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Making physical climate risk assessments relevant to the financial sector – Lessons learned from real estate cases in the Netherlands

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A B S T R A C T

Climate change is an important additional risk for the financial sector. For (large) investments in real estate, it is becoming increasingly important to take climate related risks into account. Yet, generating tailored physical climate risk information to make meaningful decisions about investment portfolios remains difficult. Using literature review, semi-structured interviews and reflection on four case studies implemented in the Netherlands, this paper presents lessons learned and recommendations for improving Physical Climate Risk Assessments (PCRA) for the financial sector. Results from the literature review show that simply selecting a PCRA methodology does not guarantee uptake of information by end-users, because there is no single approach that is suitable for all contexts. From the case interviews, we conclude that effective PCRA information is helpful for the financial sector in several ways; first, it supports investors to pinpoint which assets need attention and how much money is required to mitigate the impacts. Second, they serve as a template upon which clients make purchasing decisions. Third, they serve as a tool for determining the choice of building materials and the structure of properties. Fourth, they assist firms in the development of plausible adaptation strategies. Furthermore, we identified five cardinal points (that incorporate the perspectives of both providers and end-users) to improve the PCRA process: 1) Engagement and co-production, 2) Needs identification, 3) Data availability and quality, 4) Internal integration, and 5) Communication. These recommendation points will serve as a valuable reference to guide the selection and implementation of the most appropriate PCRA method for a given situation.

1. Introduction

Climate change is likely to increase the exposure of natural and human systems to multiple risks. Developing efficient approaches to climate change risk assessment to support adaptation decisions in the present and future has become imperative (IPCC, 2014). Regardless of future mitigation efforts to reduce emissions, an appreciable level of climate change is still expected (IPCC, 2018). Therefore, failure to effectively plan for and manage future climate risks can result in significant damage to businesses, economy,

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infrastructure, industry and society in general (Stern, 2013). Impacts of climate change on social, environmental, and economic systems could potentially have catastrophic impacts; major floods, droughts, wildfires, and storms have increased in frequency and intensity (IPCC, 2014). Climate change is considered a systemic risk because it has the potential to result in instability of the economic system (Gelzinis and Steele, 2019). For example, it is estimated that once 4 degrees celsius rise in temperature is reached, the global economy will lose up to $23 trillion per year, an amount that exceeds the permanent damage of the 2007–2008 financial crisis (Kompas et al., 2018).

Climate change presents two main sources of risks to financial investors: *physical climate risks* that expose assets to the consequences of climate change and *climate transition risks* related to the impacts of changes in policies and regulations to reduce greenhouse gas emissions (NGFS, 2019; GFSG (Green Finance Study Group), 2016). Until now most studies have focused on transition climate risk including attempts to characterise these risks (Bolton and Kacperczyk, 2021; Nguyen et al., 2020). There are, however, increasing concerns about physical climate risk on businesses, particularly equity, debt, and real estate assets in investors' portfolios (BoE (Bank of England), 2018; DNB, 2018). Physical climate risks are direct threats of climate change that pose both distinct and systemic risks to different sectors. This kind of risk can be acute (event driven) such as floods, droughts and storms or chronic (longer-term shifts) such as long term heat stress, droughts, and sea level rise (TCFD, 2017). Extreme and variable rainfall patterns and higher temperatures result in severity of the risk that can potentially result in destabilizing losses for the financial sector affecting banks, and insurance companies with direct and indirect exposure to different assets (Gelzinis and Steele, 2019; Kjellstrom et al., 2018; Morel et al., 2015; Sullivan and Gouldson, 2016). This study focused on improving the assessment of these kinds of physical climate risks because it helps to understand how global warming could impact the financial sector and which policies might effectively reduce financial instability due to climate damage (Dafermos et al., 2018).

For investors, climate change can significantly increase the physical risk profile of investments (Sakhel, 2017; Battiston et al. 2017; IEA, 2017; Carney, 2015). For example, it is estimated that by the end of the 21st century, a wide range of built assets in real estate, infrastructure, timber, agriculture and tourism sectors will be affected by climate change causing a risk value of about 4.2–43 trillion US Dollar (Groth and Seipold, 2020; EIU (Economist Intelligence Unit), 2015). The likely negative impacts of climate change for some companies in the financial sector will range from an increase in production costs to the collapse of core businesses (IPCC, 2014; Linnenluecke et al., 2013; Agrawala et al., 2011; Linnenluecke and Griffiths, 2010; Aragón-Correa and Sharma, 2003). However, depending on the core activities, supply chain and location of the business, the level of climate risk will differ significantly from one company to another (CDP, 2018; BSR, 2016; Groth and Brunsmeier, 2016; CDP, 2015; Brunsmeier and Groth, 2015). Hence, there is an increasing attempt within the financial sector to minimize risks and take advantage of the opportunities that come with a changing climate (Groth and Brunsmeier, 2016; UN Global Compact, 2015; IPCC, 2014).

Financial regulators and other relevant stakeholders have raised concerns about climate risks on real asset values (Carney, 2015). Recently investors have called on companies to address climate change issues and legislators are increasingly requesting investors to report on climate change risk for informed analysis of exposed assets (Lepousez et al., 2017). The effects are supported by recommendations from the Task Force on Climate-Related Financial Disclosures (TCFD) on improving the standards for reporting climate-related risks and opportunities and the recently published recommendations on technical screening criteria for reducing physical climate risks in the EU Taxonomy (TEG, 2020; TCFD, 2017). However, studies have shown that many companies either do not report the costs of physical climate change impacts or tend to underestimate them (Goldstein et al., 2019).

