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A state-of-the-art decision-support environment for risk-sensitive and pro-poor urban planning and design in Tomorrow’s cities

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ABSTRACT

In this Special Issue introductory paper, we present the Tomorrow’s Cities Decision Support Environment (TCDSE). As the negative impacts of natural hazards continue to escalate around the world due to increasing populations, climate change, and rapid urbanisation (among other factors and processes), there is an urgent requirement to develop structured and operational approaches towards multi-hazard risk-informed decision making on urban planning and design. This is a particularly pressing issue for low-to-middle income countries, which are set to be impacted ever more disproportionately during future natural-hazard events if the “business as usual” urban-development approach continues unabated. Urban poor residents of these countries will significantly suffer under risk-insensitive development trajectories.

The proposed TCDSE addresses this crucial challenge. It facilitates a participatory, people-centred approach to risk-informed decision making, using state-of-the-art procedures for physics-based hazard and engineering impact modelling, integrating physical and social vulnerability in a unified framework, and expressing the consequences of future disasters across an array of stakeholder-weighted impact metrics that facilitate democratisation of the risk concept. The purpose of this introductory paper is to provide a detailed description of each component of the TCDSE, characterising related data inflows and outflows between modules. We conclude with a short operational end-to-end demonstration of the TCDSE, using the Tomorrowville virtual urban

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testbed. Individual components of the TCDSE are further dealt with in detail within subsequent papers of this Special Issue.

1. Introduction

1.1. Motivation

As worldwide populations grow, climate extremes occur more frequently, and the presence of urban centres continues to increase across the globe (particularly in low to middle-income countries), there is a crucial need to develop next-generation frameworks to support decisions related to risk-sensitive urban planning and design [1,2] This is underlined by the findings of the recent 2022 Intergovernmental Panel on Climate Change (IPCC) Working Group II ‘Impacts, Adaptation and Vulnerability’ report [3], which finds (*with high confidence*) that risk-informed urban planning is critical for resilience and positive human wellbeing. These frameworks, which holistically combine uncertain projections of sociodemographic and economic factors as well as hazards (including climate-change impacts), and explicitly facilitate a people-centred, participatory approach, can be used to understand how important decisions on urban planning affect the consequences of the next natural hazard event (e.g., earthquake, mass movement, flood, typhoon, volcanic eruption [4,5].

The most marginalised inhabitants of cities and urban areas in low and middle income countries often live in informal settlements and are among the most severely affected by the impacts of natural hazards [6]. Furthermore, amplifications in natural-hazard risk are projected for these vulnerable groups in the coming decades (due to poor-quality infrastructure and climate change, among other factors), which points to an urgent need for decision support frameworks to explicitly consider the impacts they will experience in tomorrow’s disasters [6]. This requires implicit recognition of the fact that risk is not absolute but differs according to life experience and associated coping capacity (or systemic vulnerability), which is the central underlying ethos of the Tomorrow’s Cities project (Galasso et al., 2021). However, traditional natural-hazard risk quantification approaches, which mostly focus on direct economic losses due to physical damage, are not particularly useful in this context. This is because the effect of $1 in direct physical-damage-induced losses is not consistent across different income groups [7–9]. In addition, many other factors – including age [10], gender [11], disability [12], homelessness status [13], sexual orientation and identity [14], and indigenous group membership [15]– influence how disasters impact specific individuals or groups. Thus, a paradigm shift in risk characterisation, accounting for an equitable, holistic array of perspectives and incorporating explicit consideration of the differentiated impacts of natural hazards on people, is essential for creating urban futures that work for all groups within stratified societies.

The Tomorrow’s Cities Decision Support Environment (TCDSE) proposed in this paper addresses these challenges and requirements, facilitating a practical state-of-the-art approach to disaster risk reduction that supports important social equity objectives in urban planning [16–18]. In particular, the TCDSE moves beyond exclusively analytical approaches to disaster risk assessment [19–22], embedding such quantitative tools within a broader procedural framework for multi-stakeholder engagement that ultimately democratizes the concept of risk (i.e., characterises risk in terms that are explicitly meaningful to relevant stakeholders). The proposed TCDSE builds on previous foundational work of the authors within the framework of the Tomorrow’s Cities project, which (together with the specific advancements of this paper and, more broadly, in this special issue) is described in detail in the following subsection.

1.2. A brief chronicle of the Tomorrow’s Cities Decision Support Environment

The TCDSE has evolved over time. An initial conceptual “Version #0” of the TCDSE was proposed by Galasso et al. (2021). This concept reviewed and addressed a number of limitations of existing approaches to natural-hazard risk quantification, including an overwhelming focus on current (static) exposure and vulnerability that may not capture future trends, hazard-siloed procedures, a failure to holistically consider both physical and social vulnerability, and explicit exclusion of relevant actors (e.g., members of local community groups, civil society, and decision makers across different levels of governance) from participation in or control over the overall risk quantification process, including the characterisation and validation of underlying assumptions. The paper then provided benchmark structured guidance towards proactive, pro-poor, and people-centred multi-hazard risk-informed urban planning. In particular, the proposed TCDSE framework – based on a solid foundation of co-production and participation - integrated state-of-the-art physical and social vulnerability assessment approaches, promoted the use of a wide range of impact metrics to provide a more holistic account of the impacts of a disaster in terms that that are explicitly understood and valued by relevant actors (i.e., facilitating risk democratisation), and encouraged the explicit inclusion of uncertainties inherent in future projections of risk.

The Galasso et al. (2021) framework was then translated into a simplified simulation-based analytical approach [4]; hereby referred to as Version #1), which exclusively accounted for future projections of physical and social risk in the context of earthquake (ground shaking) hazard. Version #1 represents an initial practical implementation of the TCDSE’s novel features, advancing the state of practice in understanding disaster risk by (1) providing a harmonised methodology for integrating physical and social impacts of disasters that facilitates flexible characterisation of risk metrics beyond asset losses; (2) explicitly incorporating a participatory approach to risk-informed decision making (i.e., risk metrics are driven by the needs and aspirations of the considered stakeholders); and (3) being designed to specifically explore the risks of tomorrow’s urban environment, using a simulation-based approach to rigorously capture the uncertainties inherent in future projections.

However, Version #1 requires additional enhancements in the context of more broadly supporting risk reduction for tomorrow’s urban citizens, particularly those that are poor and/or marginalised. Firstly, there needs to be an explicit consideration of multiple hazards (and their potential interactions) that may affect an urban region [23]. Furthermore, the urban environment itself can influence the trajectory of hazards in the built environment (e.g., localized flood hazard may be increased by the presence of impermeable surfaces). Therefore, it should act as an input to the hazard calculations [24]). To promote effective urban governance, the framework also requires improvements that facilitate co-produced visions of future urbanisation, which transcend traditional planning processes and incorporate carefully considered and collaboratively agreed multidimensional policy bundles that include progressive urban policies and interventions, offering a voice to the urban poor. The comprehensive TCDSE proposed in this study (hereby referred to as Version #2), which effectively exploits inter-disciplinary risk knowledge through a pro-poor and people-centred lens, incorporates these required enhancements [25].

