers to spare capacity purposely created within systems so that they can accommodate disruption, extreme pressures or surges in demand;
- Flexible: flexibility implies that systems can change, evolve and adapt in response to changing circumstances through the introduction of new knowledge, practices and technologies;
- Resourceful: resourcefulness implies that people and institutions are able to rapidly find different ways to achieve their goals or meet their needs during a shock or when under stress;
- Inclusive: inclusion emphasizes the need for broad consultation and engagement of communities, including the most vulnerable groups;
- Integrated: integration and alignment between city systems promotes consistency in decision-making and ensures that all investments are mutually supportive to a common outcome.

Then, the model offers 12 key-indicators in order to assess the 7 aforementioned qualities. The CRF provides and interesting and comprehensive picture of urban resilience including all urban aspects. The CRF is also based on many and well documented past disasters that affected cities. Therefore, the CRF can currently be identified as one of the most relevant resilience model dedicated to cities and urban systems.

The objective of this paper is to provide a concrete application of a resilience conceptual model. The model has been identified in a previous review of the main and current resilience conceptual models realized by [Gonzva 2017]: the "Behind the Barriers" model. This model and its application to an urban technical system are presented in the following sections.

3 THE RESILIENCE CONCEPTUAL MODEL "BEHIND THE BARRIERS"

The resilience conceptual model "Behind the Barriers" (BB) is associated to urban technical systems such as transportation networks, wastewater networks, power supply networks, etc. According to [Barroca & Serre 2013], the model aims at guiding the implementation of resilience strategies and building a reference framework for mediation, exchanges and description of such strategies. These strategies should be regarded as part of the global management of natural risks affecting a city. Hence, the model is particularly suitable for the study of the natural hazards damaging urban critical infrastructures.

This conceptual resilience model required a given technical system and a given natural hazard. In this context, the model is based on the identification of four complementary types of resilience (Figure 1). More specifically, the cognitive resilience is the first pillar of the resilience insofar as knowledge about the risk and the needs of the impacted system and area during or after a crisis is absolutely necessary for drawing up relevant strategies for resilience. Based on this knowledge, the functional resilience, as the second pillar of the model, consists in maintaining the functioning of the system in order to provide the service during and after a crisis. Hence, functional resilience is implemented by working on reliability, increasing redundancy within the system, protecting the most critical components, etc. Beyond these two resilience dimensions so-called "barriers", the system is considered without sufficient protections in the case of a natural hazard occurrence. The correlative resilience corresponds to the capacity of getting correlation between the service providing by the potentially damaged system and the required use. Thus, during the crisis, the correlative resilience highlights the degraded level of service provided by system and the necessary adaptation of the demand (users, passengers, etc.). Finally, the organizational resilience expresses the capacity of local areas impacted by a crisis to mobilize general conditions or larger areas for the recovery. This fourth pillar of resilience is the capacity to promote post-damage recovery especially to technical systems by involving other cities.

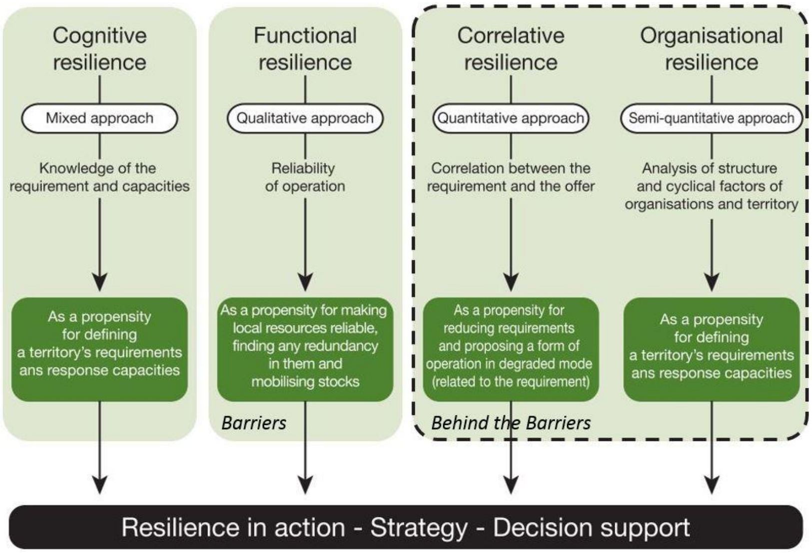

Figure 1. The conceptual model "Behind the Barriers" [Barroca and Serre 2013]

The model was applied to the public waste management during a post-disaster period: after the occurrence of a flood event. Indeed, during flooding, water degrades everything it touches, thereby producing very important quantities of waste. Thus, adapting waste management system and anticipating flooding contributes to improving urban areas' resilience. This is the reason why the model BB appeared relevant for this analysis of an urban technical system impacted by natural events [Beraud 2013].