Despite the potential value of Physical Climate Risk assessment (PCRA) in estimating climate threats and generating actionable information to address the threats, little attention is given to it in the financial sector (Hamaker-Taylor et al., 2018). Several issues limit organisations' ability to conduct PCRAs. First, inadequate financial and human resources to conduct PCRAs (Mukheibir and Ziervogel, 2007; Pini et al., 2007). Second, lack of in-house expertise to conduct PCRAs because it is not part of the organisation's core business (Dessai et al., 2005; Measham et al., 2011). Third, inadequate stakeholder consultation during the planning and implementation of PCRAs, resulting in mistrust of risk information and limited use for decision-making (Jones et al. 2014; Storbjörk, 2010). Fourth, climate risks are often difficult to price and hedge (Krueger et al., 2020). Consequently, investors rely on consulting firms for tailored climate risk information to address their needs. Studies have shown that the lack of transparent scientific validation of often black-box approaches raises concern for both science and practice (de Bruin et al., 2020). Furthermore, investors find it difficult to use climate model (global and regional scale) results to estimate the actual risks of their assets at different spatial and temporal scales. Moreover, simply selecting a climate risk assessment method or approach does not guarantee effective decision making in adaptation planning (Tonmoy et al., 2019). The information and processes required to operationalise the PCRA methods are context specific, depending on the objective of the adaptation decision, its context and the nature of the problem (Pidgeon and Fischhoff, 2011; NRC (National Research Council), 2009).

Therefore, this paper rather than focusing on quantifying physical climate risk aims at providing a set of recommendations that will improve PCRA for the financial sector, by reflecting on four different case studies in the Netherlands and existing literature. Two of the case studies focused on individual assets; the Hotel at Wilhelminakade in Rotterdam and The Wall shopping centre in Utrecht (both managed by MVGM). The other two cases focused on asset portfolios, from Vesteda and Syntrus Achmea Real Estate & Finance. The remainder of this paper is structured as follows; Section 2 presents a review of existing PCRA methodologies, their benefits, and limitations. Section 3 details the significance of the Netherlands as a case country, and describes the four case studies in relation to purpose, process, and results. Analysis of client feedback on the usefulness of incorporating PCRA information into general financial decision making is presented in section 4. Section 5 discusses and concludes the lessons learned to improve PCRA for the financial sector.

2. Overview of physical climate risk assessments

2.1. The concept and context of climate risk

In its sixth assessment report (AR6), the IPCC defines risk as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems". The report also argues that the concept of risk should not focus on the outcomes of the climate events only but be linked with the consequences of such events for human or ecological systems (IPCC, 2020). Thus Climate risk should be the result of a combined interaction of three main components; hazards, vulnerability and exposure (Cardona et al., 2012a, b, Oppenheimer et al. 2014; IPCC, 2020). However many physical climate risk assessments (PCRA) still focus on the hazard element of the risk assessment (Cardona et al., 2012a, b). Detailed explanations of these components have been presented by the IPCC (2014).

Performing a complete PCRA requires good sources of data for each component, an effective approach to gathering the different kinds of data and a sound methodology for combining components, analysing the risk and engaging relevant stakeholders.

2.2. Data sources for PCRA

Data on the exposure component is based on asset-specific information; asset location and financial value. In cases where this data is not available proxies on activities are used to capture this exposure. The vulnerability component of the climate risk assessment can be very difficult to determine. Data required to determine the vulnerability of a company, for example, depends explicitly on its physical assets such as the design and material of the buildings and its reliance on for instance high water and energy consumption, as well as its links with the value chain and adaptive capacity. Therefore any risk assessment that does not consider the degree of sensitivity or adaptive capacity at the asset level will paint a more generic picture of climate change risk on a company's activities (Gallo and Lepousez, 2020).

The process of generating hazard data can be classified into; (i) Historical observations and extreme value theory and (ii) Dynamical models. (i)The Historical observation and extreme value theory are to directly estimate hazards from historical observational records. In cases where available records are too short to characterize certain hazards, the extreme value theory is often used (Coles et al., 2001; Sobel and Tippett, 2018). For example, determining the probability of a 1 in 200 extremes in areas where weather data is unavailable for 200 years. However, certain conditions may make extreme value theory unsuitable. First, due to climate variability and change, historical observations of hydrological and meteorological variables are not representative anymore for the future (Jain and Lall, 2001; Milly et al., 2008; Sobel and Tippett, 2018). Second, continuous time-series data at regular intervals are unavailable for certain rare, high impact events such as tropical cyclones. Third, extreme value theory does not capture the spatial occurrence of hydro-meteorological events, though relevant for spatiotemporal analysis of impact. (ii) Dynamical models are used to study the behaviour of the system outside the observational records. For national and local level analysis, data is dynamically downscaled from global and regional levels (Duvel et al., 2017; Harris and Lin, 2013). Models have biases and errors affecting their use for PCRA. Climate models have significant biases, especially in the simulation of precipitation and extreme events. This can limit the robustness of the risk assessment and affects the trust of end users in the results (Bakker, 2015). However, some models (e.g., Van der Wiel et al., 2016; Shaevitz et al., 2014) perform better in producing data on these events than others depending on their computational power to resolve the physics of the particular events.

Climate data for harzard analysis are often sourced from Global climate models (GCMs) and Regional climate models(RCMs). Examples of GCMs include the Community Atmosphere Model version (CAM) (Wehner et al., 2014), European Centre for Medium-Range Weather Forecasting-Hamburg (ECHAM) (Roeckner et al., 2003; Scoccimarro et al., 2011), Florida State University (FSU) (LaRow et al., 2008); NASA Goddard Earth Observing System Model version (GEOS) (Suarez et al., 2008), National Centers for Environmental Prediction Global Forecasting System (NCEP GFS) (Saha et al., 2014), NASA Goddard Institute for Space Studies (GISS) (Schmidt et al., 2014), Met Office Hadley Centre Model version 3-Global Atmosphere (HadGEM) (Walters et al., 2011), Geophysical Fluid Dynamics Laboratory High-Resolution Atmosphere Model (HiRAM) (Zhao et al., 2009), and Meteorological Research Institute (MRI) (Mizuta et al., 2012; Murakami et al., 2012). The resolutions of these models vary from 28 to 130 km. Examples of regional climate models also include Action De Recherche Petite Echelle Grande Echelle (ARPEGE) (Gibelin and Déqué 2003), Climate High Resolution Model (CHRM) (Vidale et al. 2003), Community Land Model (CLM) (Steppeler et al. 2003), Hadley Centre Regional Climate Model (HadRM3) (Buonomo et al., 2007), High-Resolution Atmosphere Model (HIRHAM) (Christensen et al. 1996), Regional Atmospheric Climate Model (RACMO) (Lenderink et al., 2003), Rossby Centre Atmosphere-Ocean model (RCAO) (Doscher et al., 2002; Jones et al. 2004), Regional Climate Model system (RegCM) (Giorgi and Mearns 1999), REgional MOdel (REMO) (Jacob 2001) and PROgnostic at the MESoscale (PROMES) (Castro et al. 1993).

