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Contributing to urban resilience to floods with neighbourhood design: the case of Am Sandtorkai/Dalmannkai in Hamburg

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Abstract

On-going changes in cities caused by rapid urbanisation and climate change have increased both the flood probability and the severity of flooding. Consequently, there is a need for all cities to adapt to climate and socio-economic changes by developing new strategies for flood risk management. The following risk paradigm shifts from traditional to more integrated approaches, since one of the main emerging tasks for city managers is the development of resilient cities. The concept of resilience is becoming more and more important, despite the many challenges that interfere with its implementation. The goal of this research is to create knowledge on how to operationalise flood resilience at the neighbourhood level through neighbourhood design. A research approach was used and a qualitative analysis tool, the DS3 model, was developed in order to study a particular neighbourhood of HafenCity, in Hamburg. Results show that design measures involving transportation infrastructure, land use (open public spaces) and buildings have been the main contributions to the flood resilience of the neighbourhood.

Introduction

Flood events consistently demonstrate the necessity to question the preparedness of cities for flooding (EEA, 2008). This is especially the case when considering the backdrop of urbanisation and population growth and climate change, the causes of floods are shifting and their impact is accelerating (Shelfaut *et al*., 2011).

The recent shift in flood risk management, consisting in accepting that Men cannot fully dominate the nature, shows that while it is accepted that floods cannot be prevented, the impacts on, and vulnerability of, the flood risk prone urban systems can be reduced. Today, the concept of urban resilience is emerging as a new approach in the flood risk management field (Cutter *et al*., 2008), leading to projects and strategies that better integrate water and flood risk into city planning and disaster preparedness. Resilience is presented as one of the means by which urban systems can cope with unexpected shocks and achieve sustainability over time (Godschalk, 2003). Reorienting flood risk management by using the concept of resilience introduces creative thinking and innovations into current strategies, focusing on dynamic, systemic and integrated approaches. This takes all the functions of a city and its interactions into account in an organised and multiscale manner (Serre *et al*., 2013). For this, the DS3 model has been developed at this scale (Serre *et al*., 2012) and our hypothesis is that we can use and adapt this model to assess the resilience to flood of a neighbourhood.

Even if resilience applied to the urban context overcomes conceptually and methodologically sectorial analyses, it is difficult to make it operational because it provides multiple translations, in terms of issues and methodology development (Toubin *et al*., 2014). Indeed, urban resilience is currently sometime seen as a 'fashionable' concept from both a theoretical, as well as practical, point of view (Reghezza-Zitt and Rufat, 2015); however, its operationalisation is still unclear. Although its relevance appears evident, actions aiming at flood resilience implementation or operational assessment remain limited (Barroca and Serre, 2013).

Urban planning and design practices create new urban dynamics and possibilities for urban development and transformation; they promote changes in the urban fabric and, therefore, offer opportunities for flood resilience operationalisation. Regarding these disciplines, the neighbourhood scale is interesting for developing new planning and design policies to implement flood resilience as it is often the scale of urban project operations (Saint-Pierre *et al.*, 2010). Although this scale is not the most tackled from a flood risk management perspective compared with larger scales, the neighbourhood scale makes inventing, experimenting and testing possible (Redeker, 2008; Heilemann *et al.*, 2013). The implementation of new strategies and/or measures can be more immediate than on larger scales. In fact, it is at the local scales that cities invest in transformations and/or development. In Europe, some initiatives have already appeared, especially in the North of the EU (wwwFloodResilienCity.eu) to create neighbourhoods with the objectives of making these neighbourhoods more resilient to floods, but this practice is still unusual and it is not clearly demonstrated how these regenerated neighbourhoods are resilient or not. Even though international organisations such as the United Nations and the World Bank (UNISDR, 2005) have emphasised the importance of urban resilience to achieving the sustainable development of cities, it is still not being considered as an essential element of urban projects: the resilience to floods is cursorily addressed at the scale of neighbourhood new or regeneration projects (Balsells *et al.*, 2014). Moreover, even though these neighbourhoods have been defined as being 'resilient', a conceptual framework to analyse and justify how specific urban design strategies and/or measures contribute to improving the flood resilience of neighbourhoods does not exist.

Clear integration between flood resilience and urban design practices at the neighbourhood level has yet to be established. Indeed, there are a lack of tools to raise awareness of this concept and to provide guidance to urban design professionals (architects, planners and engineers) on how to integrate flood resilience into their daily practices (Balsells *et al.*, 2014). Otherwise, from a scientific point of view, almost no reference, except maybe (Colten *et al.*, 2008; Van Herk *et al.*, 2011; Ashley *et al.*, 2012) can be found concerning studies focused on the neighbourhood scale but more on social and organisational perspectives: the resilience of communities. Other resilience assessment models exist (Barroca and Serre, 2013; Serre *et al.*, 2013; Zevenbergen *et al.*, 2015), but not specifically developed for urban planners to supply them resilient options at the scale of their professional concerns, neighbourhoods.

The aim of this research is to address the need for a relationship between theory and practice to study how the concept of resilience can be transformed as an operational way for an operational regeneration urban planning at the neighbourhood scale to integrate flood risks. As a result, knowledge on how to operationalise flood resilience at the neighbourhood level through neighbourhood design is produced. With this aim, on-going developments or already implemented neighbourhoods, identified as presenting 'good practices' for the integration of flood risk in their design as an urban objective, are going to be studied. Thus, given the context presented above, a research methodology was first developed in order to carry out the study.

In this research, a neighbourhood is considered to be a social, economic and physical/technical system. Consequently, studying neighbourhood resilience involves thinking about it in a holistic manner, taking these different urban dimensions into account. In this study, neighbourhood resilience is defined as 'the ability of a neighbourhood to absorb disturbance and recover its functions following these disturbances' (Serre *et al.*, 2013). Hence, with this research approach, the analysis of the flood resilience of a neighbourhood is based on its operation. As such, focusing only on the physical/technical dimension of urban neighbourhoods, and based on a neighbourhood's operation under normal and flooding conditions, the concept of major infrastructure (MI) has been developed to define those urban components which are essential for the neighbourhood's operation and into which it is necessary to integrate flood resilience measures. Three different spatial levels of analysis were identified as being relevant to study neighbourhood resilience. Finally, using these spatial levels of analysis, and the conceptual DS3 (Spatial Decision Support System) model (Serre *et al.*, 2012) we analysed the resilience of neighbourhoods thanks to three capacities described in the DS3 model: resistance, absorption and recovery.

