# Towards a Generic Metamodel for Urban Resilience Assessment

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**ABSTRACT**

The proliferation of natural and artificial disasters in the last decades has made urban resilience enforcement a strategic goal of city governments worldwide and a hot research topic for academics and practitioners. Consequently, several urban resilience assessment and improvement frameworks have been proposed. Some frameworks have associated operational tools, but these systems are not interoperable with other frameworks' utilities, forcing cities to use different tools for evaluating various aspects of resilience. Since data must be converted manually from one tool to another, the conversion may be error-prone and tedious. In this paper, we report the steps toward defining an urban resilience metamodel that intends to be at the core of a multi-framework urban resilience management portal. Our goal is to provide city administrators with a single operational tool able to evaluate resilience according to different frameworks, thanks to the definition of semantic interoperability mechanisms between the frameworks and the metamodel.

**Keywords**

Urban Resilience; City Resilience; Metamodel; Semantic interoperability.

## INTRODUCTION

Accountability and transparency of government actions and policies are among the main requirements of citizenship nowadays. These requirements are even more vital when policies deal with people's safety and security, as in the case of Urban Resilience (UR) enforcement. By UR, "*we refer to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity*" (Meerow et al., 2016).

Several UR frameworks have been developed in the last decade to address building more resilient cities (Büyüközkan et al., 2022; Yang et al., 2021)). Most of them are conceptual and focused on various aspects of UR, with a majority dealing with climate change. In general, UR frameworks define an iterative UR building process that includes, in one way or another, the actions included in Deming's cycle (Plan-Do-Check-Act, or PDCA) (Deming, 2018; Moen & Norman, 2009). Each cycle starts by choosing and applying some procedures or policies. Next, an evaluation based on a multi-dimensional UR model is performed; the assessment is made using sets of questionnaires addressed to the stakeholders involved in the process. Several indicators take their values from the responses to such questionnaires. Finally, a dashboard summarizes the results of the evaluation. From them, city administrators may plan the next iteration of the process by defining and enacting policies whose success is evaluated in the subsequent process iteration (see, e.g., the one described in (Assumma et al., 2020)).

In general, current tool support for UR frameworks could be more holistic, i.e., there is no tool supporting the overall UR building process. Instead, only specific phases of the process, if any, are supported, e.g., the evaluation stage, where questionnaires are managed using general-purpose polling tools; the answers to the questionnaires are exported to some format and loaded in analytical tools like MS Excel. This activity is error-prone and requires human participation in these repetitive tasks. Additionally, different frameworks perform evaluations in specific aspects of UR in a way that city administrators interested in two or more parts of UR (e.g., climate change, urban planning, etc.) are forced to use various frameworks (and their corresponding tools, if any), which requires multiple definitions of the city profile, and hinders a unified view of the city resilience level. As Ribeiro & Pena (2019) state: *"Although the concept of urban resilience points to a broad set of basic characteristics, there are few tools that incorporate them in an integrated way. Thus, this shortage of procedures and operational tools to evaluate the potential resilience of an urban system represents a gap in this research area, creating a challenge and opportunity for future work in this area"*.

Following this challenge, we try to answer the research question: *"is it possible to develop a single, multi-criteria tool to support UR improvement processes?"*. With this question in mind, the INCREMENTAL project's goal is to develop a portal for the holistic management of UR building processes (Canós et al., 2022). The portal aims at serving as a central resource for cities interested in developing UR improvement processes. Based initially on the Smart Mature Resilience (SMR) model (Smart Mature Resilience, 2018), the portal aims to cover as many UR frameworks as possible in the mid-term. Such comprehensive coverage requires semantic interoperability between the models underlying the different UR frameworks. To achieve it, in this paper, we describe our ongoing work in defining a generic UR metamodel that, situated at the core of our UR management portal, allows us to explain the different UR models as instances of the metamodel. In doing so, city administrators will have a single resource to manage different perspectives of UR without using different tools for each one.

The so-called *Urban Resilience Metamodel* (URM) is structured in 5 packages, each addressing a different aspect of UR management. In this paper, we focus on the package describing the fundamental concepts of the UR model. We show the entities of the model and their interrelationships and outline the semantic mappings between the models of three UR frameworks (namely, SMR, the City Resilience Index, and RAF) to illustrate how they can be described as instances of URM.

The remainder of this *work-in-progress* paper is structured as follows. After providing background about the SMR approach to UR building, we outline all the packages of the metamodel and give a detailed description of the UR Model. Next, we show how SMR and two other UR frameworks are modeled as instances of our generic metamodel. Some conclusions close the paper.

## BACKGROUND

Our work is grounded in the approach to UR building defined in SMR, an EU's Horizon 2020-funded research project developed between 2015 and 2018. Its main goal was to define a UR maturity model, plus a roadmap for UR improvement following the so-called European Resilience Management Guideline (ERMG). As a result of the SMR project, a set of tools, user manuals, and video tutorials were produced. ERMG was successfully applied in 7 European cities (visit https://smr-project.eu for details).