2.3. Approaches to PCRA

Throughout the literature three main approaches to data gathering and climate risk assessments are identified; qualitative, quantitative and semi-quantitative. The qualitative approach is often the simplest and does not allow for a numeric evaluation of risks. This approach to PCRA uses questionnaires to collect relevant information, providing a subjective estimate of risk based on ranking and aggregation starting from the end-user level, and perhaps the first step to integrate end-users' knowledge into the analysis (Komendantova et al., 2016; Farrokh et al., 2013; Greiving, 2006; Greiving et al., 2006; Olfert et al., 2006; Schmidt-Thomé et al., 2006). The quantitative approach characterizes the risks in more detail. It aims to ensure a sense of objectivity and uses numeric evaluation methods such as Bayesian networks, weighted sum and probabilistic approaches. This approaches offers a rigorous analysis of the risk components (e.g. Farrokh et al., 2013; Marzocchi et al., 2012; Garcia-Aristizabal and Marzocchi 2012; Greiving, 2006; Greiving et al., 2006; Olfert et al. 2006; Schmidt-Thomé et al., 2006). The semi-quantitative approach allows for the evaluation of the relationships between agents and processes and the respective exposures of a given element at risk (Farrokh et al., 2013; Kappes et al., 2012).

2.4. Methodology for PCRA

PCRA methodologies have over the years shifted in approach. It started from scenario-driven impact assessments (Parry and Carter, 1998; Carter et al., 1994) to model-driven vulnerability assessment that focuses on solutions and interventions for policymaking (IPCC, 2018; Jones and Preston, 2011; IPCC, 2014; Burton et al., 2002). These risk assessment methods have evolved from a top-down approach that begins with observing and modelling climate data, evaluating the impacts and providing appropriate adaptation options, towards a 'bottom-up' approach that starts with an evaluation of exposure and vulnerability, leading to the assessment of risk, and resulting in the identification and implementation of adaptation options (IPCC, 2014; IPCC, 2018; Palutikof et al., 2019; and Street et al., 2019). More recently, the IPCC introduced a new definition of climate risk which is the result of the combined interaction of hazards, vulnerability and exposure (Oppenheimer et al., 2014; IPCC, 2014).

An extensive review by Gallina et al., (2016) classified the various PCRA methods into multi-risk and single-risk assessments. The multi-risk assessment methods aim at an integrated assessment of multiple risks derived from different natural and man-made hazardous events (e.g., Farrokh et al., 2013; FEMA, 2017; Schmidt-Thomé et al., 2006). In this context, many organisations have developed tools and services for multi-risk assessments. For instance, the World Bank and Munich Re (https://www.munichre.com) developed a tool for spatial analysis of large-scale natural hazards (e.g. floods, droughts, cyclones, earthquakes). Though useful for global policies, the tool is unable to provide risk assessment at a finer resolution (Dilley et al., 2005). The RiskScape was developed to quantify direct and indirect losses of hazards on people's lives and property. RiskScape allows for comparison of information from hazard exposure, assets and vulnerability by specifying a relation between hazard, asset characteristics, and the potential damages (Schmidt et al., 2011; GNS and NIWA, 2010). HAZUS is a GIS-based tool used to estimate potential losses from several individual hazards to support mitigation planning efforts for physical damages to buildings and infrastructure. The Hazus provides standardized tools and data for estimating risk from earthquakes, floods, tsunamis, and hurricanes. It also combines expertise from many disciplines to create actionable risk information that increases community resilience. However, an important limitation of the HAZUS method is its inability to allow simultaneous assessment of multiple hazards, their damages, their interactions and cascading effects (FEMA, 2017). Another GIS-based tool called CAPRA can be used for a probabilistic analysis of different hazards and their related losses (Bernal, 2010).

Single-risk assessment method focus on evaluating individual risks emerging from one particular hazard at a specific time and geographic location (e.g., Marzocchi et al., 2012). Single-risk assessment methods have for example been used for PCRA for flood and coastal risk assessment (Jäger et al., 2018; Zhou et al., 2012) and infrastructure (Tsavdaroglou et al., 2018; McConnach et al., 2011; Etkin et al., 1998). Furthermore, Nieuwkerk et al. (2011), extensively explained some single-risk assessment methods for estimating the direct and indirect damages of urban areas exposed to water safety, pluvial flooding, drought and heat stress. The HIS SSM assessment model is an example of such a method used for assessing losses from flood risk (Groot Zwaaftink and Dijkman, 2007). Most climate change risk assessments are either focusing on selected hazards or targeted sectors. Yet, multi-risk assessment methods have in the last decades received a great level of attention (Mavrommatis et al., 2019). Moreover, certain PCRA methods such as the 'impact chain' (IC) developed by Schneiderbauer et al. (2013) can be used for both single and multi-risk assessment and applied in different sectors. The IC focuses on identifying and describing important links between the different components of climate risks. Then indicators are selected for each of these components, and the data collected are normalized before being aggregated with different weights. The IC approach has gained attention from different organizations partly because of its ability to bring context-specific information into the risk assessment.