The aim of this study was to apply the research methodology (and the tools developed within it) to a particular case study in order to be able to discuss its relevance in achieving the research objective. First, the research methodology and the tools developed will be described. The application of these tools will be presented, using the study of a particular neighbourhood of Hamburg: Am Sandtorkai/Dalmannkai, HafenCity. Using the DS3 model, certain design measures of the neighbourhood contributing to improved flood resilience are identified. Finally, the results of the analysis and the research methodology are discussed.

Methodology

The research methodology is aimed at creating knowledge on how to operationalise flood resilience at the neighbourhood level through neighbourhood design. This research approach, concerning the analysis of flood resilience, is based on the operation of a neighbourhood, particularly on the urban components which are essential for its proper operation. Yet, it is important to have a good understanding of a neighbourhood's operation under normal and flood conditions to identify these essential urban components.

Focusing on the physical factors of urban neighbourhoods, to improve general understanding of a neighbourhood's operation under normal conditions, an operational safety exercise was developed: Functional Analysis (FA) to identify the functions that have to be performed at this scale (Zwingelstein, 1996). Using the knowledge acquired, an example of a neighbourhood under flooding conditions was studied. The chosen neighbourhood was one in New Orleans which was flooded after hurricane Katrina (Balsells *et al.*, 2012). This stage led to the development of the MI concept and to the identification of three important spatial levels of analysis to study neighbourhood flood resilience. Finally, based on these results and on this research approach, the conceptual DS3 model (Serre *et al.*, 2012) was identified and adapted for use as an analysis tool for this research. It is important to highlight that the result of using this analysis tool was not intended to give a quantitative assessment but rather to provide qualitative analysis, leading to the identification of design measures contributing to the flood resilience of a neighbourhood. Here, design measures are defined as actions taken as a means to achieving a goal which can be incorporated into the development or redevelopment of urban projects.

Using the tools developed, a particular neighbourhood of Hamburg was then studied. The sources of information to carry out the study were based on research and literature (project website – http://www.hafencity.com, research papers, documents and books from the HafenCity InfoCenter), neighbourhood visits (the neighbourhood was visited once, in May 2013), personal information and support of expert professionals (interviews with seven stakeholders involved in the project were conducted (architects, engineers and urban planners)). Using these different sources of information, answers to general questions about the neighbourhood context were sought, especially regarding flood risk (i.e. What are the objectives of the project? What is the nature of the project? What are the main flood risk issues in the area? What are the most important past flood events?) and questions about the integration of flood risk within the neighbourhood design (i.e. Has flood risk been considered as a constraint or an opportunity within the project? What are the main means considered to integrate flood risk through the urban design of the neighbourhood?).

Understanding a neighbourhood's operation

A neighbourhood is '*a part of a city with its own appearance and characterised by distinctive features which give it a degree of unity and individuality*' (Merlin and Choay, 2010). According to its location and geography within the city, its unique physical and social history, the population profile, individual neighbourhoods can, and do, offer a specific number of urban functions and in varying degrees or mixes. Since specific functions are represented in a neighbourhood, specific activities and flows, and consequently urban dynamics, can be identified within it. As it has been shown at the city level (De Rosnay, 1975; Cambien, 2008; Lhomme, 2012), discussing and modelling urban systems at the neighbourhood level is also possible. Thus, in the same way as a city, a neighbourhood can be considered to be an open and complex system which is characterised by exchange processes within its environment and one which is continuously changing and developing.

In this research, a neighbourhood is considered to be a social, economic and physical/ technical system. Consequently, studying neighbourhood resilience involves thinking about it in a holistic manner, taking these different urban dimensions into account. This research considers the physical/technical implications of urban neighbourhoods as a starting point as these aspects are propagating flood risks in cities and territories, organisational resilience is then a perspective of this first approach focusing on this dimension, and using a systemic approach, means that it is possible to then identify a system whose main urban components include: buildings, transport networks and energy networks. Thus, to improve understanding of how the neighbourhood system works an operational safety exercise was developed: FA. FA is a systemic method of understanding and describing how a system works (Serre *et al.*, 2008). It defines the boundaries of the system, its environment, and the functions it provides (Zwingelstein, 1996).

The functional diagram block shown in Figure 1 indicates contact and normal operational flow relationships between a neighbourhood's individual components and its external environment factors.

The study of a neighbourhood operation under flooding conditions (Balsells *et al.*, 2012) has shown the fact that high dependences and interdependences between some of the neighbourhood components can become real issues during flooding. Lhomme *et al.* (2013) demonstrated that among a neighbourhood's components, urban networks play a major role in urban flooding; they are a good example of critical infrastructure (CI). In this research, CI includes all networks and buildings (Figure 2) that are essential for the functioning of society, whose incapacity or destruction could have an important effect on many people over a long period of time (Balsells *et al.*, 2013). However, this concept is not applied to local urban scales such as the neighbourhood scale. This is because flows and exchanges processes characterising the urban system's operation are less important at the neighbourhood scale than on larger