At the core of the SMR suite of tools, there is the *Resilience Maturity Model* (RMM, see Figure 1) organized along five maturity levels or stages (*Starting, Moderate, Advanced, Robust*, and *verTebrate*). The resilience level of a city is assessed along four main dimensions (*Leadership and Governance*, *Preparedness, Infrastructure*, and *Resources and Cooperation*). Each dimension is further subdivided into several sub-dimensions (*L1, L2*, etc.) to sum up to 10 subdimensions. At the intersection between each stage and sub-dimension (a cell in the table), there is a list of good practices or policies that cities must implement to move to the further stage. Completing such

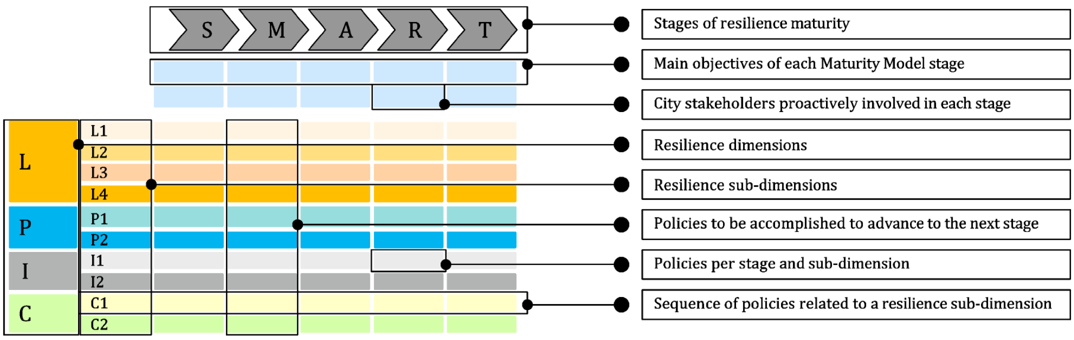


**Figure 1 Overview of SMR's Resilience Maturity Model (taken from CEN, 2018)**

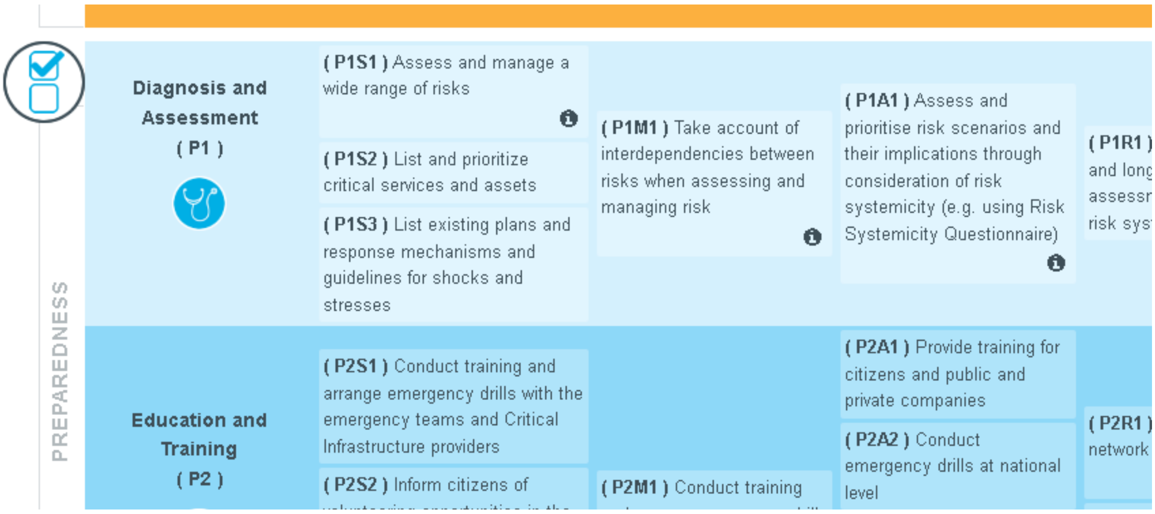


**Figure 2. Detail of policies defined for P1 and P2 in SMR (taken from SMR's Resilience Maturity Model, 2018)**

policies makes the city scale up to the next level in the maturity hierarchy.

Figure 2 shows an excerpt of RMM corresponding to the sub-dimensions P1 (*Diagnosis and Assessment*) and P2 (*Education and Training*). Notice that policies are just enumerated, and cities can implement them in their most convenient ways. The identifiers of policies (e.g., *P2M1*) are built from the subdimensions (e.g., *P2*) and stage (e.g., $M_i$ with i=1, 2, 3…).