The rest of the paper is structured as follows. Section 2 provides a detailed description of the different operational components (modules) of Version #2, also highlighting the information inflows and outflows across each module. Section 3 details a short end-to-end operational demonstration of the TCDSE using a virtual urban testbed. We then end with some conclusions.

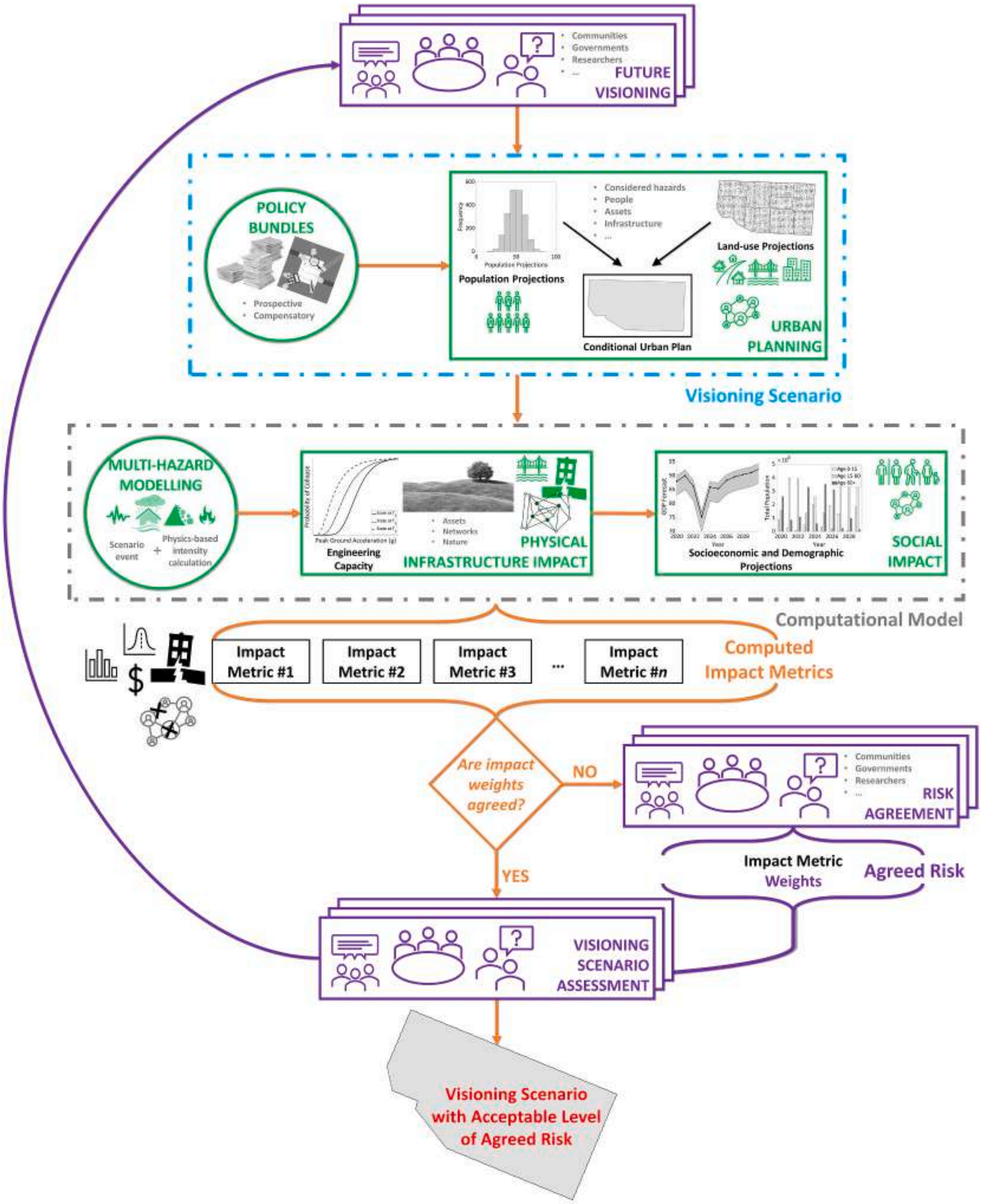

Fig. 1. Proposed TCDSE for risk-sensitive urban planning in Tomorrow's cities (Version #2).

2. Description of the proposed TCDSE

The practical TCDSE introduced in this paper is designed to be flexible enough for application to any scale of urban context, e.g., from a single public infrastructure project like a school to an interacting set of systems across a whole city. It consists of several interconnecting modules (see Fig. 1), which alternately involve stakeholder engagement phases (i.e., **Future Visioning, Risk Agreement, Visioning Scenario Assessment**) and technical tasks (i.e., **Visioning Scenario, Computational Model**). Summaries of each module's required inputs and outputs are provided in tables across subsequent subsections. The main workflow that underpins the TCDSE is described as follows. The stakeholder engagement phase of the **Future Visioning** module identifies conceptual physical and social constraints of the future urban context of interest, including appropriate policies for reducing future urban risk. The outputs of this process are used to frame the characterisation of a **Visioning Scenario**, which consists of a specified (and detailed) representation of the future physical (natural and built) and social environment within the urban extent of interest (also accounting for any influences from relevant policies identified in **Future Visioning**). The **Visioning Scenario** is one of the fundamental inputs to the **Computational Model**, which characterises pre-defined impacts of selected multi-hazards on parts of the urban extent defined in the **Visioning Scenario**, accounting for its underlying physical and social fragilities, vulnerabilities and capacities. These impacts are synthesised into a measure of agreed (i.e., democratized) risk, accounting for diverse stakeholder perspectives on the considered impact metrics surfaced in the **Risk Agreement** module. The process is repeated iteratively (via feedback loops) to compare the magnitude of an agreed risk metric resulting from different **Visioning Scenarios**. The ultimate outcome of the TCDSE process is a final **Visioning Scenario** associated with a value of an agreed risk metric that has been collaboratively deemed as acceptable in the **Visioning Scenario Assessment** module, which represents a third stakeholder engagement phase.