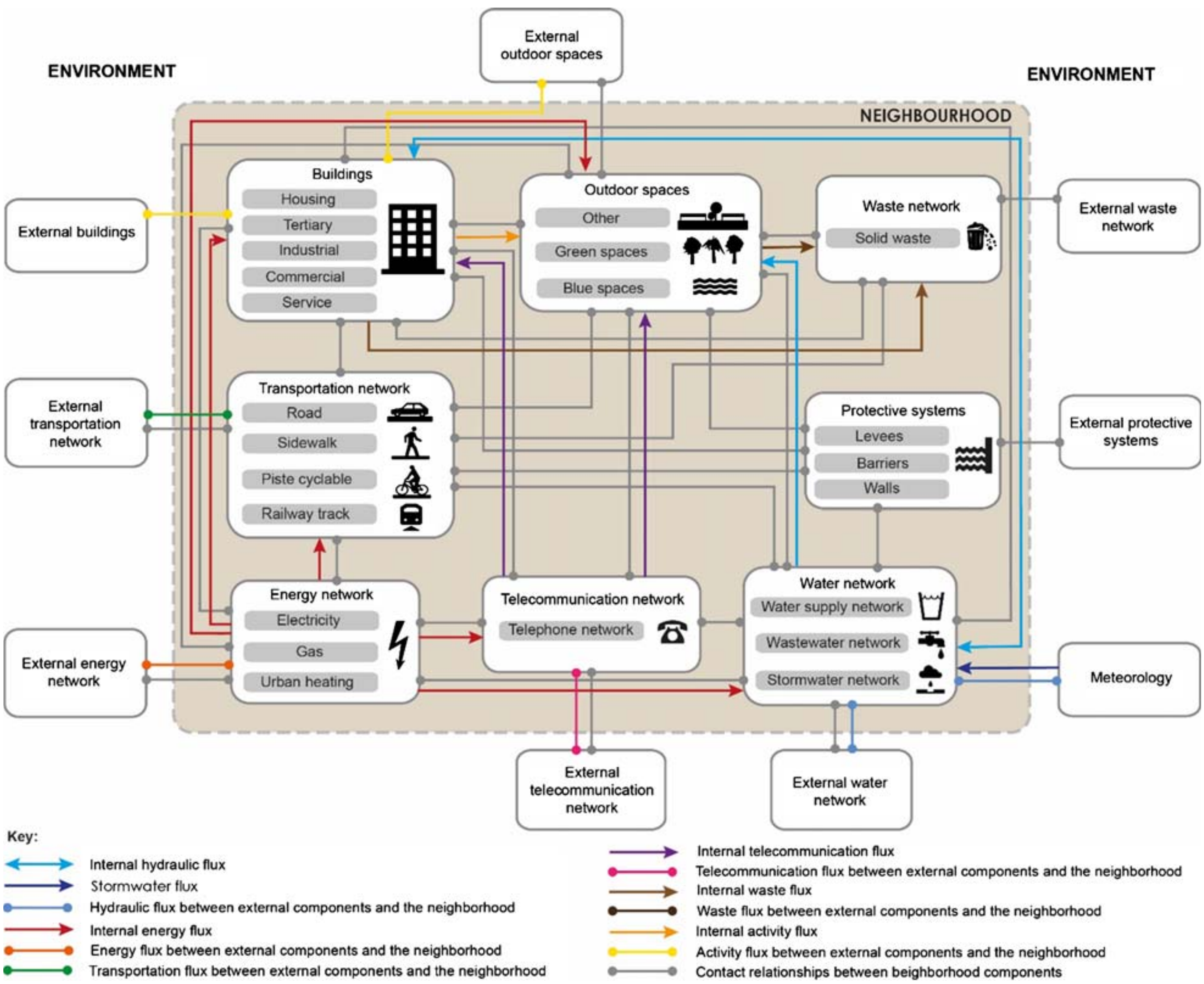


Figure 1 Functional diagram block of contact and normal operational flow relationships.

scales (city, region and catchment) and the people and urban functions involved in its operation are minor. Hence, the concept of MI has been developed for this research in order to define those urban components which are essential for the proper operation of a neighbourhood, whose failure would have a serious impact on its inhabitants. MI could also correspond to CI, so its incapacity could have an impact on larger scales than the neighbourhood scale (Figure 2). Thus, even though, among these components, urban networks play an important role, other components can also be considered.

Furthermore, based on the FA developed, and the neighbourhood challenges under flooding conditions, three different analyses for each capacity could be suggested. The first analysis involves the direct connections between a neighbourhood and its environment. It is used to identify which connections within a neighbourhood contribute to improved resistance, absorption and recovery capacities. This analysis concentrates on the neighbourhood scale, considering the neighbourhood as a black box. The second analysis involves relationships between the neighbourhood's components and therefore relates to the intraneighbourhood scale. It is intended to determine design measures concerning relationships between the neighbourhood's components and the functions which can add to the neighbourhood's capacities. Finally, the third analysis focuses on specific neighbourhood components, to specify how each component is involved in improving the neighbourhood's capacities.

The conceptual DS3 model adapted for this research

Serre *et al.* (2012), according to their urban resilience definition, developed an analysis tool to study the resilience of

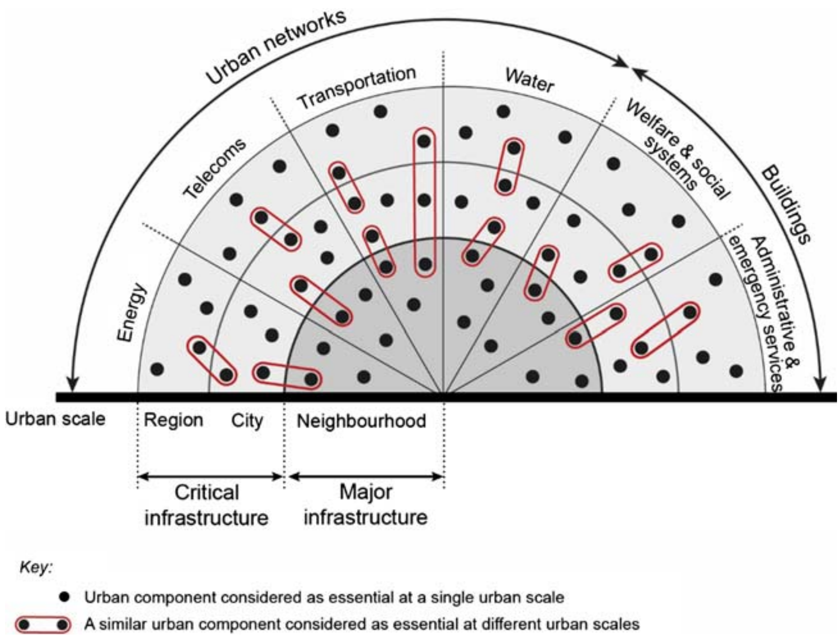


Figure 2 CI and MI across urban scales (Balsells *et al*., 2013).

urban networks: the DS3 model. As hypothesis, we argue this model, based on resistance, absorption and recovery capacities applied to CI networks, can be adapted to the neighbourhood scale. Indeed, in this model, three capacities were identified as essential for studying the resilience of urban networks: resistance, absorption and recovery. The Serre *et al.*'s (2012) approach is based on the operation of interconnected urban systems at the city level and focuses on a physical urban dimension. It considers that CIs, particularly technical systems, are the essential vector for flood resilience. As this research is also based on the urban system operation, but at the neighbourhood level, it appeared apparent that the DS3 model could be adapted and used as an analysis tool in this study. Even though there are other models or approaches (Barroca and Serre, 2013; Zevenbergen *et al*., 2015) aimed at the analysis or assessment of urban resilience, the Serre *et al.*'s (2012) approach is closest to the approach used here. Moreover, the three capacities considered to be essential to studying resilience in the DS3 model are consistent with the definition of neighbourhood resilience developed in this research.