Another essential tool in SMR is the Risk Systemicity Questionnaire (RSQ) (Pyrko et al. 2017), which helps identify the most critical risks for a city. The questionnaire presents various risk scenarios to be explored by the users. Besides this, the Self-Assessment Tool (SAT) also uses questionnaires to assess the maturity level through questions about the degree of completion of the policies associated with each stage and dimension in RMM. Several indicators are used to evaluate the degree of achievement of policies in a similar way to (Cutter et al. 2010).

## THE URBAN RESILIENCE METAMODEL (URM)

As pointed out by (Ribeiro et al., 2019), most UR frameworks are grounded in multi-dimensional models, just like SMR. Some of them include maturity levels, while others do not consider maturity. But essentially, there is a common ground that allows some kind of vocabulary unification. URM aims to generalize the properties observed in several UR frameworks, as described later. Our goal is to be able to explain any framework as one of its instances. The overall structure of URM includes the following packages:

`URModel:` describes the main concepts of resilience models, such as dimensions, which can be refined into sub-dimensions, policies, or indicators, among others.

`MeasurementModel:` adds a measurement model to URModel to describe the relevance (or weight) of each element of the model concerning the others, so that an assessment of the degree of achievement of the UR goals can be obtained.

`ProcessModel:` defines a BPMN-like process metamodel. The frameworks' UR building processes will be described in this metamodel. Its compatibility with industry-standard process metamodels will allow a process support system to enact and monitor the development of the UR building processes (Penadés et al., 2022).

`QuestionnaireModel:`allows the definition of the sets of questions to be asked to the different stakeholders during the evaluation stage of the UR building process.

`QuestionnaireAnswerModel:`handles the answers that the stakeholders will give to the questionnaires.

In the remainder of this paper, we give a complete description of the `URModel` package. We use the Unified Modelling Language (UML) Class Diagram Notation. A full specification of the URM is currently in its final stages within the INCREMENTAL project.

### The URModel package

Figure 3 shows the expanded view of the `URModel` package. We consider UR models (`ResilienceModel` class) as two-faceted artifacts. On the one hand, they are structured as a list of `Dimensions` that can, in turn, be divided into sub-dimensions (which are also dimensions). On the other hand, many UR models are organized in maturity levels or `Stages`. At the intersection between stages and dimensions, a `Strategy` is defined. It consists of a set of policies (`Policy` class) to be developed. The policies aim to solve, avoid, or alleviate some `Risks` and can be refined into actions to be taken. There may be some orderly relationship between policies, which states that some must be applied before others. Also, some `Stakeholders` can be involved in the development of some policies. Some classes in this package have relationships with classes in other packages that are not described here.

Indicators are aimed at measuring the degree of accomplishment of policies. They can be either qualitative or quantitative, as described in the `MeasurementModel` package (not shown here). Indicators can be defined not only to assess the degree of accomplishment of a policy but also to measure the development of actions. The structure of the metamodel requires that, in case of maturity-less models (i.e., where stages are not part of the model), we use a generic "no-stage" instance of the `Stage` class to have access to policies and indicators via the association between `Stage` and `Dimension`.