The entire process incorporates a number of different modes of interaction. The **Future Visioning, Risk Agreement**, and **Visioning Scenario Assessment** modules consist of physical or virtual governing spaces (called "Decision Fora") in which (technical and/or non-technical) stakeholders gather together to engage (and in which some digital tools such as Virtual Reality may be deployed to focus or frame the underlying discussions). These governing spaces can be existing or new, formal or less formalised, and can operate regularly or intermittently. The list of actors partaking in decision fora includes, but is not limited to, potential future residents within the urban setting of interest (with a particular emphasis on the urban poor and the most marginalised social groups), various levels of government, engineering communities, and relevant urban disaster risk researchers. Given complex power relationships in urban areas, all relevant actors must be represented in these fora. Differences in power between different actors are recognised; these influences should be mitigated through careful facilitation and selection of the participants. The decision fora should explicitly aim to raise the voice of more marginalised groups among future residents, who are known to bear the brunt of the impacts of disasters [26] but are still mostly excluded from decision making (e.g., Galasso et al. [27] and Geekiyanage et al. [28]). The **Visioning Scenario** module and **Computational Model** function exclusively within a digital environment that is formalised by relevant experts. Urban planners and policy makers characterize the **Visioning Scenario,** leveraging stakeholder perspectives and insights surfaced during the **Future Visioning** process. Within the **Computational Model**, physical scientists model multi-hazard scenarios (informed by stakeholder feedback gathered during **Future Visioning**), engineers select or derive appropriate functions for quantifying the impacts of these scenarios on physical infrastructure in the urban environment, social scientists provide approaches for translating or enriching these impacts to determine the effects on social systems, and a modelling architecture developed by conventional risk modellers is used to facilitate end-to-end calculations. The digital environment is ultimately incorporated within an integrated user-friendly software accessed through a web interface, which relevant technical pracitioners (e.g., disaster-impact analysts) can employ.

2.1. *Module descriptions*

2.1.1. *Future visioning*

The **Future Visioning** module is designed to co-produce a range of conceptual ideas of what tomorrow's city (or other urban context of interest) could look like amid relevant hazards it may be exposed to, accounting for governance structures (including budgetary constraints) and potential opportunities for improving resilience to future multi-hazard impacts. This is achieved through decision fora in which multiple actors collectively imagine, discuss, and propose diverse visions of their future city (or relevant parts of it), including the related policies and actions that can contribute to their development. A vision is defined as a 'desirable state in the future'; this can mean different things for different people, however (and does not necessarily relate directly or exclusively to disaster impact considerations), underlying the importance of giving voice to different actors. There are various methodological options for generating and validating visions in a participatory manner. These include the use of Delphi techniques in multiple rounds of

Table 1
Summary of the inputs and outputs of the **Future Visioning** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Questions to constrain visioning discussions/ workshops with actors	What are the most relevant hazards for your city to account for in the future? How do you envision the urban layout of your city in 30 years?	Set of policies	See Table 2
Data collected as part of background research in a specific city	Census data	Physical, social, and hazard information	Outputs of the urban future visions generated by different actors (including spatial municipal plans and any pertinent natural-hazard information beyond that considered in spatial municipal plans)

questioning [29], workshops [30], and semi-structured interviews [31]. The visioning process may also involve integrating primary and secondary data collected through background research (e.g., household surveys, census) within a specific geographical, social, economic, and political context. Visioning methods are selected depending on the preferences of participants and researchers as well as the practicalities of each context.

Visions output from the module form the basis of the policies to be assessed within the **Policy Bundles** module, include some of the physical and social details that underpin the conditional urban plan in the **Urban Planning** module, and provide context for the scenarios simulated in the **Multi-hazard Modelling** module. A summary of the module's inputs and outputs is provided in Table 1.

2.1.2. *Policy bundles*

The **Policy Bundles** module represents a collation of various policies proposed in the **Future Visioning** exercises to achieve the proposed future visions, by avoiding and/or mitigating the creation of new or increased risk in the future (***prospective*** disaster risk management, DRM) and/or strengthening the social and economic resilience of individuals and social groups in the face of residual risk that cannot be effectively mitigated (***compensatory*** DRM [32,33]; see Table 2. Policies can be targeted both at single-hazard and multi-hazard scenarios, depending on the urban context and the impact metrics examined in the **Computed Impact Metrics** module.

When contemplating the selection of individual policies and how they are combined, the following questions may help as input to the **Future Visioning** exercises:

1) *Is the policy aimed at prospective or compensatory DRM*? Effective policy bundles will generally aim for a balance between the two categories;
2) *Is the policy aimed at addressing individual hazards or multiple hazards* (possibly accounting for climate change)? Whereas multi-hazard policies tend to be considered more effective, there are cases where specific policies for targeted hazards are required (e.g., preventing future urban growth within a floodplain);
3) *Is the policy 'universal' or 'targeted' at specific social groups*? For example, the urban poor and the most marginalised groups in society might require specifically targeted policies. Nevertheless, careful consideration should also be given to not further marginalising these groups through policies that could 'stigmatise' them.

Table 2
Summary of the inputs and outputs of the **Policy Bundles** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Set of policies, output from the **Future Visioning** module	Land-use zoning (including application, enforcement, and compliance): 1. Creation of urban natural reserves in hazard-prone areas, for example water reservoirs for managing excess water runoff and green infrastructure to reduce heat waves/cooling 2. Designation of hazard-prone areas for urban and peri-urban agriculture (or any other economic activity compatible with environmental services) New urban development: 1. Site selection of new urban developments in non-hazard or low-hazard prone areas 2. Urban design layout to decrease exposure to multiple hazards, by considering density and pattern (urban form) Building codes and standards (including application, enforcement, and compliance): 1. Free of cost capacity building programmes for present and future homeowners and low-income construction workers on hazard resistant housing construction techniques 2. Construction of affordable housing, compliant with risk-informed building regulations for low-income groups 3. Establishment of a regulatory control mechanism for new construction built by both the public and private sectors. Involvement of independent professional organisations at local and central levels, to ensure transparency and accountability Infrastructure: 1. Storm drainage design according to climate change projections Public education and awareness-raising: 1. Inclusion of urban disaster risk and climate change modules in school curricul 2. Disaster risk awareness-raising campaigns	(Multiple) selected policies	Creation of urban natural reserves in hazard-prone areas and storm drainage design according to climate change projections Site selection of new urban developments in non-hazard or low-hazard prone areas and inclusion of urban disaster risk and climate change modules in school curricula Designation of hazard-prone areas for urban and peri-urban agriculture (or any other economic activity compatible with environmental services)

4) *Can you envision potential synergies and/or trade-offs between policies*? When considering policy options in tandem and assessing possible combinations it is helpful to maximise their impact based on potential synergies [34]. Similarly, careful consideration needs to be paid to potential trade-offs (in terms of time scales but also social groups and sectors; de Ruiter et al., 2021).
5) Importantly, the selection of policies can include both existing policies that have proven satisfactory (and that can be sustained, scale-up or combined with other policies) as well as newly proposed policies that can be implemented in the future. A sample set of relevant policies is provided in Table 2.

2.1.3. Urban planning

The **Urban Planning** module produces a detailed spatial representation of the future physical and social environments within the urban landscape of interest. Each representation (or urban scenario) includes building-, household-, and individual-level information that significantly advances beyond a conventional land-use plan [35]. These detailed data layers (and interactions between them, such as the location of an individual's workplace) can be generated from summary statistical information (e.g., based on projected census data or population microdata samples) using various synthetic population algorithms [36] and activity-based models [37] that range in complexity depending on the underlying availability of data (an extensive review of these algorithms can be found in Mentese et al. [35]. Future urban scenarios are derived by examining, for instance, projected formal urban development plans and other outputs of the consultations with urban experts, local residents, and additional members of the participatory **Future Visioning** processes; related information defined in the **Policy Bundles** module; historical/projected data on land-use changes (e.g., from remote sensing [38,39]; and demographic trends and projections. Daily interactions between people and the built environment (A complete list of inputs to the **Urban Planning** module is provided in Table 3). The scenarios are formalised within a multi-layered geospatial database.