Based on what has just been quoted previously (*Understanding a neighbourhood's operation* section), the logic of the DS3 model adapted to this research was founded on MI damage, in order to argue by that the integration of flood resilience in the neighbourhood's operation is performed through its urban design. To this end, it was important to take all the components of a neighbourhood into account because, even though some of them are not essential for the neighbourhood's operation under normal conditions, they could have an important contribution in improving flood resilience. Each capacity and its adaptation for this research approach are presented below:

- *Resistance capacity*. This is the ability of a system to reduce the damage to its components during negative events. To study resistance capacity, it is necessary to know the potential system damages so that the failure which the system must be able to resist is identified. In this research, the resistance capacity of a neighbourhood has been defined as the ability of a neighbourhood to reduce damage to its MI. The more the MI is damaged, the more a neighbourhood will have a high probability of not operating and, therefore, it will be more difficult to recover operations. Hence, improving the resistance capacity of a neighbourhood is aimed at reducing damage to its MI. Thus, how the neighbourhood design can contribute to this is going to be studied.
- *Absorption capacity*. This is the ability of a system to operate despite negative events. The study of absorption capacity refers to the alternatives that can be offered by the system following the failure of one or more of its components. This requires studying its redundancy properties. Usually, if a component of a system ceases to work (does not achieve its function), a redundant system can mitigate this failure with an alternative. The absorption capacity of a neighbourhood is defined as the ability of a neighbourhood to cope with failures when some of its MI is damaged. A resilient neighbourhood must be able to mitigate MI failures and thereby maintain a certain level of operation. Improving the absorption

capacity of a neighbourhood consists of increasing the alternatives that can be offered by the neighbourhood following the failure of one or more parts of its MI. Consequently, how the neighbourhood design can contribute to creating alternatives will be analysed.

- *Recovery capacity*. This is the ability of a system to put its damaged components back into service according to a time and space lines (Vale and Campanella, 2005). This capacity is the most representative of the resilience concept (Serre *et al.*, 2012). Recovery does not mean returning to a previous state but rather a functional recovery of the system. The recovery capacity of a neighbourhood is defined as the ability of a neighbourhood to bring damaged MI into operation again. This can be improved by reducing the time required for the functional recovery of the MI that incurs damage. Hence, how the neighbourhood design can contribute to recovering an acceptable level of operation, as soon as possible, will be detailed.

Results

In this part, the main hydro-geomorphologic characteristics of a specific neighbourhood are presented in order to truly understand its context. Then the results of the study are presented.

Case study: Am Sandtorkai/Dalmannkai

The study area is an urban neighbourhood in the northwest of HafenCity, a new district located on the waterfront of the City of Hamburg. HafenCity is one of the most remarkable waterfront urban redevelopment schemes in the world. Its trendsetting concept will see the area of Hamburg City Centre enlarged by 40%, with the development sparking changes not only in the existing city centre, but also in the municipality (http://www.hafencity.com/en/concepts/the-foundation-of-hafencity-the-masterplan.html). The project emerged with the aim of building an attractive living environment in the heart of city closely connected with water.

The area lies in the estuary of the River Elbe, and has several harbour basins. This estuary is not protected by a surge barrier so the area is sensitive to tide dynamics. A normal tide may cause differences of 3–4 m in water levels with a high tide water level up to +2.1 m NN (mean sea level). The area occasionally experiences storm surges in the winter season, in which case the high tide water levels can increase up to +5 to +6 m NN (Mees *et al.*, 2014). The highest flood level in Hamburg was in 1976, when the city was submerged by +6.45 m NN of water, which is the reference water level (Kluge, 2012).

HafenCity lies in front of the main dike-line of Hamburg. Rather than building a dike around HafenCity, the city developed a mix of innovative strategies to manage flood risk. Indeed, HafenCity has developed its own flood protection strategy (Redeker, 2008). Am Sandtorkai/Dalmannkai is the neighbourhood chosen for this study and it was the first neighbourhood to be completed in 2009. It is characterised by a dense mix of different uses: housing, workplaces and leisure uses (shops, cafés and galleries). The coexistence of urbanity with village-like life on the waterfront gives this neighbourhood a real charm. The area of the neighbourhood is 10.9 hectares and its density is 137.61 inhabitants per hectare.

Results of the analyses

The results are presented separately, according to the three spatial levels of analysis and using a table for each one. The tables show the different design measures identified as contributing to the capacities and the justification of their contribution to each capacity. Then, for each spatial level, a particular design measure is described in detail (shown by images) and its contribution to improving capacities is detailed.

Connections between the neighbourhood and its environment

Concerning direct connections between how the neighbourhood and its environment contribute to improved capacities (Table 1), several design measures involving transportation connections have been identified (M1A, M1B and M1C) and are described in the table. Another design measure concerning green areas and public open spaces has also been found (M1D), even if it only contributes to the resistance capacity.