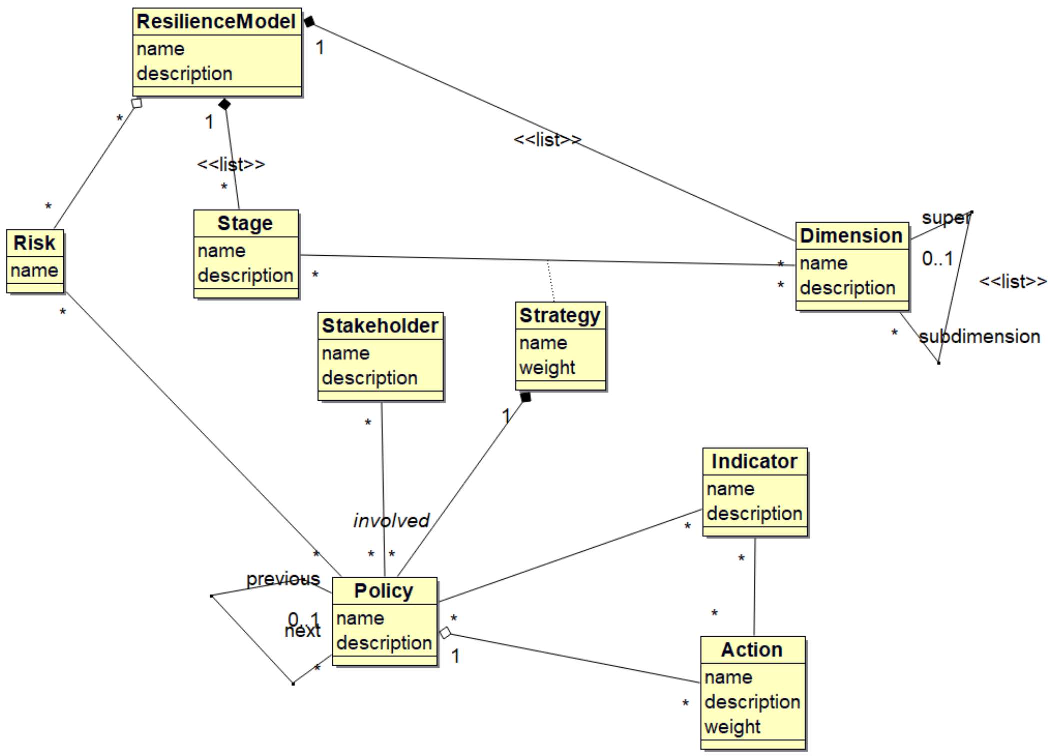


**Figure 3: URModel package class diagram**

### RESILIENCE MODELS AS URM INSTANCES

We intend to use URM as the core of a UR management portal able to cope with as many UR frameworks as possible. We aim to provide city administrators with a single resource where different aspects of UR can be evaluated from different perspectives provided by the integrated frameworks. Using the portal, city administrators can create a single city profile and use the different frameworks for assessing UR according to their respective models.

Such functionality requires the establishment of semantic interoperability mechanisms able to reduce the semantic heterogeneity between the specific framework models and URM. This means defining the semantic relationships between each model and URM and, second, representing the model as an instance of URM. In this section, we illustrate our approach with three UR frameworks: SMR, the City Resilience Index and RAF. Appendix A shows a comparative table of URM with all of them.

### Mapping SMR's RMM to URM

**Table 1. URM-RMM mappings**

| URModel classes | RMM concept |
|---|---|
| `Resilience Model` | Resilience Model |
| `Stage` | Stage |
| `Stakeholder` | Stakeholder |
| `Dimension` | Dimension |
| `(Sub)Dimension` | (Sub) Dimension |
| `Strategy` | Stage per Subdimension |
| `Policy` | Policy |
| `Indicator` | - |
| `Action` | - |
| `Risk` | - |

Table 1 shows the semantic mappings we defined to represent SMR's RMM as an instance of URM, as far as the `URModel` package is concerned. The mappings with SMR are straightforward since URM was built on top of RMM. Notice that entities like `Risk`, `Action`, or `Indicator` defined in URM are not applicable in this package for RMM. We used the mappings to draw the object diagram of Figure 4, which shows part of the representation of the RMM model outlined in Figure 2.

RMM, represented as an instance of URModel, is composed of several dimensions (namely, `LeadershipGovernance` and `Preparedness`). The latter has two sub-dimensions (`Diagnosis&Assesment` and `Education&Training`). The lowest maturity level of the model is `Starting`, an instance of the class `Stage`. The objects `Starting-Diagnosis&Assesment` and `Starting-Education&Training`) represent the intersections between (sub)dimensions and stages, and contain policies named `P1S1`, `P1S2`, and `P2S1`.

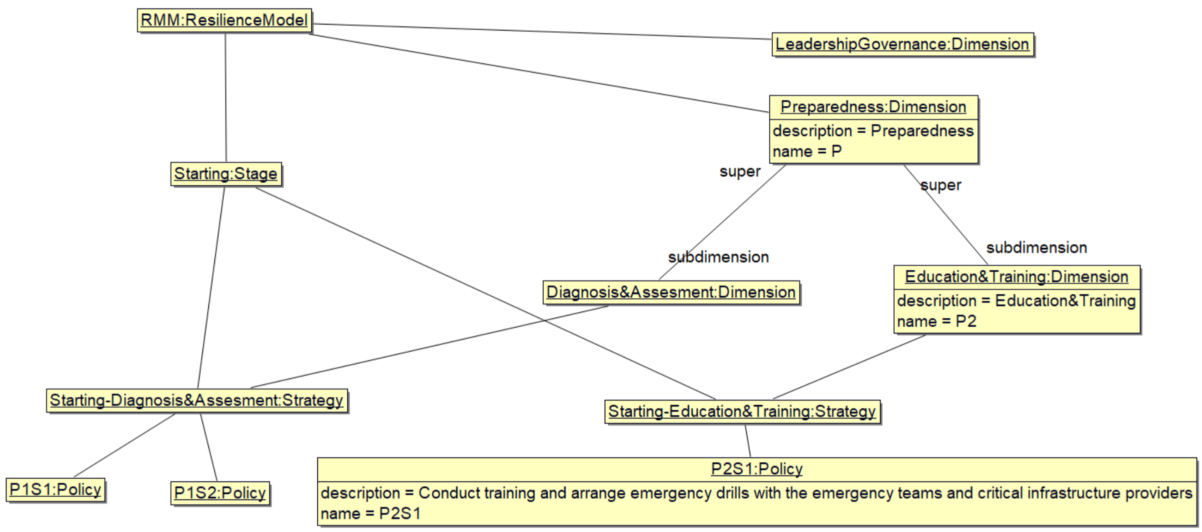


**Figure 4. Object diagram showing part of SMR Resilience Model as an instance of URM**

### Mapping the City Resilience Index to URM

Arup developed the City Resilience Framework (CRF) with financial support from the Rockefeller Foundation (Arup, 2015). Like SMR, its primary goal is to help cities to build UR against climate change under the assumption that resilience results from individual and collective action at various levels, delivered by multiple stakeholders ranging from households to municipal government.