This module feeds into the **Physical Infrastructure Impact** module (to estimate disruptions/damage to physical infrastructure such as individual buildings and critical infrastructure systems) and the **Social Impact** module (to assess the effects of the hazard on social infrastructure and different social groups). It is also used as a direct input to hazard models in the **Multi-Hazard Modelling** module in which changes to the urban landscape can alter the frequency, intensity and interconnectedness of hazards (e.g., changes in land use and/or the terrain will affect the intensity and spatiotemporal behaviour of flooding and landslide hazards).

2.1.4. Multi-hazard modelling

The **Multi-hazard Modelling** module contains simulations of single or multi-hazard scenarios and calculations related to the natural hazards of interest (see Jenkins et al. [24] for details on the current hazards modelled within this module). For example, flood hazard scenarios can integrate information on rainfall intensity or level of sediment yield to the river following a landslide or debris flow. On the other hand, earthquake hazard scenarios incorporate specific rupture characteristics, wave propagation properties, and local site response. Models included in this module are intended to be physics-based, to facilitate the fine spatial resolution of hazard modelling required for urban planning purposes.

The multi-hazard scenarios are selected based on the pertinent natural hazards identified through the **Future Visioning** processes. The **Multi-hazard Modelling** module accounts for both high-impact/low-frequency and low-impact/high-frequency event scenarios and may also consider various combinations of these scenarios over a specific timeframe. The required module inputs (see Table 4) are collected through historical records, stakeholder engagement, field surveys, and from the **Urban Planning** module (e.g., for flooding and landslide hazard models, as described in the previous section).

This module can represent different single hazards in a place (e.g., city X or part of city X impacted by floods, earthquakes, and

Table 3
Summary of the inputs and outputs of the **Urban Planning** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Selected policies, output from the **Policy Bundles** module	See Table 2; note that bundles can contain more than one policy	Features of the future physical environment	Land-use, geolocations and other characteristics of (1) buildings; (2) transport/service-related infrastructure; (3) natural infrastructure
Land-use characteristics	Land cover, housing development types, economic areas, transport and other infrastructure systems	Demographic data at polygon level and per individual	Gender, age, education level, ethnicity
Demographic and macro-economic data	Demographic projections, migration patterns	Socioeconomic data at polygon level and per individual	Income level, housing ownership, employment status, head of household, social security status
Socioeconomic characterisations of the population	Livelihood patterns, service demand for different population groups	Geolocation of mobility patterns per individual/social group	Place of residence, place of work, location of education, location of basic services (e.g., food supplies)
Land market value	Land prices	Geolocation of social infrastructure per individual/social group	Meeting places of savings groups, water groups, religious groups, worker associations, place of residence of main emergency contact
Physical, social, and hazard information from the **Future Visioning** module	Outputs of the urban future visions generated by different actors (including spatial municipal plans and any pertinent natural-hazard information beyond that considered in spatial municipal plans)		

Table 4
Summary of the inputs and outputs of the **Multi-hazard Modelling** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Hazards to consider, based on information output from the **Future Visioning** module	Any pertinent natural-hazard information beyond that considered in municipal plans, hazard information from municipal plans	Maps of hazard intensity measures for each considered hazard scenario	Maps of ground shaking, flood depths, flood duration, landslide volumes
Hazard-specific physical parameters and source data for each considered hazard scenario	Return period of interest, surface roughness (flood), earthquake rupture		
Geographic information	Topography, land use, building locations		

cyclones), but can also incorporate realistically contrived interrelationships between different hazards (e.g., earthquake triggering a tsunami and/or liquefaction, wildfire followed by a landslide) to represent a reasonable future multi-hazard experience. Comprehensive overviews of potential hazard interrelationships to be considered are provided in de Angeli et al. [40] and Tilloy et al. [41]; for example. In summary, the types of natural-hazard scenarios considered in this module are only limited by current physics-based modelling constraints.

The module's outputs are maps of severity/intensity for each hazard or multi-hazard scenario. For instance, for earthquake hazard, the outputs would be in the form of a ground-motion time series and the summarised metrics from the time series at the location of interests (where assets/infrastructure at risk are located). These outputs serve as an input to the **Physical Infrastructure Impact** module.

2.1.5. Physical infrastructure impact

The **Physical Infrastructure Impact** module represents a conventional approach to disaster impact assessment centred on urban assets (e.g., buildings, infrastructure, etc.) and spaces. It conducts calculations for assessing hazard-induced physical damage (structural and nonstructural) to the future built environment (e.g., buildings, roads, and utility pipelines), as defined in the **Urban Planning** module. Damage is computed using physics-based models of structures/infrastructure components (and systems) and/or empirical models of damage [42], both of which could account for the potential time-dependent vulnerability of the considered assets [43].

The physics-based approach to physical damage computation involves 2- or 3-D numerical models of the built environment, subjected to physics-driven representations of the hazard from the **Multi-hazard Modelling** module. The empirical approach uses fragility functions that translate condensed hazard intensity measures of the **Multi-hazard Modelling** module into asset-specific damage estimates or vulnerability functions that directly estimate losses (i.e., consequences of damage; [44,45]. Asset-specific damage from fragility functions is translated into losses, using damage-to-loss models describing how the damage relates to consequences in terms of casualties, direct repair cost, and physical functionality downtime, for example.

Network-level losses (such as infrastructure downtime) are also accounted for in this module and are estimated as part of a systemic approach to impact characterisation [46], using network analysis techniques that aggregate asset-specific losses, accounting for inter-asset functionalities. These types of losses can used to benchmark disruptions in basic service provision against international standards.

This module can also accommodate the characterisation of hazard-induced impacts on green infrastructure (e.g., Lallemant et al. [47]). These impacts may be beneficial as well as negative. An example of the former is the increase in soil quality of agricultural land due to moderate flooding. A summary of the module's inputs and outputs is provided in Table 5.