For example, one of the measures involving a transportation connection (M1C) is that part of the infrastructure (bridges) connecting the neighbourhood with adjacent parts of the city centre is flood secure (Figure 3). Indeed, since it has been constructed at +7.5 to +8 m NN above sea level, it is higher than the current reference water level (+6.45 m NN) for the city of Hamburg. During normal conditions, this bridge is reserved for pedestrians and cyclists; however, in case of a storm surge flood it would be available to rescue vehicles as well as pedestrians. Thus, having a form of transportation connection infrastructure between the neighbourhood and its environment at higher than the reference water level provides an alternative when the other infrastructure (which are at lower levels: +4 to +5.5 m NN above sea level) do not achieve their function and, as such it contributes to an improved absorption capacity. Furthermore, damages to and the time required

Table 1 Connections contributing to improved capacities

	Analysis 1	Resistance capacity Contribution of the connection to reducing damage	DS3 model absorption capacity Contribution of the connection to creating alternatives	Recovery capacity Contribution of the connection to reducing recovery time
Design measures	Transportation connection M1A: Transportation infrastructure involving multiple and public modes of transport, connecting the neighbourhood and its environment	Provides accessibility to the neighbourhood and connections to its environment (up to a certain water level) to implement prevention measures and to reduce possible damage to MI during a flood. Furthermore, it contributes to reducing the amount of private transport in the neighbourhood and therefore damage to MI that may result from the presence of private transport in the neighbourhood under flood conditions	Offers different types of connections between the neighbourhood and its environment (up to a certain water level). Thus, it provides alternatives when one or more of the transportation modes (MI) cease to work (they do not achieve their function). Their failure could be mitigated by other transportation modes	Provides different possibilities (up to a certain water level) to reach the neighbourhood in order to help MI recover from possible damage as soon as possible. As such, it contributes to reducing the time required for neighbourhood recovery
	Transportation connection M1B: Transportation infrastructure involving `soft' modes of transport connecting the neighbourhood and its environment	Provides accessibility to the neighbourhood and connections to its environment (up to a certain water level) not dependent on motorised transport modes. As such, it contributes to reducing the amount of motorised transport entering the neighbourhood and therefore damage to MI that may result from their presence under flood conditions	Provides accessibility to the neighbourhood and connections to its environment (up to a certain water level) without dependence on energy resources to operate. As such, it offers an alternative when transportation modes (MI) requiring energy cease to work (they do not achieve their function)	Provides accessibility to the neighbourhood and connections to its environment (up to a certain water level) without dependence on energy resources to operate. As such it contributes to reducing the time required for neighbourhood recovery: even if energy resource is not available these transportation modes (MI) can still achieve their function
	Transportation connection M1C: Transportation infrastructure between the neighbourhood and its environment higher than the reference water level	Provides accessibility to the neighbourhood and connections to its environment even under flood conditions. As such it offers a connection to implement prevention measures to reduce possible damage to MI, even under flood conditions	Provides accessibility to the neighbourhood and connections to its environment even under flood conditions. As such it offers an alternative when the other transportation infrastructure (MI) connecting the neighbourhood with its environment cannot be used (they do not achieve their function)	Provides accessibility to the neighbourhood and connections to its environment even under flood conditions. As such it contributes to reducing the time required for neighbourhood recovery because it offers transportation connections to rescue vehicles, as well as to pedestrians, to help MI recover from damage as soon as possible
	Green area and open public space connection M1D: Connection diminishing possible amount and speed of water transmitted between the neighbourhood and its environment	Reduces amount of water, and the speed of water, arriving at the neighbourhood transmitted from adjacent areas. As such it contributes to reducing damage to the neighbourhood because it helps to reduce the impact of the water on MI	No significant contribution	No significant contribution

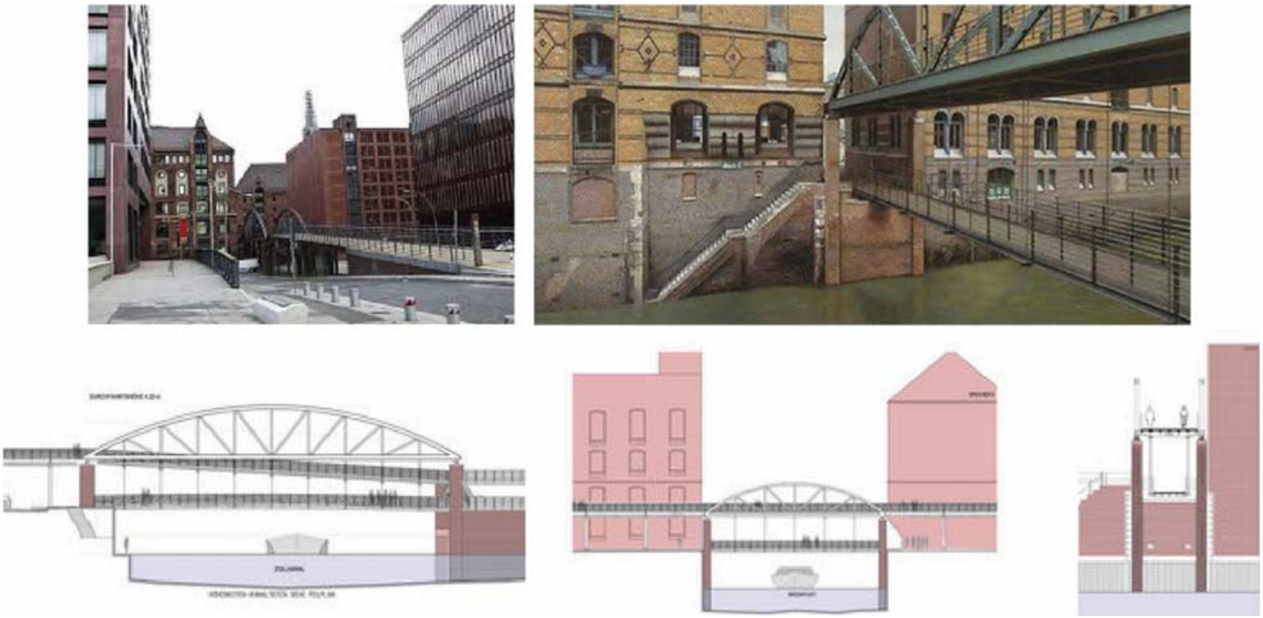


Figure 3 Example of a connection contributing to improved capacities.

for the recovery of, MI can be reduced because it provides accessibility to the neighbourhood even under flooding conditions. Consequently, it is also involved in improving resistance and recovery capacity.

Urban design measures within the neighbourhood

Now the urban design measures which have been identified as contributing to the capacities and which involve relationships between the neighbourhood's components, will be presented (Table 2).

Some urban design measures concerning transportation systems have been determined (M2A and M2B). The neighbourhood consists of several different types of transportation infrastructure (main and collector roads, residential streets, foot and cycle paths) involving multiple and public modes of interconnected transport. Furthermore, there is an extensive network of 'soft' modes of transport which mostly run separately from motorised traffic on promenades, piers and squares. Some of this infrastructure is at +4 to +5.5 m NN above sea level and some others have being built above the flood-line reference, at +7.5 m NN above sea level.