The City Resilience Index (CRI) is the main asset of CRF and evaluates the resilience of a city following a model that includes 4 categories, 12 goals, and 52 indicators (see Figure 5). The categories are *Health and Well-being*, *Economy and Society*, *Infrastructure and Environment*, and *Leadership and Strategy*. Each category includes three goals that describe what should be achieved to improve resilience in each dimension. For instance, *Health*

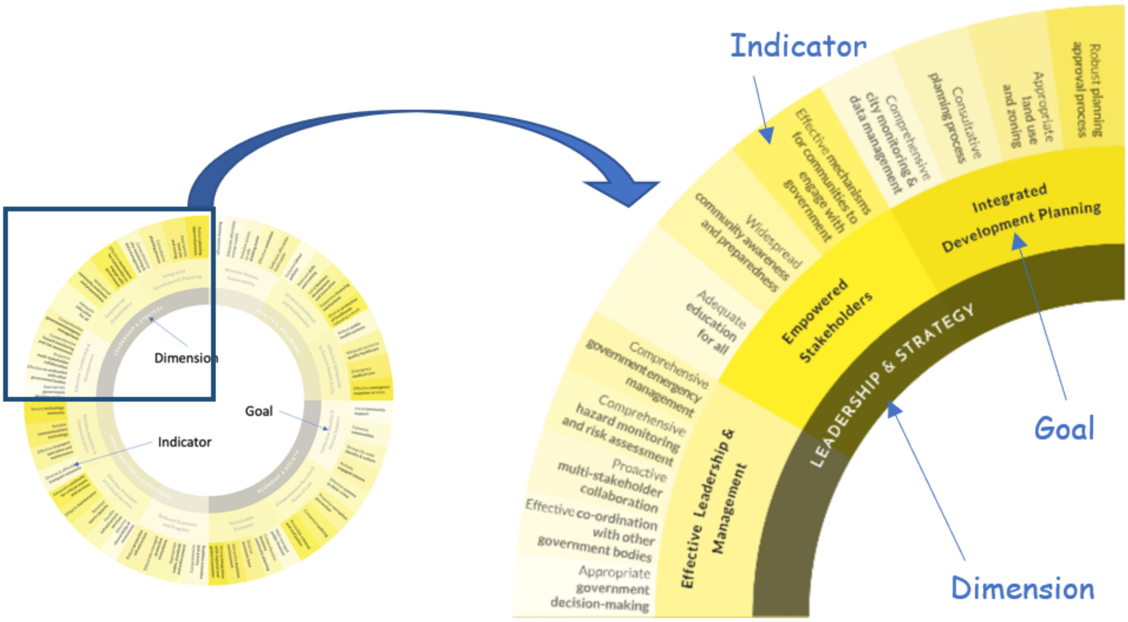


**Figure 5. The City Resilience Index (taken from (Arup,2015))**

*and Well-being* includes the goals *Minimal Human Vulnerability, Diverse Livelihood and Employment,* and *Effective Safeguards to Human Health and Life.* Notice that goals describe the outcome of actions to build resilience, not the actions themselves. The degree of achievement of each goal is measured through a set of indicators.

The semantic mappings between CRI concepts and URM classes are shown in Table 2. Some URM classes are not considered in CRI, such as `Stage`. As we have said before, to be able to access policies and indicators, we will use a generic class called no-stage. Some CRI concepts have a direct representation in URM, such as `Stakeholder` and `Dimension`, while Goal is mapped to `Policy` and Performance indicator to `Indicator`. The CRI Resiliencie Model as an instance of URM is composed of several instances of *`Dimension`* namely *Leadership&Strategy*, *Health& Wellbeing*, *Economy&Societny* and *Infraestructure & EcoSystems*. The object diagram of Figure 6 shows *`Leadership&Strategy`* as *`Dimension`* related with `NoStageXLeadership&Strategy` and this with `EmpoweredStakeholders`**.**

**Table 2 URM-CRI mappings**

| URModel classes | CRI concepts |
|---|---|
| `Resilience Model` | Resilience Model |
| `Stage` | No-Stage |
| `Stakeholder` | Stakeholder |
| `Dimension` | Dimension |
| `Strategy` | Set of policies |
| `Policy` | Goal |
| `Indicator` | Performance indicator |

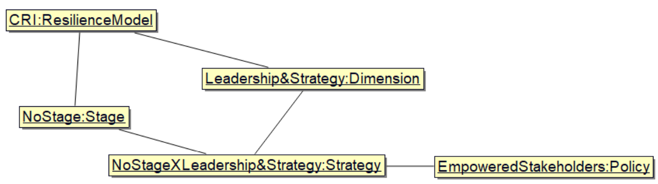


**Figure 6. Object diagram showing part of CRI Resilience Model as an instance of URM**

**Mapping the Resilience Assessment Framework (RAF) to URM**

RAF is a UR assessment framework developed in the RESCCUE (*RESilience to cope with Climate Change in Urban arEas - a multi-sectorial approach focusing on water*) project, funded by EU's Horizon 2020 between 2016-2020 (Cardoso et al., 2020). Again, the scope of RAF is climate change, but this case focused on the urban water cycle. Its main goal is to help cities to build Resilience Action Plans by providing a structured UR diagnosis, supporting decision-making, and monitoring progress in the UR building process.