2.5. Co-production of PCRA

Co-production is used to provide a more collaborative and iterative approach to climate services (Daniels et al., 2020; Dilling and Lemos, 2011) instead of a top-down transfer of knowledge from scientists to end users (Taylor, et al. 2017). The continuous interactions in co-production aim to create a more salient, legitimate and credible climate service (Cash et al. 2003) and respond to the needs of end-users. Co-production facilitates the development of trust in the process of transforming climate information into salient recognized and useable services for end users. While co-production of climate services is increasingly used in sectors such as agriculture and water (Butterfield and Osano, 2020; Nyadzi 2020; Zarei et al., 2020), health (Robert et al., 2020; Filipe et al., 2017; Dunston et al., 2009) and public services delivery (Loeffler and Bovaird, 2020; Brandsen and Pestoff, 2006), little is known of its value in the financial sector. Co-production of a PCRA between scientists and stakeholders can generate a more credible and meaningful assessment that captures risks related to physical climate change to facilitate investors' decision-making on climate-proof investments (Lemos and Morehouse, 2005).

2.6. Application of PCRA methods in the financial sector

The scientific efforts to assess climate risk in the financial sector have focused on several methods. For example, The Dynamic Ecosystem-FINance-Economy (DEFINE) model builds on the stock-flow-fund model which is used to estimate the physical impacts of climate change on financial stability (Dafermos et al., 2018). The stock-flow consistent model is also used to investigate the climate change impacts on the indebtedness of firms (Bovariet al., 2018). Lamperti et al. 2019 used an agent-based climate–macro-economic model to examine the impacts of climate-related damages on the stability of the global banking system. The Dynamic Integrated Climate-Economy (DICE) model uses the standard integrated assessment model and climate Value at Risk framework to quantify the size of loss on a portfolio of assets over a given time horizon and at a given probability due to climate change (Dietz et al., 2016). Others have used a temperature-augmented general equilibrium long-run risks (LRR-T) model to estimate the risk of global warming on assets values or equity prices (Bansal et al., 2016). Besides, the NOAA's sea level rise calculator is used to analyse the risks of sea level rise on real estate prices (Bernstein et al., 2019). The Network for Greening the Financial Systems developed Climate Scenarios to analyse climate risks to the economy and financial systems, especially for central banks and supervisors (NGFS, 2020).

Other integrated tools mainly called Catastrophe models (Sobel and Tippett, 2018) are used to perform a holistic assessment of risk, instead of just hazard. They constitute the hazard, vulnerability of assets and financial loss. The application of these models to climate risk assessment is sometimes problematic. First, they focus on insured financial losses only. It can be argued that the focus on insured losses is due to the demand by the insurance industry, therefore rather than re-inventing the wheel, those models should be adjusted to consider both insured and uninsured losses. Nevertheless, some emerging models (e.g., Souvignet et al., 2016; Bresch, 2016; Linnerooth-Bayer and Hochrainer-Stigler, 2015) now consider a wider range of assets, different risk transfer mechanisms and impacts of certain adaptation actions (e.g., Souvignet et al., 2016). Furthermore the out of the box vendor models should be used with caution, however the many catastrophe models are quite advanced by now and easily outperform all the above-mentioned approaches in terms of accuracy and rigour. Second, they tend to be black-box models with limited transparency on their underlying mechanism and data use and are often not openly available. Although some open source models (e.g., Bresch, 2014) have been developed, they are yet to be recognized as a standard for use in the industry. Third, it is more effective to predict extreme precipitation events through physical modelling. Yet the hazard components of catastrophe models are estimated from historical observations with little or no physics of extreme weather and climate events. Therefore a hybrid of statistical-dynamical approaches is been developed to include a certain degree of physics to tackle the climate change problem (Emanuel, 2006). Despite these efforts, climate risk information services for the financial sector have not been fully realized and the use of historical climate data could result in an underestimation of future risks (de Bruin et al., 2020; Hamaker-Taylor et al., 2018). The ClimINVEST project assessed the challenges of PRCA methods applied in the financial sector, especially related to the black box of methods and data sources used, as well as the difficulties with estimating financial impacts of physical climate risks (Hubert et al., 2021).

3. The case studies

3.1. *The significance of the Netherlands case*

The Netherlands is affected by both positive and negative impacts of climate change. An increase in the number of warm summer days is, for example, favourable for the Dutch tourism sector which presents some economic benefit. Also, heating costs in the winter are likely to reduce. At the same time, flood risk in the Netherlands is increasing due to higher peak river flows and sea level rise. More frequent summer droughts are negatively affecting agricultural production and result in restrictions on water use (Nwanazia, 2018).

Due to its low-lying nature, about 24 % of land in the Netherlands is below sea level. The country is uniquely positioned in the Delta of the rivers Rhine, Ijssel and Meuse and has historically been managing flood risk from rivers and sea. The largest climate-related risk in the Netherlands is flooding. Without proactive water defences through a combination of policy and infrastructure, such as dykes and locks, about 60 % of its territory is vulnerable to flooding (Slomp, 2012).

Recent studies have shown that the total precipitation and frequency of extreme events have increased over a large part of the Netherlands (Golroudbary et al., 2016; Daniels et al., 2014; Burauskaite-Harju et al., 2012). Buishand et al. (2013) found a 25 % increase in annual precipitation over the Netherlands from 1910 −2013 with 35 and 16 % increases in winter and summer respectively. In the work of Attema et al. (2014) based on the KNMI'14 climate scenarios developed by the Royal Netherlands Meteorological Institute, climate change is expected to further increase the frequency and intensity of these extreme rainfall events. For instance, by 2050, the average winter temperature of the Netherlands will increase between 1.1 degrees celcius and 2.7 degrees celcius and the sea level will be 15 cm to 40 cm higher than in 1990. This is expected to increase the likelihood of flood, prolonged periods of drought, increase salination of surface water bodies and threaten the ecosystems. Therefore, the Dutch have developed a Delta Programme set out every year to deal with the expected impact of climate change (Delta Programme, 2019). Already, the Netherlands embarks on several projects like adaptation to flooding and waterlogging, drought and heat across the nation (http://ruimtelijkeadaptatie.nl/english/examples/).