4 APPLICATION OF THE "BEHIND THE BARRIERS" MODEL TO A FLOODED RAILWAY LINE

4.1 Description of the studied incident

On June 18th and 19th 2013 due to heavy rains, the rise of the level of the "Gave de Pau" river, located in the municipality of Coarraze, caused many disorders on the French Intercity railway serving the cities of Tarbes, Pau and Lourdes. The latter is knowing as one of the world's most important sites of pilgrimage and religious tourism during the summers. About 300 meters of the railway line has been damaged at Coarraze city:

- the flooding of the two tracks involving debris (Figure 2);
- the 80-meter collapse of the track slope : the ballast and the embankment;
- the collapse of a catenary pole on the track (N°1) involving the distortion of the catenary on the other track (N°2);
- a landslide of the track N°2 due to the flooding of the platform.

Figure 2. A picture of the railway line, on 18th June 2013 (photo credit : SNCF)

With a major constraint to reopen the line before August 15th, reinforcements were studied and applied in order to rebuild and stabilize the railway embankment. Indeed, although the Gave de Pau was still flooded and with a short time window (60 days) for works, the followings repair works were carried out [Ponchart & Chretien 2014]:

- The debris, mud and trees elements removal along the impacted section;
- The reconstruction of the embankment using rip-rap for reinforcing it against scouring and erosion;
- The removal and the reinstallation of the ballast and the tracks (rails, sleepers) on the embankment;
- The installations of new catenary poles.

During the works, a shuttle service has been provided by SNCF serving passengers going to and from Pau, Lourdes, Tarbes [La République des Pyrénées, 2013; Tisnès, 2013].

4.2 Application of the “Behind the Barriers” model to Coarraze incident as an evaluation grid: first step

Based on the resilience conceptual model chosen previously, an analysis of the flooding incident occurred at Coarraze is conducted. Indeed, the objective of such an analysis is to illustrate the capabilities of the BB model as an evaluation grid. To go further than just identifying the aspects relating to the four dimensions of the resilience, a rating is assigned in order to assess the quality of the cognitive, functional, correlative and organizational resilience of this railway line against flood events from overflowing rivers The four dimensions are qualitatively assessed using four categories: very low, low, high and very high (Table 1).

A representation of these qualitative assessment is offered using a radar profile (Figure 3). The surface area of the radar illustrates the number and the efficiency of the existing resilience strategies dedicated to the system.

Table 1. *Application of the “Behind the Barriers” four dimensions to the railway incident at Coarraze*

	Cognitive	Functional	Correlative	Organizational
Coarraze incident	Many previous disorders occurred: (i) a retaining wall was built in 1875 after erosions due to the river; (ii) a reinforcement was performed in 1966 after the river flooding; (iii) a closer surveillance was applied since 2012 due to sinkholes after flooding events. In 2013, a partial topographical mapping was made for getting information of internal damages.	As expressed through the cognitive resilience, many reinforcements of the railway line were performed. But, the regular flooding of the close river regularly provoked damages.	A shuttle service were set up by SNCF serving passengers. An efficient communication with users functioning has been implemented.	It can be mentioned that several local companies were involved during the reconstruction of the line. They were rapidly chosen due to the urgency of the rehabilitation.
Analysis	A strong historical knowledge of the risk exists on this railway line and reveals its vulnerability. But, in 2013, due to the repair time constraint, there was a low level of knowledge about required human and material resources.	Despite of civil engineering works for increasing the resistance of the embankment, the reliability of the line remains low. Besides, there is no other strategy implemented such as improving the	The capacity of bus shuttle was lower than the capacity of the railway line. Nevertheless, the service remained acceptable by users during the	According to our survey based on newspaper articles and scientific papers, there was no particular mobilization of the local areas in order to accelerate the

		overall connectivity of regional railway lines.	works period.	recovery of the railway line.
Rating	Very high	Low	High	Low