RAF's assessment model is based on four main dimensions (*Organisational, Spatial, Functional,* and *Physical*), which can be divided into sub-dimensions called services. For example, the *Functional* dimension considers six services that refer to strategic urban services (in this case, *water, wastewater, stormwater, waste, energy*, and *mobility*). For each service, several resilience objectives are identified; each objective is defined in terms of specific key criteria. Each criterion is assessed through one or more metrics. Figure 7 shows the RAF tree structure of a service.

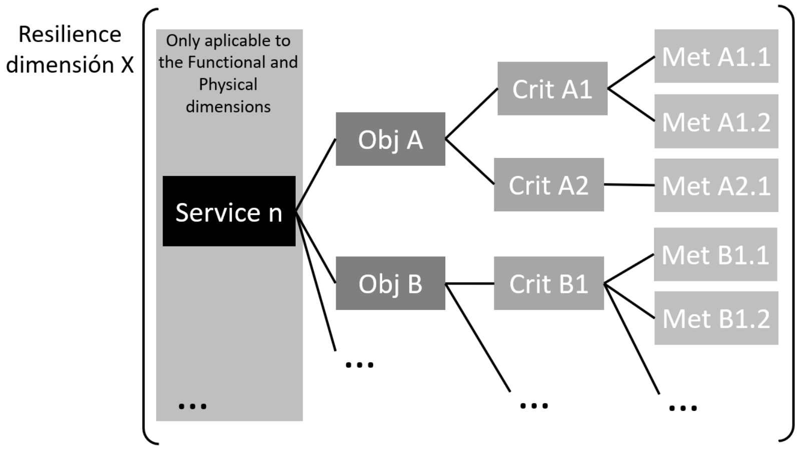


**Figure 7. Components of the RAF model (taken from (**Cardoso et al., 2020**))**

To complete the model, reference values are defined for each metric, allowing one to assign a resilience maturity level to a particular service or to all the city services. RAF defines three maturity levels, *Essential*, *Complementary*, and *Comprehensive*, from the lowest to the highest.

RAF assesses the impact of the resilience strategies implemented on cities through metrics, assigning a maturity level as the result of the assessment. The city or service can increase its maturity level by meeting the higher-level metrics, which implies a higher level of compliance with the resilience objectives in each dimension. Therefore, RAF also monitors the progress of a city or service.

An excerpt of the RAF model is shown on the left side of 8 (*Functional* dimension, *Water* service, resilience objective (*FW1-Water Service Planning and Risk Management*), criteria (*strategic planning, resilience engaged service, risk management*, …), and metrics (*FWts01* to *FWts05* for the first criterion). Each metric is specified, and a maturity level is assigned. For instance, the right side of 8 shows the *FWts01* metric.

| OBJECTIVE<br>Criterion<br>PI | | PI unit |
|---|---|---|
| **Obj.FW1 - WATER SERVICE PLANNING AND RISK MANAGEMENT** | | |
| Strategic planning | | |
| FWts01 | Water service strategic plan making and implementation | (-) |
| FWts02 | Plan alignment with the City Master Plan | (-) |
| FWts03 | Service plan monitoring and review | (-) |
| FWts04 | Exchange of information to the city | (-) |
| FWts05 | Land use zoning compliance | (-) |
| Resilience engaged service | | |
| FWts06 | Resilience in water service strategy and alignment with City Master Plan | (-) |
| FWts07 | Service strategic plan for resilience and CC | (-) |
| FWts08 | Service financial plan and budget for resilience | (-) |
| FWts09 | Water service business continuity | (-) |
| FWts10 | Co-ordination with other water services in the city | (-) |
| FWts11 | Learning from other water services | (-) |
| Risk management | | |
| FWts12 | Risk information related to the water service | (-) |
| FWts13 | Damage and loss estimation | (-) |