2.1.6. Social impact

The **Social Impact** module facilitates a people-centred “bottom-up” component [48] in impact characterisation for risk-informed decision support. It aims to “quantify” and “qualify” the differential impact that future multi-hazard scenarios might have on different social groups in the city or other scale of analysis, particularly those most marginalised (see Table 6). It does so by:

Table 5
Summary of the inputs and outputs of the **Physical Infrastructure Impact** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Features of the physical built environment, output from the **Urban Planning** module	Geolocations and other characteristics of (1) buildings; (2) transport/service-related infrastructure; (3) natural infrastructure	Physical damage and direct asset loss estimates (including network-level losses across interdependent infrastructure systems)	Asset repair cost, asset downtime, number of casualties
Maps of hazard intensity measures for each considered hazard scenario, output from the **Multi-hazard Modelling** module	Maps of ground shaking, flood depths, flood duration, landslide volumes	Hazard impacts on natural infrastructure	Increase in soil quality of agricultural land
Engineering models that describe the behaviour of engineered assets to single/multiple hazards	Seismic fragility models, flood depth-damage functions		

Table 6
Summary of the inputs and outputs of the **Social Impact** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Physical damage and direct asset loss estimates (including network-level losses across interdependent infrastructure systems), output from the **Physical Infrastructure Impact** module	Asset repair cost, asset downtime, number of casualties	Hazard impacts across different social groupings	Population dislocation disaggregated per income level, Education loss disaggregated per age
Demographic data at polygon level and per individual, output from the **Urban Planning** module	Gender, age, education level, ethnicity	Contextual vulnerability information	Causes of disproportionate population dislocation across certain income levels
Socioeconomic data at polygon level and per individual, output from the **Urban Planning** module	Income level, housing ownership, employment status, head of household, social security status		
Geolocation of mobility patterns per individual/social group, output from the **Urban Planning** module	Place of residence, place of work, location of education, location of basic services (e.g., food supplies)		
Geolocation of social infrastructure per individual/social group, output from the **Urban Planning** module	Meeting places of savings groups, water groups, religious groups, worker associations, place of residence of main emergency contact		

1) Disaggregating outputs from the **Physical Infrastructure Impact** module based on overlapping inequalities (derived from relevant categories of demographic and socioeconomic differentiation from the **Urban Planning** module, e.g., gender, race, age, income). This is done through quantitative approaches to intersectionality;
2) Assessing the influence of outputs from the **Physical Infrastructure Impact** module on disruption/improvement of mobility patterns and other flows of people, services, and commodities for individual and intersecting social groups that are specified in the **Urban Planning** module. Examples include access to work, education, and food/essential items due to transport infrastructure damage (e.g., ± variation in commuting time for workers to workplace, children to school, and consumers to markets; e.g., Miller and Baker [49]).

Thus, the quantitative part of this module assesses how social categories individually and jointly influence multi-hazard impacts. The quantitative component of the module is further enhanced by qualitatively:

1) Contextualising multi-hazard impacts by understanding the root causes and underlying drivers of vulnerabilities [50] as well as the conditions that enable/constrain the capacities of different social groups in each city [51];
2) Incorporating intangible impacts (e.g., on social relations, mental health, happiness, spirituality, aesthetic, heritage) that are derived from a qualitative enquiry.

2.1.7. *Computed impact metrics*

Computed Impact Metrics are formal quantitative and/or qualitative summaries of the **Social Impact** module outputs (i.e., estimated multi-hazard impacts across different individuals and/or social groups); see Fig. 2 and Table 7. They are used to assess and compare **Visioning Scenarios** within a democratized risk agreement process (details to follow). The exact nature of these metrics should be predetermined before entering into the TCDSE (the definition of the metrics is, therefore, currently outside the scope of the

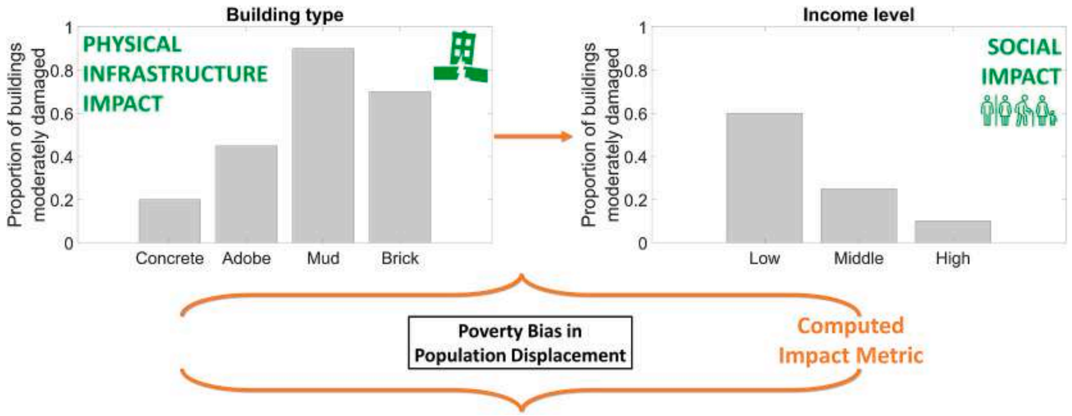

Fig. 2. Illustration of how one sample of a **Computed Impact Metric** is determined. In this case, the **Social Impact** module first outputs the proportion of households with moderate damage across different income groups for the sample, which is based on relevant building damage information provided by the **Physical Infrastructure Impact** module. The output of the **Social Impact** module is further converted into the number of low-income households displaced (because of moderate damage) relative to the average number of displacements across all income groupings to produce the sample value of the "Poverty Bias in Population Displacement" **Computed Impact Metric.**

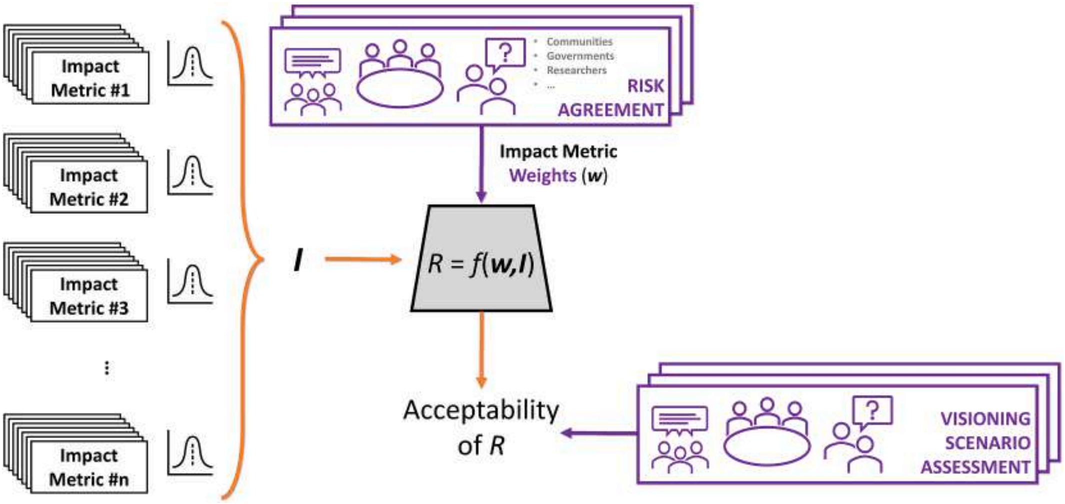

Fig. 3. Illustration of the interaction between the **Computed Impact Metrics**, **Risk Agreement,** and **Visioning Scenario Assessment** modules. The agreed risk metric *R* is derived based on the **Computed Impact Metrics *I*** and associated importance weightings ***w*** determined in the **Risk Agreement** module. The **Visioning Scenario Assessment** module then determines the acceptability of *R*. If *R* is deemed acceptable, the process is stopped. Otherwise, a further iteration of the whole TCDSE process is initiated, beginning with the **Future Visioning** module.