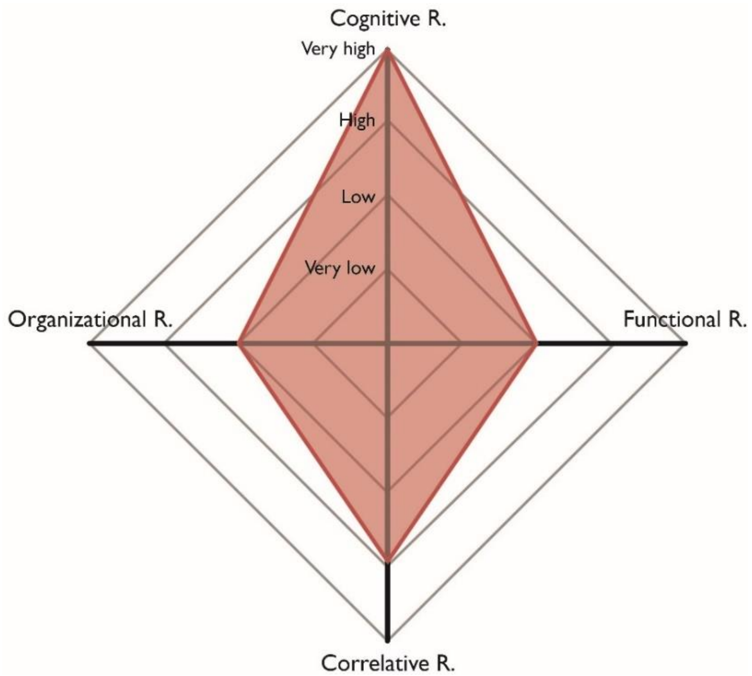

Figure 3. A representation of Coarraze incident assessment using “Behind the Barriers” resilience model

4.3 Application of the “Behind the Barriers” model to Coarraze incident as an action grid: second step

The second step allows by the BB model is focused on action. The first evaluation step provides a global view of the existing strategies available for technical systems’ operators in order to increase the resilience on a system against one or several natural hazards. Then, a second step concerns the ability of the model to act as an action grid: this analysis highlights the aspects on which existing strategies are dedicated.

In the example developed in this paper, the first level of analysis using the BB model shows that the resilience capacity of this railway line against flood events is mainly composed of cognitive and correlative-oriented strategies. Therefore, in order to increase the resilience of this transportation line, the BB model reveals that the development of functional-oriented and/or organizational-oriented strategies could be very relevant.

In this context, other incidents occurred in the world on transportation lines and the risk management strategies implemented can be very useful. For example, in 2012, Sandy storm struck New-York city and particularly damaged the metro. In order to maintain sufficient level of mobility in the city, many organizational solutions were employed: between Brooklyn and Manhattan, 330 buses replaced the missing subway service (the so-called “bus-bridges”) and ferry services to areas particularly hard-hit by the storm were increased or especially implemented with affordable prices during weeks [Kaufman *et al*. 2012]. Thus, the case of Sarry storm shows that the resilience of New-York city’s overall transportation network is basically based on strong organizational-oriented strategies. Therefore, as indicated by [Barroca & Serre 2013], the BB model aims at conveying a common conceptualization, providing references for mediation, exchanges, and description; helping to develop a framework for analysis of the relevance of existing rules; and helping guide resilience strategies. In that case, the BB framework for resilience allows an identification and a transfer of good practices in terms of cognitive, functional, correlative and organizational-oriented strategies for resilience.

5 Conclusion

Rail transportation lines appear to be vulnerable to natural hazards and especially the flood events. The cities are highly dependent on these technical systems, considering them as critical infrastructures to ensure their functioning. Improving the resilience of cities against natural hazards can be efficiently obtained by improving the own resilience of these critical infrastructures, such as transportation systems. For this purpose, a lot of resilience conceptual models exist in the international scientific literature for conducting analyses of urban technical systems facing natural hazards. These models can be classified into 3 main categories: models aiming at using metrics for assessing resilience through criteria, indicators or required capacities; models consisting in defining a comprehensive framework for shaping the concept of resilience into several complementary dimensions; and models characterizing resilience as a set of successive steps for any analysis.