For a long time, climate change was treated as a "water" problem in the Netherlands and the primary response was better flood protection and improved water delivery and storage. Recently however it has been acknowledged that climate change represents a unique challenge for De Nederlandsche Bank (the Dutch central bank) and the many financial institutions in the country (de Bruin et al., 2020). Flood risk is the top on the agenda of these institutions. The unusual drought during the spring and summer of 2018 triggered the need to perform an analysis of financial risks and opportunities that come with a range of extreme events (Actiam, 2018). According to De Nederlandsche Bank (DNB), the potential flood damages under different dike breach scenarios are between EUR 20 and 60 billion. Also, physical assets can be directly affected by increased flood risk and credit and investment portfolios will be affected indirectly because of depreciation (DNB (De Nederlandsche Bank), 2018).

In response, the supervisory authority (DNB) and institutions in the Dutch financial sector are promoting the understanding of physical climate risk and are exploring options to manage the financial consequences of climate change (de Bruin et al., 2020). The

DNB is for example investigating ways to incorporate climate-related risks in its supervisory assessment framework (Elderson, 2018). The DNB is also developing stress tests for both physical and transition-related risks to assess long-term risks faced by financial institutions. For example weather-related risks for general insurers, and transition risks, based on different future scenarios of policy and technology (Sleijpen, 2018).

Dutch financial institutions are taking steps in assessing climate risk for their assets and portfolios. The Dutch Climate Impact Atlas offers an important (open and free) source of climate information and financial institutions are experimenting with this data to perform risk assessments. The Climate Impact Atlas is an open-access collection of interactive maps showing current and future climatic risks related to coastal flooding, pluvial flooding, drought and heat in the Netherlands (Laudien et al, 2019). Climate Adaptation Services (CAS), manages the atlas and offers help desk support to its users.[1] For this study, we evaluated four PCRA cases;1) the Hotel at Wilhelminakade in Rotterdam, 2) The Wall shopping centre in Utrecht, and 3) Two Dutch real estate portfolios. Case studies 1 and 2 focused on the individual, location specific asset climate risk assessments. Case study 3 focused on a portfolio climate risk assessment for two Dutch investment managers.

3.2. Case study 1: Hotel Wilhelminakade, Rotterdam

3.2.1. Purpose

MGVM real estate was interested in potential climate related risks in areas where real estate is being developed or traded. The hotel is located along with the Wilhelminakade Rotterdam (Fig. 1) next to the Meuse River. It is vulnerable to floods caused by either high water levels in the river and/or high sea levels due to for example storm surges. The risk assessment focused on the potential risks of floods from the Meuse/Rhine river system and the sea. The site of the hotel is not protected by dikes but is mostly elevated with quays ranging from just under 3 m above sea level in the city to 5.5 m above sea level on the second Maasvlakte. The Maasvlakte is built to support infrastructure on reclaimed land. The main risk of flooding in the area is when three phenomena coincide: the high sea level in combination with high water levels on the Meuse and Rhine rivers. High sea levels can be caused by storm surges during springtide. Higher water levels in the river are often caused by high rainfall in the Meuse and Rhine basins.

3.2.2. Process

The Client and insurance company expressed the need for understanding the physical climate risk on the property they were planning to buy from MVGM. The climate risk assessment was based on data from the Dutch Climate Impact Atlas (https://www.klimaateffectatlas.nl/en/), the climate effect atlas of the Province South Holland (https://ruimtelijkeadaptatie.nl), the Climate Atlas of the city of Rotterdam (https://www.climateadaptationservices.com/projecten/klimaateffectatlas-voor-de-stad-rotterdam/) and the adaptation strategy of the city of Rotterdam (http://www.deltacityofthefuture.nl/cities/rotterdam/climate-change-adaptation). MVGM included the climate risk assessment report in the portfolio presented for the real estate sale of the Hotel. The PCRA report was further refined into a shorter and more standardized report with a risk score per climate hazard following a discussion with MVGM. MVGM requested an additional PCRA for the Wall in Utrecht (see case study 2).

3.2.3. Results

The hotel was found to be exposed to changes in the water level of the river and storm surges. Projections show that sea levels will increase by 20–40 cm in 2050 and 45–80 cm by 2085. Maximum river levels are expected to increase up to 40 cm in 2050 (using a return period of 1 in 1000 years). Flood inundation depth in the area is likely to remain below 80 cm, yet the storm surge barrier has a chance of failure leading to flooding. Fig. 2 shows that although the current flood risk at the location of the hotel is estimated relatively low, an increase is expected toward the end of the century. The statistical return period of flooding of the Wilhelminakade area will increase from 1: 10.000 years to a 1:1000 year return period under a 60 cm sea level rise by 2085.

3.3. Case study 2: The Wall, Utrecht

3.3.1. Purpose

MVGM requested a PCRA that include risk indicators and an outlook for The Wall building in Utrecht. The individual location specific asset climate risk assessment was conducted for The Wall, which is a 65000 m^2 shopping centre located in Utrecht, by the A2 highway (Fig. 3). The location of the shopping centre allows for easy access to major highways along the north–south connection in the Netherlands which links Amsterdam (the capital city) to other European markets. The case study aimed at assessing the risk of the shopping centre to floods (fluvial and pluvial flooding), droughts and heat stress.

3.3.2. Process

The data used for this climate risk assessment is publicly available at the Climate Impact Atlas for the Netherlands website (https://www.klimaateffectatlas.nl). Since physical climate risks have a direct impact on assets at a local level, a tailor-made approach was considered to examine the specific geographic and climatic conditions of The Wall's area. A digital story map was developed to present the results of the climate risk assessment the including risk indicators. A GIS-based story map is an interactive map on which a story is

[1] The Dutch Climate Impact Atlas provides insights into climate change impacts related to flooding, waterlogging, drought and heat in the Netherlands, see https://www.klimaateffectatlas.nl.