Moreover, some significant land use strategies have also been analysed (M2C and M2D). The neighbourhood has incorporated a high density of uses with a higher proportion of public spaces (terraces and promenades) than necessary access roads. Indeed, road areas take up a low percentage of the land area. What's more, the neighbourhood is characterised by an open multidimensional topography (M2D): urban spaces extend over different levels (Figure 4). While all buildings, and most of roads, are built on artificially raised flood-protected bases, around +8 m NN above sea level, embankment promenades remain at +4 to +5.5 m NN. All open public spaces, whether green areas or promenades, are on the waterside and are closely interlocked. In these lower areas, occasional flooding will be acceptable. This topography provides the neighbourhood the same protection level as the areas of the city which are surrounded by dikes (information from a stakeholder's interview). Thus, an open multidimensional topography provides flood protection to the neighbourhood, creates space for water and allows the neighbourhood's operation even under flood conditions. This can reduce possible damage, as well as reduce the time required for the recovery of the neighbourhood (MI). While components located at a lower levels are less critical (open public spaces such as green areas and promenades), components located at higher levels are more critical (buildings and roads). Therefore, it can be seen that topography increases according to the criticality level of the neighbourhood's components. Additionally, there is no dependency on the protection systems for the recovery of the neighbourhood's operation. This contributes to the improvement of the resistance and recovery capacities and can also contribute to improved absorption capacity, because it provides an alternative to getting around the neighbourhood when the lower areas (+4 to +5.5 m NN above sea level) are flooded.

Finally, some technical network measures have been identified (M2E). Even though technical networks are connected with the rest of the city of Hamburg, they were

Table 2 Design measures contributing to improved capacities

	Analysis 2	DS3 model: Resistance capacity Contribution of the design measures to reducing damage	DS3 model: Absorption capacity Contribution of the design measures to creating alternatives	DS3 model: Recovery capacity Contribution of the design measures to reducing recovery time
Design measures	Transportation measures M2A: Different types of transportation infrastructure involving multiple, public and `soft' modes of transport serving the neighbourhood and being interconnected with each other	Provides connections between all neighbourhood components through different transportation infrastructure (up to a certain water level). As such it contributes to reducing possible damage to MI because it facilitates getting around the neighbourhood to implement prevention measures during a flood	Provides connections between all neighbourhood components through different transportation infrastructure (up to a certain water level). As such it offers an alternative when some transportation infrastructure (MI) does not achieve its function	Provides connections between all neighbourhood components through different transportation infrastructure (up to a certain water level). As such it contributes to reducing the time required for neighbourhood recovery because it offers different possibilities for getting around the neighbourhood to recover MI from possible damage as soon as possible
	Transportation measures M2B: Extensive network of infrastructure involving 'soft' modes of transport	Provides connections between neighbourhood components without dependence on energy resources. As such it contributes to reducing the amount of motorised transport in the neighbourhood and, therefore, reduces damage to MI that may result from their presence under flood conditions	Provides connections between neighbourhood components without dependence on energy resources. As such it offers an alternative when some transportation modes, requiring energy, cease to work (they do not achieve their function)	Provides connections between neighbourhood components without dependence on energy resources. As such it contributes to reducing the time required for neighbourhood recovery: even if energy resources are not available these transportation modes (MI) can still achieve their function allowing people to get around the neighbourhood after flooding
	Land use measures M2C: Open multidimensional topography	Provides flood protection to neighbourhood (without dependence on protective systems) and creates space for water, allowing neighbourhood operation under flood conditions. Components located at lower levels are less critical than components at higher levels. As such it contributes to reducing possible damage to MI and therefore to the neighbourhood operation	Provides flood protection to neighbourhood (without dependence on protective systems) and creates space for water, allowing the neighbourhood operation under flood conditions. Thus, it provides an alternative to get around the neighbourhood when lower areas are flooded	Provides flood protection to neighbourhood (without dependence on protective systems) and creates space for water, allowing neighbourhood operation under flood conditions. Components located at lower levels are less critical than components at higher levels. As such it reduces the time required for neighbourhood operation recovery
	Land use measures M2D: Open spaces and well connected green areas	Reduces impermeability of the neighbourhood and creates space for water within it. As such it contributes to reducing possible damage to MI because it diminishes amount of flood water flowing within the neighbourhood	No significant contribution	Reduces impermeability of the neighbourhood and creates space for water within it. It reduces amount of flood water flowing within the neighbourhood and therefore improves accessibility to recover MI from possible damage. As

Table 2 Continued

Analysis 2	DS3 model: Resistance capacity Contribution of the design measures to reducing damage	DS3 model: Absorption capacity Contribution of the design measures to creating alternatives	DS3 model: Recovery capacity Contribution of the design measures to reducing recovery time
			such it contributes to reducing the time required for neighbourhood recovery
Technical networks measures M2E: Technical networks adapted to flooding	Contributes to reducing possible damage in the neighbourhood since technical networks (MI) are adapted to floods and therefore possible negative impacts to MI are reduced	No significant contribution	No significant contribution
Water network measures M2F: Separate sewer system (dual system for the separate draining of sewage and rainwater)	Contributes to reducing damage to MI and therefore to neighbourhood operation. Hence, it allows more water conveyance thereby reducing possible damage to wastewater pipelines	No significant contribution	No significant contribution
Energy network measures M2G: Decentralised heat production generated locally by means of regenerative energy sources	Provides energy to the neighbourhood in a decentralised manner by means of regenerative energy sources. As such it contributes to reducing damage to MI that depends on energy resources to operate	Provides energy to the neighbourhood in a decentralised manner by means of regenerative energy sources. As such it offers an alternative when remote district heating (MI) ceases to work (it does not achieve its function)	Provides energy to the neighbourhood in a decentralised manner by means of regenerative energy sources. As such it contributes to reducing the time required for the recovery of MI that depend on energy resources to be recovered

Figure 4 Example of a design measure contributing to improved capacities.