Table 7
Summary of the inputs and outputs of the **Computed Impact Metrics** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Hazard impacts across different social groupings, output from the **Social Impact** module	Population dislocation disaggregated per income level	Values/characterisations of agreed impact metrics	Poverty bias in population displacement

TCDSE). The development of these metrics must be open-source and well documented to enable participatory examination of the risk characterisation process.

The relative importance of each impact metric is not considered at this stage. Instead, the subsequent **Risk Agreement** module re-engages actors (e.g., through workshops) to collectively weight impact metrics and produce characterisations of agreed risk. Impact metrics may also contain a temporal dimension, e.g., the number of displaced populations within six months of the event.

Examples of potential impact metrics are:

- A ***poverty bias indicator***, which measures the extent to which low-income people are disproportionately affected by some type of disaster-induced loss [52]. This metric is shaped by a consequence measurement like economic loss, related infrastructure damage, unemployment, social network disruption etc. That is disaggregated by income.
- ***Infant mortality***, which would be shaped based on estimates of fatality by age [53]**.**
- ***Population displacement***, which could depend on socio-demographic factors, the extent of housing damage (i.e., loss of functionality), and the strength of social networks [54].
- ***Education inaccessibility***, which measures the extent to which the school-going population are inhibited from participating in educational activities, as a result of damage/loss to (1) school buildings; (2) relevant transport infrastructure between schools and residences of school-going children; and (3) critical service-related infrastructure associated with schools (e.g., D'Ayala et al. [55])**.**

The metrics are computed through a simulation-based engine that uses Monte Carlo sampling to capture uncertainties in: (1) the urban planning component of the **Visioning Scenario** (e.g., building locations, composition of household members within a given residence); (2) **Multi-hazard Modelling** scenarios (hazard intensities); (3) **Physical Infrastructure Impact** quantification (e.g., damage states); and (4) **Social Impact** quantification (e.g., the ability or not of a child to attend school in the presence of infrastructure damage). Quantitative impact metrics are therefore expressed in the form of a probability distribution. Qualitative indicators that contain discrete descriptions of consequences (such as "high", "medium", and "low") are used when there are insufficient data available to quantitatively define an impact metric or when it may not be appropriate to measure a consequence explicitly.

2.1.8. Risk agreement

The **Risk Agreement** module is central to the TCDSE. It consists of decision fora that allow different actors with diverse knowledge to lead and influence conversations about disaster risk, ultimately accommodating **democratisation of the concept of risk.**

In simple terms, the **Risk Agreement** module is included in the TCDSE process to empower different actors to actively participate in risk-informed decision making for the urban space, directly addressing the need for local involvement in disaster risk reduction set out in numerous policy documents [56]. It is specifically designed to determine priorities around multi-hazard impacts, which are derived through preference elicitation methods such as the analytic hierarchy process or multi-attribute utility theory [57], for instance. The final outcome is a set of co-produced weights that reflect the collective relative importance of each **Computed Impact Metric** to all involved actors (see Table 8).

2.1.9. *Agreed risk*

Agreed risk is a subjective translation of the **Computed Impact Metrics** that incorporates the importance weightings output from the **Risk Agreement** module. For each iteration (run through) of the TCDSE, an agreed risk metric (R) is computed by: 1) weighing the set of quantified **Computed Impact Metrics** output from the computational engine based on the **Risk Agreement** module weightings; and 2) combining the weighted metrics into a summary scalar value, using a predetermined mathematical function. That is,

$$R = f(\boldsymbol{w}, \boldsymbol{I}) \tag{1}$$

where $f(.)$ is a mathematical function (an example of which is presented in Section 3), **w** is a vector containing the individual impact-metric weightings w_m that are produced in the **Risk Agreement** module , **I** is a vector containing the set of computed impact metrics I_m, and R is as previously defined.

2.1.10. *Visioning scenario assessment*

The **Visioning Scenario Assessment** module consists of decision fora that advance the process of democratising risk, further facilitating the important participation and empowerment of different local stakeholders in risk-sensitive decision making [58]. These fora specifically determine whether the computed **Agreed Risk** metric value is acceptable (i.e., below some tolerance level) for future residents to live with (see Table 9).

If the agreed risk metric value is deemed acceptable, the iterative process is stopped, and the accompanying urban plan and policy bundles produced in the **Visioning Scenario** phase become the final output of the TCDSE. Otherwise, the process begins again in the **Future Visioning** module. Fig. 3 provides a detailed illustration of the interaction between the **Computed Impact Metrics**, **Risk Agreement,** and **Visioning Scenario Assessment** modules.

3. Demonstration

We now provide a brief end-to-end operational demonstration of the TCDSE, using the 500-ha Tomorrowville virtual urban testbed introduced in Mentese et al. [35]. Here we use a simplified set of scenarios, impact weighting scheme, agreed risk function, policies etc. To demonstrate the general potential of the TCDSE to support decisions, rather than to argue for specific forms of the calculations, threshold values of the risk metric, or links to the policy options. For this hypothetical case study, members of the Tomorrow's Cities Early Career Research Working Group (ECRWG; see Filippi et al. [25] assume the role of stakeholders within the Decision Fora of the **Future Visioning, Risk Agreement**, and **Visioning Scenario Assessment** modules. We assume that there are two predetermined **Computed Impact Metrics:** (1) Total number of high- and middle-income households displaced, $Disp_{mid\text{-}high}$; and (2) Total number of low-income households displaced $Disp_{low}$, i.e. $\mathbf{I} = \{\, Disp_{mid\text{-}high}, Disp_{low} \,\}$. Note that we neglect uncertainty for this demonstration, such that the **Computed Impact Metrics** are scalar numbers. The agreed risk mathematical function $f(.)$ is taken to be a straightforward summation in this demonstration, such that R is expressed as:

$$R = I_1 \times w_1 \ + \ I_2 \times w_2 \tag{2}$$

where all variables have been defined as part of equation (1).

3.1. *Iteration #1 of the TCDSE*

The first case-study iteration of the **Future Visioning** module develops a conceptual vision of what Tomorrowville would look like in 50 years under a "business-*as*-usual" (BAU) urban growth scenario. Through this process, the ECRWG decision fora identify that the number of Tomorrowville residents will double in the next 50 years and that the hazards of most concern are earthquakes, flooding, and landslides. This representation is formalised as a **Visioning Scenario** (VS#1) with an **Urban Plan** that consists of the building footprints in TV0 (present day configuration of Tomorroville) and TV50_b1 (urban layout of Tomorrowville containing only new buildings to be built between now and 50 years in the future, which are configured in a hazard-insensitive way; see Mentese et al., 2022) and all associated physical and social information that is assigned in accordance with the relevant algorithms provided in Mentese et al. [35]. In short, this urban plan accommodates a population of approximately 80,000 residents and incorporates over 10,000 buildings across nine land-use polygons (which include clusters of high-, medium- and low-income residential areas). **Policy Bundles** is empty for this first iteration, reflecting the BAU vision outlined.