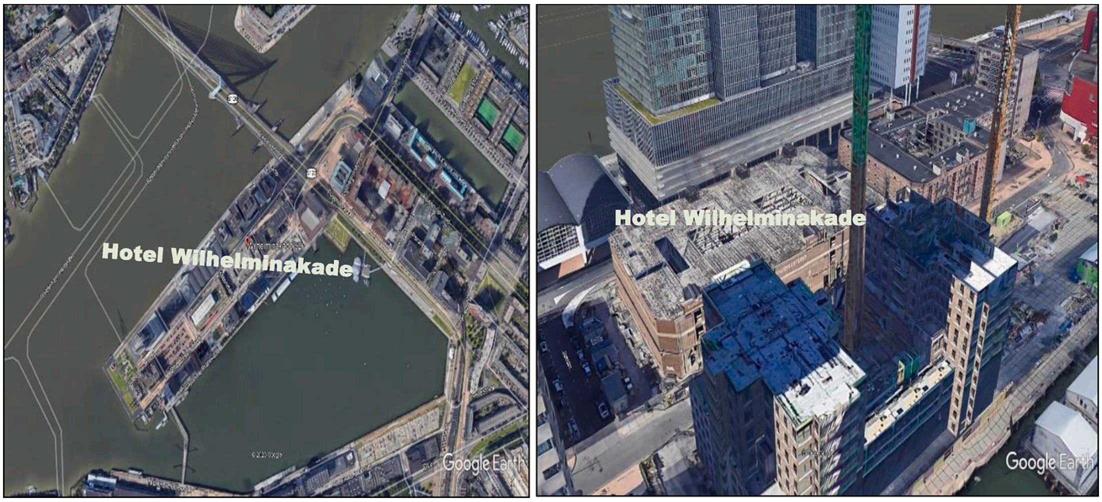

Fig. 1. The Hotel Wilhelminakade, Rotterdam.

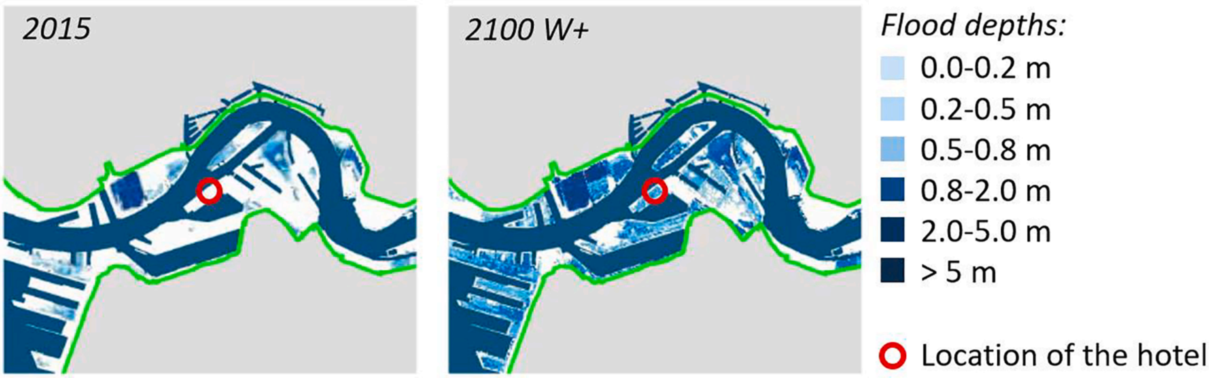

Fig. 2. Estimated flood depth for a 1000-year flood, in 2015 (left) and 2100, under a 'W+ (worst case) climate scenario ().
Source: Rotterdam Climate Initiative, 2013

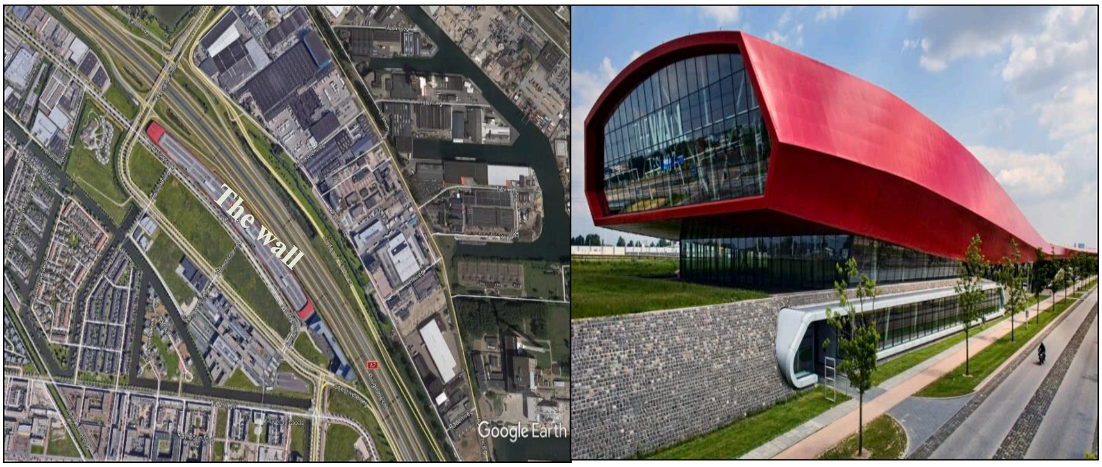

Fig. 3. The Wall shopping centre in Utrecht, the Netherlands.

told. It offers the possibility to provide the user with insight into the possible consequences of climate change using storylines. Such a storyline can, for example, focus on certain consequences, a specific area and/or a certain period. In this case study, the storyline focused on four climate hazards, The Wall location and the impacts of climate change for the period until 2050.

3.3.3. Results

Results of the risk assessment show that the Wall, though exposed to fluvial flooding, it is not particularly vulnerable due to the high protection standards of the surrounding dikes. The wall is moderately at risk of pluvial floods. It is estimated that an extreme rainfall event of 70 mm in 2 h has a probability of occurrence of around once every 100 years. Consequently, this will affect access to the main roads to The Wall and part of the A2 highway can be flooded and be inaccessible. Fig. 4 shows a 3D image of the water depth resulting from the extreme rainfall event. Inundation depth is estimated to be between 20 and 30 cm, potentially damaging the buildings foundation, grid infrastructure or sewer systems, depending on threshold heights of the construction. With drought triggered soil subsidence and erosion, it is estimated that a yearly average of 2 mm/yr of land subsidence occurs in the area around the Wall. The Wall is, therefore, both exposed and vulnerable to drought-driven soil subsidence. Concerning the local urban heat island effect, the Wall with its concrete rooftop and 14,000 parking spots, is not able to absorb radiation, creating a local island of heat to the city-level heat island effect of around 1.5 degrees Celsius. The wall is therefore highly at risk of heat stress.