Table 3 Specific neighbourhood components contributing to improved capacities

		DS3 model		
	Analysis 3	Resistance capacity Contribution of the component to reducing damage	Absorption capacity Contribution of the component to creating alternatives	Recovery capacity Contribution of the component to reducing recovery time
Design measures	Buildings M3A: Multi functionality of buildings	Provides flood protection and allows the operation of buildings under flood conditions. Urban functions located at lower levels of buildings are less critical than functions located at higher levels. As such it contributes to reducing possible damage to buildings (MI) and therefore to neighbourhood operation	No significant contribution	Provides flood protection and allows the operation of buildings under flood conditions. Urban functions located at lower levels of buildings are less critical than functions located at higher levels. As such it contributes to reducing the time required for building (MI) recovery and therefore for neighbourhood operation recovery
	Buildings M3B: Temporary flood protection measures of buildings	Provides flood protection and allows the operation of buildings under flood conditions. As such it contributes to reducing possible damage to buildings (MI) and therefore to neighbourhood operation	No significant contribution	Provides flood protection and allows the operation of buildings under flood conditions. As such it contributes to reducing the time required for building (MI) recovery and therefore for neighbourhood operation recovery

designed under the precondition that they have to work in case of flooding, as planned during the design of the neighbourhood. Relevant characteristics have also been selected for energy and water networks (M2F and M2G). On the one hand, the neighbourhood's sewer system consists of separate systems for the drainage of sewage and rainwater. On the other hand, buildings are supplied with remote district heating and heating generated locally, for example, from decentralised geothermal or solar thermal plants.

Specific neighbourhood components

Regarding the neighbourhood's components involved in improving capacities (Table 3), buildings are the only type of component which has been considered to be relevant for analysis.

One of the buildings' measures is their multifunctionality (M3A). The basements inside the buildings provide flood-protected underground parking for cars. In case of high water, parking entrances have to close their flood gates. These are waterproof doors and protect the area behind them from flooding. Public amenities (shops, bistros and galleries) are located on the ground floors of most of buildings, while apartments, offices are located in the highest levels of the buildings.

Another measure which has been identified is the temporary flood protection measures of buildings (M3B) (Figure 5). These measures are aimed at keeping floodwater out of buildings; they need to be activated before flood water arrives. They provide flood protection to the neighbourhood's buildings allowing urban functions within them under flood conditions. Thus, they can contribute to reducing possible damage to the buildings and the time required for the recovery of buildings (MI), and therefore contribute to the neighbourhood operation.

Discussion

The set of design measures identified are presented in Table 4 according to the three levels of analysis and the three capacities.

Almost all the measures identified in the first level of analysis are related to transportation connections, affecting the three capacities in a similar manner. These design features mainly have the function of providing accessibility to the neighbourhood and different types of connection with its environment at different water levels. The other kind of measure, concerning green areas and open public space connection, only contributes to the resistance capacity. The resistance capacity is here improved by the function of reducing the amount of water and speed at which water arrives at the neighbourhood. Thus, results of the first level highlight the impact of transportation infrastructure on improving capacities, and therefore, the neighbourhood's flood resilience.

In the second level of analysis, most of the measures identified are related to transportation and land use

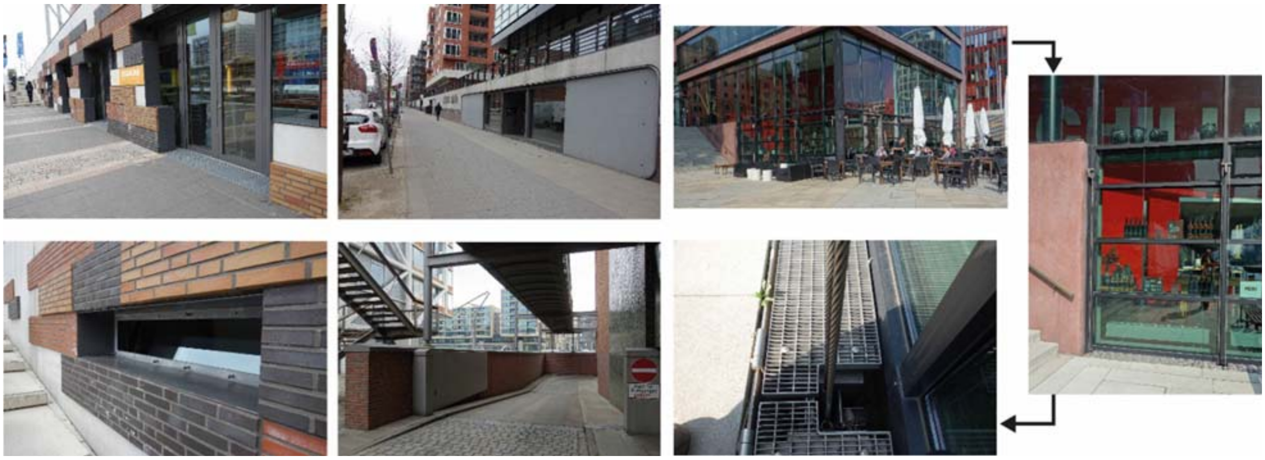
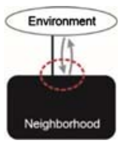
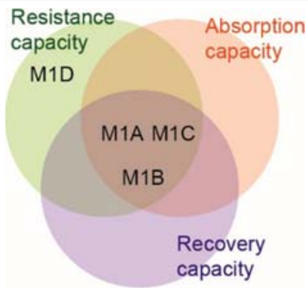
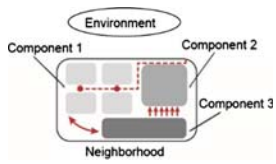
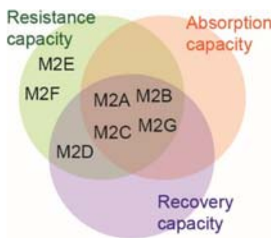
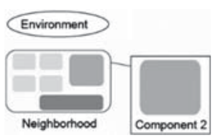
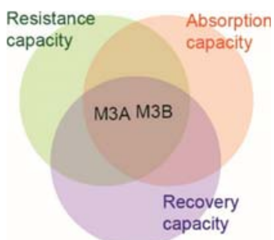


Figure 5 Example of a design measure of a component contributing to improved capacities.