The objective of this paper is to illustrate the capabilities of a resilience conceptual model named "Behind the Barriers" from an incident occurred in 2013 on a French railway intercity line impacted by a river flooding. The level of resilience of this transportation line is assessed using the model as an evaluation grid on the one hand and as an action grid on the other hand. From the identification of four complementary types of resilience, the model aims at providing a common and operational-oriented conceptualization of the resilience, providing references for exchanges and description between stakeholders and helping to develop a framework for assessing existing rules. An interesting perspective could be now to go further into a quantitative way, meaning that the "Behind the Barriers" model could be used as evaluation and action grids thanks to a scoring of different options for improving the resilience of urban technical systems against natural hazards.

REFERENCES

ARUP. (2014). "City Resilience Framework." London.

Barroca, B. & Damien, S. (2013). Behind The Barriers: A Resilience Conceptual Model. *S.A.P.I.EN.S*, April.

Beraud, H. (2013). Initier la résilience du service de gestion des déchets aux catastrophes naturelles - le cas des territoires urbains et de l'inondation. PhD thesis, Paris-Est University.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Kathleen, T., Wallace, W. A., & Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, 19, 733–752.

Chang, S. E., & Shinozuka, M. (2004). Measuring Improvements in the Disaster Resilience of Communities. *Earthquake Spectra*, 20, 739–755.

Cimellaro, G. P., Reinhorn, A. M. & Bruneau; M. (2010). Seismic Resilience of a Hospital System. *Structure and Infrastructure Engineering,* 6, 127–144.

D'Lima, M., & Medda, F. (2015). A New Measure of Resilience: An Application to the London Underground. *Transportation Research, Part A: Policy and Practice,* 81. Elsevier Ltd, 35–46.

Enei, R., C. Doll, S. Klug, I. Partzsch, N. Sedlacek, N. Nesterova, J. Kiel, L. Rudzikaite, A. Papanikolaou, V. Mitsakis. (2011), *Deliverable 2: Vulnerability of transport systems - Main report*. Report prepared within the research project WEATHER funded under the 7th framework program of the European Commission.

Gonzva, M. (2017). Résilience des systèmes de transport guidé en milieu urbain : approche quantitative des perturbations et stratégies de gestion. PhD thesis, Paris-Est University.

Gonzva, M., Barroca, B., Gautier, P.-E. & Diab, Y. (2017). Modeling Disruptions Causing Domino Effects in Urban Guided Transport Systems Faced by Flood Hazards. *Natural Hazards*, 183–201.

Haut Comité Français pour la Défense Civile (HCFDC). (2013). *Retour d'expérience suite à l'ouragan Sandy sur la côte Est des Etats-Unis.* Paris. 92 p.

Kaufman, S., Carson Q., Levenson, N. & Hanson, M. (2012). Transportation During and After Hurricane Sandy. Rudin Center for Transportation, NYU Wagner Graduate School of Public Service.

Kellermann P., Schöbel A., Kundela G., & Thieken A.H. (2015). Estimating flood damage to railway infrastructure - The case study of the March River flood in 2006 at the Austrian Northern Railway. *Natural Hazards and Earth System Sciences*, 15, 2485–2496.

La République des Pyrénées (2013). *SNCF : la ligne Pau-Lourdes rouvrira "autour du 15 août"*, newspaper article published on July 17th.

Moran, A. P., Thieken, A. H., Schöbel, A., & Rachoy, C. (2010). Documentation of Flood Damage on Railway Infrastructure, *Data and Mobility*, 61–70.

Ponchart, I., & Chretien, M. (2014). Remise en état d'urgence du remblai ferroviaire de Coarraze après une crue majeure du Gave de Pau." In: 2nd International symposium railway geotechnical engineering - GEORAIL 2014, 473–482. Marne-la-Vallée, France.

Tierney, K., & Bruneau, M. (2007). Conceptualizing and Measuring Resilience - A Key to Disaster Loss

Reduction." *TR News 250*, May-June, 14–18.
Tisnès, P.-M. (2013). Les trains sur de bons rails, *Sud-Ouest* Newspaper, published on August 9th.