Table 8
Summary of the inputs and outputs of the **Risk Agreement** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Different leading questions to shape discussions with different actors Values/characterisation of agreed impact metrics, output from the **Computed Impact Metrics** module	What are the most relevant impacts on your built and socioeconomic environments? Poverty bias in population dislocation	A set of weightings for each of the computed impact metrics	N/A

Table 9
Summary of the inputs and outputs of the **Visioning Scenario Assessment** module.

Inputs	Relevant Examples	Outputs	Relevant Examples
Agreed risk metric value	N/A	Judgement on the acceptability of the agreed risk metric value	N/A

The first iteration of the **Multi-hazard Modelling** module examines VS#1 under three hazard scenarios that are modelled using physics-based approaches: (1) An $M = 6$ earthquake occurring in the vicinity of the Tomorrowville urban extent; (2) A fluvial-pluvial flooding event with a current estimated recurrence interval of 100 years; and (3) A "high intensity" debris flow corresponding to a peak rainfall intensity of 150 mm/h. These scenarios are described in detail in Jenkins et al. [24]. The **Physical Infrastructure Impact** module then characterises the effects of the hazards on the built environment using relevant earthquake fragility and flooding vulnerability models for each building, as documented in Gentile et al. [45] and the nearest recorded value of the appropriate hazard intensity measure. Note that each building is assigned the earthquake damage state with the highest probability of occurrence for the given seismic intensity measure (although damage uncertainty could be accounted for by taking a weighted average of the damage states), and the final output of this module for the flooding and debris flow events is the corresponding loss ratio (or damage factor) that is linearly interpolated from the associated flooding vulnerability function. The **Social Impact module** then disaggregates building damage for each hazard across households of different income groups. The result for a given hazard scenario is a series of household-level vectors containing damage descriptions for each building that a household depends on (residence, workplace, school, hospital, as appropriate). For the earthquake event, for instance, a household who lives in a residential building with assigned damage state (DS) 2 containing one working adult whose industrial workplace is assigned DS 1, two children whose school suffered DS 3, and where the nearest hospital experiences DS 5, would be assigned a damage vector $\mathbf{D} = \{2,1,3,5\}$. The series of household-level building damage vectors is grouped into three different income levels that reflect the high-, middle-, and low-income divides across Tomorrowville. It is assumed that a household will be displaced in a given hazard scenario if at least two buildings that they depend on are "moderately" damaged, i.e., reach at least DS 2 for the earthquake scenario or suffer a damage ratio of at least 0.2 in the flooding and debris flow events. Then, $Disp_{mid\text{-}high}$ and $Disp_{low}$ are computed by finding the total number of unique households in the relevant income group that are displaced across at least one of the three examined hazard scenarios. For the first iteration, $Disp_{mid\text{-}high} = 1367$ and $Disp_{low} = 4457$.

The next step in the process involves a convening of the ECRWG decision fora within the **Risk Agreement** module. The decision fora hold a pro-poor view, believing that the mitigation of $Disp_{low}$ should be prioritised over that of $Disp_{mid\text{-}high}$. They ultimately determine that the weightings assigned to $\mathbf{I}$ should be $\{0.7,0.3\}$. This produces a first agreed risk metric value R of 3530.

The ECRWG decision fora finally convene within the **Visioning Scenario Assessment** module. This process determines that any value of R above 2450 (i.e., around 14% of the total number of households expected to occupy Tomorrowville in 50 years) would be unacceptable, such that VS#1 is rejected, and the TCDSE is initiated for a second iteration.

3.2. Iteration #2 of the TCDSE

The second iteration of the ECRWG decision fora's participation within the **Future Visioning** module produces a conceptual vision of Tomorrowville's future growth in 50 years if a hazard-informed approach to urban growth was adopted, preventing development from taking place on or near the floodplain. Given that the earthquake scenario was uniquely responsible for over 95% of the household displacements projected to occur for VS#1, the **Future Visioning** decision fora further determine that a strengthening of the seismic building code would also be important for future construction. This outline is translated into **Visioning Scenario** #2 (VS#2), in which the **Urban Plan** consists of TV50_b2 (urban layout of Tomorrowville containing only new buildings to be built between now and 50 years in the future, which are configured in a hazard-informed way) instead of TV50_b1 (see Mentese et al. [35], but all other information remains the same as in VS#1. **Policy Bundles** then incorporates the hazard-informed urban growth directive reflected in the urban plan and a regulation that mandates the construction of future buildings using more stringent earthquake codes.

The **Multi-hazard Modelling** module examines the same hazard scenarios as in Iteration #1. The median parameter of earthquake fragility functions assigned to future buildings is increased by 20%, to reflect the updated seismic building code mandate. (Note that in a realistic case-study application, the medians of the functions could be more precisely adjusted in line with the acceptable probability of collapse proposed in the updated building code). All other aspects of the **Physical Infrastructure Impact** and **Social Impact** modules remain unchanged with respect to Iteration #1. The same assumptions are used to derive the $Disp_{mid\text{-}high}$ and $Disp_{low}$ **Computed Impact Metrics**, which respectively total 408 and 3699 for this iteration. Since the weightings of each impact metric have already been determined by the **Risk Agreement** module in Iteration #1, the process skips directly to computing R, which equals 2712. Since $R > 2450$, the **Visioning Scenario Assessment** module deems VS#2 unacceptable and a third iteration of the TCDSE process is required.

3.3. Iteration #3 of the TCDSE

The third iteration of the ECRWG decision fora's participation within the **Future Visioning** module leads to a **Visioning Scenario** #3 (VS#3) that is physically identical to VS#2 but incorporates an additional soft policy in **Policy Bundles** that provides one-off cash payments to cover all hazard-induced moderate damages to residential properties. All elements of Iteration #3 are therefore identical to Iteration #2, except for a crucial change to how displacement is defined. In this iteration, a residential property is only flagged as potentially causing household displacement if it is at least "extensively" damaged, i.e., reaches at least DS 3 for the earthquake scenario or suffers a damage ratio of at least 0.5 in the flooding and debris flow events. All other relevant buildings are still included in calculating potential displacement if they have “moderate” damage. The additional soft policy leads to an R of 2493, which is still larger than the acceptable limit set such that a fourth iteration of the TCDSE is necessary.