Table 4 Synthesis of the results achieved

Levels of analysis		Design measures identified
Analysis1: neighborhood scale 		M1A: Transportation infrastructure involving multiple and public modes of transport connecting the neighbourhood and its environment M1B: Transportation infrastructure involving 'soft' modes of transport connecting the neighbourhood and its environment M1C: Transportation connection infrastructure between the neighbourhood and its environment higher than the reference water level M1D: Connection diminishing possible amount and speed of water transmitted between the neighbourhood and its environment
Analysis 2: intraneighborhood scale 		M2A: Different types of transportation infrastructure involving multiple, public and 'soft' modes of transport serving the neighbourhood and being interconnected with each other M2B: Extensive network of infrastructure involving 'soft' modes of transport M2C: Open multidimensional topography M2D: Open spaces and well-connected green areas M2E: Technical networks adapted to flooding M2F: Separate sewer system M2G: Decentralised heating production generated locally by means of regenerative energy sources
Analysis 3: component scale 		M3A: Multifunctionality of buildings M3B: Temporary flood protection measures of buildings

strategies. In particular, measures related to transportation strategies contribute similarly to the three capacities. Their function is to provide a connection between the neighbourhood's components at different water levels. Then, measures regarding land use strategy essentially perform the function of creating space for water in the neighbourhood. The 'Open multidimensional topography' affects the three capacities in a similar way; however, the 'Open spaces and well-connected green areas' only participate in the resistance and recovery capacity. Indeed, this second measure improves the permeability of the neighbourhood, reducing amount of water flowing within it. However, it does not allow for temporary water storage, which could increase mitigation options and, therefore, alternatives for the neighbourhood (Balsells *et al.*, 2013). Some measures concerning technical networks have also been identified, mainly contributing to the resistance capacity, like separating the sewer systems. However, here it was difficult to apply the model. Indeed, to better understand the operation of technical networks and how their design affects the capacities, more specific data about the conception, the nature of the materials for example needs to be acquired (Serre *et al.*, 2008; Mugume *et al.*, 2015).

Finally, at the third level, only two design measures have been identified, both related to the same neighbourhood component: the buildings. Their function is essentially to provide flood protection to the buildings, allowing their operation even under flooding conditions. The resistance and recovery capacities are affected similarly by these design features, however, they do not contribute to the absorption capacity. Indeed, the design of buildings gives means of reducing possible damage to the buildings and thereby improves the resistance and recovery capacity of the neighbourhood. However, it has not been considered how the design of buildings could create alternatives for the neighbourhood. It is also important to emphasise the fact that buildings are the only component involved. It may be due to the fact that some years ago several initiatives evolved concerning resilience of buildings, from both theoretical and practical points of view. Nowadays, it is possible to find important and complete literature regarding the flood resilience of buildings. Nevertheless, the measures are mostly aimed at reducing the flood impact on buildings and on assets located inside of these buildings, as was the case in the studied neighbourhood.

Generally the results show that the resistance capacity is the most improved as all the design measures contribute in some way to this capacity. This may be due to the fact that this capacity is the easiest to develop, especially for already existing urban areas. Even though a mix of design measures have been implemented to manage flood risk rather than building a dike around the neighbourhood, the influence of traditional flood risk management is still important in this neighbourhood design. This could show the lack of knowledge among urban design professionals, as well as the lack of tools that currently exist, on flood resilience operationalisation.

Moreover, it is in the second level of analysis (intraneighbourhood level) where more design measures have been identified. Defining design measures at this level can be easier when focusing on physical dimension of neighbourhoods. However, in the first level, organisational aspects could be more involved to improve flood resilience through the neighbourhood design. Hence, social connections between the neighbourhood and its environment contributing to the capacities should be studied. Regarding the third level of analysis, with a deeper analysis of the neighbourhood (considering subcomponents and materials of the neighbourhood components) more design measures could be identified.

This case study is not enough for the validation and enrichment of the tools developed. This is beyond of the scope of the research presented in this article, but some points of attention are presented here. Results from this research show that the DS3 model used as a qualitative analysis tool is clever to apply as the concept of resilience is defined and transposed as operational capacities. These capacities are interesting for studying the physical implications of a neighbourhood for improving its flood resilience. However, if other urban dimensions had also been considered, maybe other capacities would have been integrated, such as the capacity of self-organisation when considering social dimension.

Conclusions

Urban development, regeneration and retrofitting can be seen as an opportunity to operationalise, and therefore improve flood resilience, that are not currently being taken advantage of. Indeed, the Flood Directive obliges to take into account flood risks as all the EU territory is supposed to be likely flooded, but in some EU countries, flood risk is even now not clearly addressed. Literature provides almost no guidance on how to operationalise flood resilience at the neighbourhood level, particularly through urban design practices. There is a lack of tools which can help urban design professionals know how to integrate flood resilience in their daily practices. Yet, there is a growing need to share information and best practices in the field of flood resilience operationalisation across cities and countries.

The research approach and the analysis tools presented in this article allow identifying the design measures of a neighbourhood which contribute to improved flood resilience at the neighbourhood level. However, further research is recommended for their validation, as is international comparison between case studies. After more validation, the research approach and tools presented could therefore have international relevance as they could help urban planners, architects, engineers and other stakeholders to better understand the requirements to shape flood resilient neighbourhoods through neighbourhood design.

Regarding the results achieved in this particular case study, design measures involving transportation infrastructure, land use (open public spaces) and buildings offer the main contributions to the capacities and, therefore, to the flood resilience of this particular neighbourhood and we have been able to assess how each infrastructure design contributed to the resilience of the neighbourhood, through the three capacities of the DS3 model. The results are consistent with the assertion in the methodology part of the paper regarding the fact that MI has a main role in the proper operation of the neighbourhood (under normal and flood conditions) and therefore improving its flood resilience (such as 'transportation infrastructure' and 'buildings' in this example), but other urban components should also be considered when improving flood resilience at the neighbourhood level (such as 'open public spaces and green areas' in this example).

Even though economic aspects have not been considered, most of the design measures identified as contributing to the capacities are aligned with other objectives related to sustainable urban development, which in turn contributes to its cost effectiveness (Toubin *et al.*, 2012). Moreover, knowledge acquired from this research highlights the importance of a social dimension when focusing on urban design practices at local scales; thus, further research is recommenced into social aspects involved in the urban design of neighbourhoods.

Finally, transferring best practices to other neighbourhoods from other countries is likely to be a major challenge as each neighbourhood, and more particularly each country, has its unique geographical, cultural, and socio-economic features requiring customised design strategies and measures. Nevertheless, it represents a first step towards increasing the awareness of urban design professionals about flood resilience operationalisation.

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