**FUNCTIONAL**

**WATER**

| PI code | PI name | Unit |
|---|---|---|
| **FWts01 - Water service strategic plan making and implementation ( - )** | | |
| Does the service have a strategic plan and is it implemented | | |
| **Dimension** | Functional | |
| **Subdimension** | Water | |
| **Resilience objective** | Water service planning and risk management | |
| **Criteria** | Strategic planning | |
| **Source** | UNISDR Scorecard P1.1 (adapted) | |
| **Importance** | Essential | |
| **Level** | Strategic | |
| **Metric type** | Single choice | |
| This metric conditions the metric FWts02 and FWts03. | | |

| **Development assessment rule** | **Development** |
|---|---|
| Yes | **3** |
| Partially. The plan exists, but it is still not implemented OR Not all the responsible utilities have an implemented plan | **1.5** |
| No | **0** |

**Figure 8 . Excerpt of the RAF model: dimensions, objectives, assessment criteria, and metrics (left) ; *FWts01* metric specification (right) (taken from (**Cardoso et al., 2020) **)**

The semantic mappings between RAF components and URM classes are shown in Table 3. Notice that some RAF components directly map to URM, such as `Dimension` or `Stakeholder`. In contrast, the maturity level is mapped to `Stage`, service to `(Sub)dimension`, resilience objectives to `Policy`, and criterion to `Indicator`. The `Strategy` class defined in URM hasn't a direct mapping in RAF; this concept corresponds to objectives by dimension according to the maturity level of the associated metric. Finally, entities like or `Action` defined in URM are not applicable in this package for RAF. On the other hand, metrics are part of the RAF core, but in

URM, they would not be in the `URModel` package but will be represented in the `MeasurementModel` package (outside the scope of this paper).

Figure 9 shows the object diagram, which represents part of the RAF model outlined in Figure 8. As an instance of URModel, RAF is composed of several dimensions (namely, `Organizational` and `Functional`). The latter has two subdimensions (`water` and `wastewater`). The lowest maturity level of the model is `essential`, an instance of the class `Stage`. The object `essentialWater` represents the intersection between resilience objectives by dimensions according to the maturity level of the associated metrics, and contains resilience objectives, for instance the resilience objective called `Obj.FW1(Water Service Planning & Risk Management)` represents an instance of the class `Policy.`

**Table 3. URM - RAF Mappings**

| URModel classes | RAF components |
|---|---|
| `Resilience Model` | Resilience Model |
| `Stage` | Maturity Level |
| `Stakeholder` | Stakeholder |
| `Dimension` | Dimension |
| `(Sub)Dimension` | Service |
| `Strategy` | Resilience Objectives by dimension & maturity level |
| `Policy` | Resilience Objective |
| `Indicator` | Criterion |

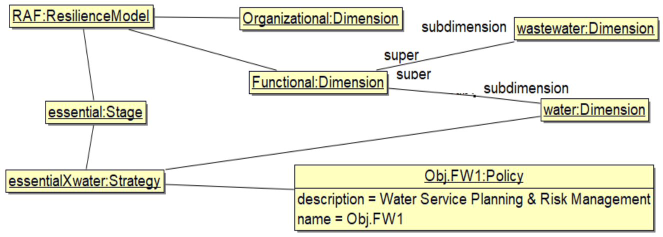


**Figure 9. Object diagram showing part of RAF Resilience Model as an instance of URM**

## CONCLUSIONS AND FUTURE WORK

A large amount of knowledge about UR has been generated in the last decade. However, UR has yet to be addressed holistically from an Information Technology perspective. In this work-in-progress paper, we have reported on our ongoing work toward developing a portal supporting UR building processes. The portal aims at being a multi-framework operational tool allowing the definition, enactment, and monitoring of UR improvement processes. The key to its realization is to grant semantic interoperability between the models underlying the different UR frameworks so that cities can be evaluated from different perspectives with a single tool, avoiding the errors inherent to the data migration among different systems. Additionally, facilities for comparing different cities would be feasible on a model-neutral basis.

The URM metamodel outlined in this paper is the key to semantic interoperability achievement. We have shown how a resilience model can be described as an instance of the metamodel by defining semantic mappings between its concepts and the metamodel classes, and have illustrated our proposal with three examples of these mappings. As expected, some general concepts present in the URM are non-existent in other models. Although the exercise does not guarantee all models fit well in URM, this initial result provides some evidence of the generalization's feasibility. We are currently working on adding more frameworks to our metamodel to gain more evidence of its completeness.

The value of a generic metamodel lies in the ability to represent a comprehensive coverage of properties that are not necessarily present in resilience models developed for specific purposes, such as climate change preparedness and urban planning. The main benefit of starting from a generic model, such as the URM, is the possibility of achieving generalization and standardization, enabling cities to evaluate their urban resilience improvement initiatives using a single tool. Moreover, integrating a new framework may also extend it to add features missing in its original version; for instance, a stage-less framework like RAF could be enriched with all the maturity-related features implemented in the `MeasurementModel` package.

We plan to develop the UR portal as an open system to which new frameworks can be added at a reasonable cost. Consequently, we need to find a way to provide some automation to both the definition and verification of new semantic mappings. Ontologies or knowledge graphs are candidate models to handle the semantic relationships between models. Another aspect yet to be covered in this work is the comparison with similar attempts to produce a generic model, such as the one produced by Nojavan et al. (2018). This is also a planned task in our project.