3.4. Case study 3 and 4: Dutch real estate portfolios

3.4.1. Purpose

Following a meeting on physical climate risk that was part of the ClimINVEST project - two Dutch investment managers wanted to carry out a climate risk assessment of their real estate portfolios. Both organisations finance, develop and invest in real estate and are among the largest real estate managers in the Netherlands: Vesteda and Syntrus Achmea Real Estate & Finance (SAREF). Vesteda makes investments for pension funds and insurance firms, in sustainable Dutch residential properties, focussing on middle-income tenants by providing them access to affordable housing and improving the quality of residential areas and communities. SAREF invests on behalf of institutional investors such as pension funds, insurers and charitable institutions. For these clients, they seek sustainable solutions, including shops, homes, offices and international real estate. Both Vesteda and SAREF seek to understand the potential risk of their assets to physical climate risk.

3.4.2. Process

Both Vesteda and SAREF requested for a PCRA to incorporate climate risk into due diligence and other investment decision-making processes and the will to implement transparent climate reporting. Therefore, as a first step, a climate risk assessment of their portfolios was necessary. The needs of Vesteda and SAREF were identified for a transparent and uniform risk score that can be used by the market. Both organizations were looking for a first assessment of – what they called - gross risk, as opposed to net risk (the risk after identifying and implementing actions to mitigate climate risk). The risk assessments were carried out based on data from the Dutch Climate Impact Atlas. By disclosing technical documentation that provided the organizations with all relevant metadata, such as the source of the data, year of production, spatial resolution etc., full transparency about the methods and assumptions behind the risk

Fig. 4. Potential water depth after a 2-hour downpour of 70 mm of rain. An extreme event like this occurred in the nearby town of Kockengen in 2013 and caused major damage. Under the current climate, a downpour like this may happen once every 100 years. Under climate change, it is expected that this probability will increase to once every 50 years towards the end of the century (WENR and CAS. 2020; KNMI, 2015.

assessments was pursued. The results of the risk assessments were used in the respective business plans of both organisations, documents that describe the current business position and provide a vision for the upcoming years.

Both organizations received quarterly updates of their portfolio risk assessment, in line with portfolio mutations. Whenever new content became available in the Dutch Climate Impact Atlas, such as improved maps depicting heat stress, this was discussed and processed in the algorithm behind the risk assessment, leading to updated scores. Transparency was established about the fact that knowledge on climate change evolves, and therefore risk scores may change when new data becomes available. Insight into physical climate risk led to the following steps: (1) the will of both organisations to identify adaptation measures that may mitigate the risks described in the risk assessment; (2) a need for an inventory of building-specific features (e.g. roof type, building material) that affect an asset's vulnerability in light of climate risk; (3) engaging with municipalities on local resilience strategies.

3.4.3. Results

Both organizations now periodically assess physical climate risk for their real estate portfolios, using open data, with transparency regarding the assumptions and limitations behind the method used. There were also efforts towards the development of in-house capacity on the topic of climate risk assessment and management, with both organisations seeing this as a new, permanent aspect of annual reporting. Different visualizations are used to communicate climate risk to the stakeholders within both organizations. Impact diagrams were co-produced, that present simplified, visual summaries of the climate impacts relevant to real estate. Diagrams were developed for different climate hazard themes, such as heat, drought and pluvial flooding, and summarize all relevant hazards and impacts connected to them. As these diagrams are simplified representations, they are consequently incomplete. Nevertheless, they proved to be a useful tool in bringing about awareness of physical climate risk. The concept of these impact diagrams was first presented in the Dutch National Climate Adaptation Strategy (NAS, 2016). Fig. 5 provides an example of an impact diagram for pluvial flooding.

In their reporting, both organizations use maps to communicate the exposure of their respective real estate portfolios to different hazards. Maps from the Climate Impact Atlas are combined with asset locations, resulting in visualizations as represented by Fig. 6.

4. Case study interviews and feedback analysis

Using a structured questionnaire with open and close-ended questions, we purposively interviewed four representatives of the three companies that had requested the services of Climate Adaptation Services company (CAS) for a PCRA and were willing to be involved in the study. Two of the respondents were sustainability managers in their respective companies. One was a real estate advisor and the other a researcher. The interview aimed at understanding (i) client perception on the PCRA performed (ii) how climate risk information is incorporated in a general financial investment decision, and (iii) the degree of influence climate risk information have on investment decisions. Each interview lasted about an hour and responses were documented and analysed (interview questions are shown in appendix 1).