3.4. Iteration #4 of the TCDSE

This iteration of the **Future Visioning** module leads to a replacement of the soft policy of VS#3 with a higher one-off cash payment that instead covers hazard-induced extensive damages, but is limited to low-income households due to foreseen budgetary constraints. This soft policy acknowledges the significantly larger value of $Disp_{low}$ compared to that of $Disp_{mid\text{-}high}$ across the three previous iterations (see Table 10). It means that low-income residential properties only contribute to the potential displacement of associated households in this iteration if they are “severely” damaged, i.e., reach at least DS 4 for the earthquake scenario or suffer damage ratios of at least 0.7 in the flooding and debris flow events. All other relevant buildings need only have “moderate” damage to potentially trigger displacement. VS#4 and Iteration #4 are otherwise identical to VS#3 and Iteration #3, respectively. The modification of the soft policy in **Policy Bundles** leads to an R of 2416, which is deemed acceptable by the **Visioning Scenario Assessment** ECRWG decision fora, and the process is terminated. The final output of the TCDSE is therefore VS#4. A summary of the different information associated with each demonstrated iteration of the TCSDE is provided in Table 10.

3.5. The importance of democratising risk

We repeat the same four iterations of the TCDSE as described in Sections 3.1 to 3.4 but this time assume that the ECRWG decision fora adopt an income-neutral approach in the **Risk Agreement** module, such that the weights assigned to $Disp_{mid\text{-}high}$ and $Disp_{low}$ are both equal to 0.5. The results of this analysis are summarised in Table 11. It is observed that the optimum Visioning Scenario in terms of R (denoted as $R_{neutral}$ in Table 11) is VS#3 instead of VS#4. Furthermore, the process should be terminated after Iteration #2 (given its acceptable value of $R < 2450$) to produce a final output of VS#2. This “what-if” analysis leads to a number of crucial insights. First, it emphasises the significant role that the stakeholder’s risk perceptions play in the process of determining the correct risk-management approach; different subjective stakeholder impact-metric weightings can lead to different optimum visioning scenarios. Second, it underlines the significance of adopting a pro-poor approach in mitigating the impacts of hazards on the most vulnerable; the VS#4 output of the TCDSE process for the pro-poor impact-metric weighting scheme leads to a 11% reduction in the number of low-income households displaced compared to the VS#2 output of the income-neutral approach, but has no compensatory increasing effect on the number of middle- and high-income households displaced.

4. Conclusions

This paper has described a state-of-the-art approach for supporting decision making on future multi-hazard risk-informed urban planning. In particular, the proposed Tomorrow’s Cities decision support environment (TCDSE) encompasses state-of-the-art physics-

Table 10
Summary of the different TCDSE iterations included in the hypothetical demonstration. All hazard scenarios examined in the **Multi-hazard modelling** module are identical across all iterations. Note that the weights assigned by the **Risk Agreement** module to $Disp_{mid\text{-}high}$ and $Disp_{low}$ equal 0.7 and 0.3, respectively. The highest acceptable value of R determined in the **Visioning Scenario Assessment** module is 2450.

Iteration	Urban Plan	Policy Bundles	$Disp_{mid\text{-}high}$	$Disp_{low}$	R
#1	TV0 and TV50_b1 building footprint layouts. All other information is assigned per the procedures detailed in Mentese et al. [35]. Please see Mentese et al. [35] for more details	N/A	1367	4457	**3530**
#2	Same as Iteration #1, except TV50_b1 is replaced with TV50_b2 (see Mentese et al. [35] for more details)	Hazard-informed urban growth; Updated seismic building codes	408	3699	**2712**
#3	Same as Iteration #2	Hazard-informed urban growth; Updated seismic building codes One-off cash payment to cover all moderate residential damages	111	3514	**2493**
#4	Same as Iteration #2	Hazard-informed urban growth; Updated seismic building codes One-off cash payment to cover low-income extensive residential damages	408	3277	**2416**

Table 11
Summary of results obtained for the iterations detailed in Table 10, if an income-neutral approach is adopted in the **Risk Agreement** module, i.e., the weights assigned to $Disp_{mid\text{-}high}$ and $Disp_{low}$ are instead equal to 0.5 and 0.5, respectively. Also shown are the R values obtained for the original weighting case of Sections 3.1 to 3.4 (denoted as $R_{original}$).

Iteration	$Disp_{mid\text{-}high}$	$Disp_{low}$	$R_{neutral}$	$R_{original}$
#1	1367	4457	**2912**	**3530**
#2	408	3699	**2054**	**2712**
#3	111	3514	**1813**	**2493**
#4	408	3277	**1843**	**2416**

based approaches to hazard and (possibly) engineering modelling, a seamless unification of physical and social impacts, and a flexible impact quantification procedure that facilitates a democratisation of the risk concept. These features are interwoven with direct stakeholder engagement fora that ensure co-production is placed at the heart of risk-sensitive option selection and offer a voice to the most marginalised, explicitly promoting pro-poor decision making on future natural-hazard risk. The importance of the latter was emphasised through an end-to-end demonstration of the entire process, using the Tomorrowville virtual urban testbed.

The operation leads to a risk-sensitive future visioning scenario (consisting of an urban plan and a set of pertinent policies) owned not only by the planning authorities, municipalities, the government or the private sector, but also by the communities who will live in these future cities. It therefore represents a significant advancement in the state of the art towards inclusive, people-centred disaster risk reduction, as advocated by global policies [59] and world-leading international agencies like the United Nations [60], the International Federation of Red Cross [61], and the World Bank [62].

It is important to note that the TCDSE presented in this paper should be regarded as a work in progress; module definitions are evolving in real time and will continue to develop and be refined as the process is increasingly applied. For instance, it is not clear yet how agreed risk should be characterized in the presence of both qualitative and quantitative impact metrics. Furthermore, the hypothetical case-study application provided in Section 3 only demonstrates the effectiveness of the TCDSE in supporting decisions related to pro-poor risk-informed urban development under idealised conditions. The framework has yet to be tested in a real-life setting with non-fictitious stakeholders, where the process of collective, democratized decision making is complicated and consensus on risk may be challenging to achieve. In addition, the physics-based approaches to hazard and impact characterisation encouraged as part of the **Computational Model** may not be feasible in all contexts, given the rich information and significant computational demands required. The most sophisticated versions of the synthetic population algorithms and activity-based models that produce physical and social information for the **Urban Planning** module require detailed data samples (accounting for relevant dependencies among different variables), which are unlikely to be developed as part of conventional urban plans. However, data-related challenges to implementing the TCDSE emphasise the importance of appropriately collecting/generating these data in the future. Addressing both data- and computational-related issues will be increasingly facilitated by technological improvements and associated cost reductions. Finally, the proposed framework should not be regarded as a panacea for urban planning decision making in general. Disaster risk is just one factor to be considered in urban development, and the outcomes of the TCDSE should be appropriately contextualized and balanced with other important challenges (e.g., gentrification, poverty, health, and environmental effects). This type of trade-off could be incorporated within the democratized risk agreement process, if the alternative consequences of urban development can be suitably represented in quantitative or qualitative form for comparison with disaster-related impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The source code for the operational demonstration of the TCDSE provided in Section 3 will be made available in a Github repository (https://github.com/TomorrowsCities) upon acceptance of the manuscript. This repository will also host updates to the quantitative components of the TCDSE as they become available in the future.

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