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**BIBLIOGRAPHY**


Arup (2015). The City Resiliencie Index. https://www.arup.com/projects/city-resilience-index (Accessed on December 2022)

Assumma, V., Bottero, M., De Angelis, E., Lourenço, J. M., Monaco, R. and A Soares, A. J. (2021*). A decision support system for territorial resilience assessment and planning: An application to the Douro Valley (Portugal)*. Science of The Total Environment, Vol 756. DOI: 10.1016/j.scitotenv.2020.143806.

Büyüközkan, G., Ilıcak, Ö. and Feyzioğlu, O. (2022). *A review of urban resilience literature*. Sustainable Cities and Society, Volume 77. https://doi.org/10.1016/j.scs.2021.103579.

Canós, J. H; Penadés, M. C.; Borges, M. R. S.; Bueno, S.; Hernantes, J.; Labaka, L.; Bañuls, V. (2022). Towards Digital Transformation of a City Resilience Framework. *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS-55)*. January 2022. http://hdl.handle.net/10125/79643

Cardoso, M.A., Brito, R.S., Pereira, C., David, L., Almeida, M.C. (2020). Resilience Assessment Framework (RAF). Description and Implementation. *Rescue project,* December 2020. https://toolkit.resccue.eu/wp-content/uploads/2021/01/D6.4.pdf (Accessed on Dec 2022)

Cen Workshop Agreement 17301.(2018). *City Resilience Development - Maturity Model*, https://www.en-standard.eu/din-cwa-17301-city-resilience-development-maturity-model-english-version-cwa-17301-2018/, August 2018.

Cutter, Susan & Burton, Christopher & Emrich, Chris. (2010). *Disaster Resilience Indicators for Benchmarking Baseline Conditions.* Journal of Homeland Security and Emergency Management - J HOMEL SECUR EMERG MANAG. 7. 10.2202/1547-7355.1732.

Deming, W. Edwards. *Out of the Crisis*, reissue. MIT press, 2018.

Meerow, S, Newell, J. P. , Stult, M, *Defining urban resilience: A review,* Landscape and Urban Planning, Volume 147, 2016, Pages 38-49, https://doi.org/10.1016/j.landurbplan.2015.11.011.

Moen, R., and Norman, C., "The History of the PDCA Cycle". *Proceedings of the 7th Asian Network for Quality (ANQ) Congress*, Tokyo, September 17, 2009.

Nojavan, M., Salehi, E. & Omidvar, B., (2018). *Conceptual change of disaster management models: A thematic analysis*, Journal of Disaster Risk Studies 10(1) https://doi.org/10.4102/jamba.v10i1.451.

Penadés, M. C., Sánchez-Díaz, J., Carsí, J. Á., Núñez, A. G. and Canós, J. H.(2022) Building Urban Resilience: A Dynamic Process Composition Approach. *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS-55)*. January 2022. http://hdl.handle.net/10125/79628

Pyrko, I., and Howick, S. and Eden, C. (2017) Risk systemicity and city resilience. *Proceedings of EURAM 2017: 17th Annual Conference of the European Academy of Management*. Glasgow, Scotland, University of Strathclyde.

Ribeiro, P. J. G., & Pena Jardim Gonçalves, L. A. (2019). *Urban resilience: A conceptual framework.* Sustainable Cities and Society, 50, Article 101625.

Smart Mature Resilience (2018), European Resilience Management Guideline, https://bit.ly/3Z6NVLz. Accessed 11th December 2022.

SMR's Resilience Maturity Model (2018), https://smr-project.eu/tools/maturity-model-guide/resilience-maturity-model/ (Accessed on December 2022)

Yang, Q., Yang, D., Li, P., Liang, S., & Zhang, Z. (2021). *Resilient City: A Bibliometric Analysis and Visualization*. Discrete Dynamics in Nature and Society, 202. https://bit.ly/3lJrfCD

## APPENDIX A. OUTLINE OF THE SEMANTIC MAPPINGS BETWEEN RESILIENCE MODELS AND URM

| URModel classes | RMM concept | CRI concept | RAF concept |
|---|---|---|---|
| Resilience Model | Resilience Model | Resilience Model | Resilience Model |
| Stage | Stage | No-stage | Maturity Level |
| Stakeholder | Stakeholder | Stakeholder | Stakeholder |
| Dimension | Dimension | Dimension | Dimension |
| (Sub) Dimension | Subdimension | | Service |
| Strategy | Stage per Subdimension | Set of policies | Resilience Objectives by dimension & maturity level |
| Policy | Policy | Goal | Resilience Objective |
| Indicator | | Perfomance indicator | Criterion |
| Action | | | |
| Risk | | | |

URM

`Dimension:  A top Dimension in the dimension hierarchy`

`(Sub)Dimension: A Dimension related to another Dimension through the super relationship`