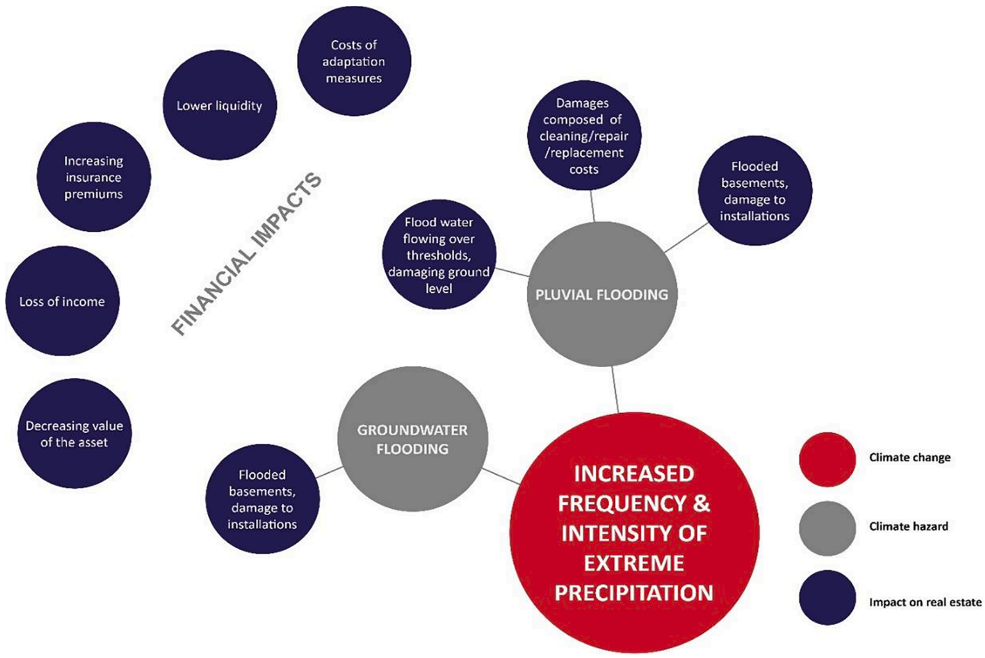

Fig. 5. An example of an impact diagram for pluvial flooding. It was co-developed with real estate stakeholders during a workshop on physical climate risk in 2019 (Source: CAS (Climate Adaptation Services), 2019).

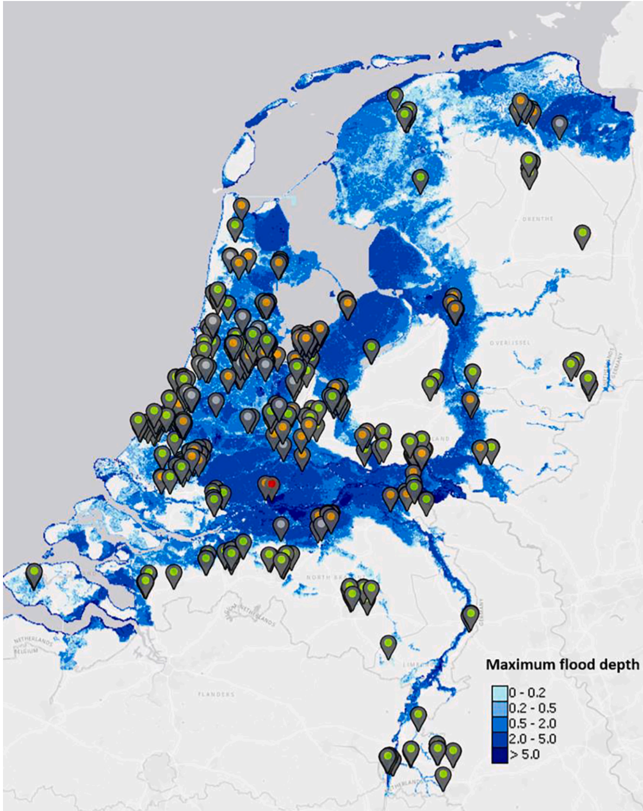

Fig. 6. Example visualization of exposure of a real estate portfolio to flood risk. The map shows a 1:1000 year flood event, with the maximum flood depth in meters. The portfolio, of which the latitude and longitude are randomly shifted due to confidentiality reasons, has been mapped out using a red to green colour ramp. Green represents a low risk, while red represents a high risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: HKV, 2020

4.1. Engagement, benefits and identified challenges of PCRA

All the interviewees appreciated the level of engagement in the PCRA process. It was observed that the co-production process resulted in new insights into the issues and direct the PCRA in a way that made all parties comfortable. The dialogue and interaction that occurred during the PCRA process offered the opportunity to better focus on the relevant issues regarding the companies' concerns. Every company has unique characteristics so there is a need for close collaboration to identify specific needs to generate risk metrics for different financial institutions.

Interviewees recognized that the PCRA is new in the financial sector and yet the information generated was highly appreciated by the firms. Involving them throughout the project life offered a learning opportunity and provided detailed explanations about climate risk than they knew earlier. The results served as a starting point for a conversation on the subject of physical climate risk to their assets. Additionally, it helped them understand the theoretical background of the physical risk in a more practical manner with clarity on what the risk is, where they are and how to start dealing with them. Despite the level of satisfaction, there were still some issues that need to be improved. These were particularly related to technicalities and the use of certain climate jargons that were not all clear. For example, presenting flood risk in terms of "1 in 100 years" expression was difficult to comprehend. The sources of data and procedure for analysis were not clear. Details of the factors that contribute to the risk and how these factors may evolve in the future need to be properly communicated.

One key challenge is the temporal and spatial scale of the information. Firms prefer to receive specific asset level information instead of general portfolio level information as this will help improve precision in decision making. For instance, proper communication of future changes might be useful. Also, uncertainties must be accurately presented to guide the interpretation of results and conclusion(s) drawn. Results should be standardized for easy interpretation following the TCFD guidelines. To improve upon the PCRA results, multi-stakeholder consultation by PCRA service providers must be done. Companies should also be open to sharing asset level information and of course, provided it would not affect their competition. Proper engagement and explanation of data and analysis ensure uptake of information.

4.2. Interest, awareness and capacity building in PCRA

Analysis of the interviews shows that CRA information provides a complete and better picture concerning current but also future damages and how they affect the value of assets. Most investors are interested in hazard information (e.g. storm damage, heat, flood, subsidence) for decisions concerning when and how directly or indirectly properties and finances are affected by climate change. Respondents claim their companies focus more on potential monetary loss, business interruptions and the wellbeing of tenants when it comes to PCRA information. Additionally, PCRA information guides investors when acquiring new assets. For example, an apartment that has high energy use efficiency and is climate-proof against hazards easily gets financed by banks with interest discounts. Also, the difficulties in obtaining flood insurance in the Netherlands push especially foreign investors and insurance companies to obtain risk profiles of assets. In General, since the catastrophic North Sea flood in 1953, insurance companies in the Netherlands regard flood damage as uninsurable and therefore do not cover it (Botzen et al., 2008; Heerkens, 2003). The Dutch government, however, has become increasingly reluctant to provide compensation to flood disaster victims. The government has now put in place legal arrangements for flood damage insurance and compensation because the private insurance companies refused to extend coverage to floods (Kok and Barendregt, 2004; de Vries, 1998). Therefore Private flood insurance is very limited in the Netherlands except for example flood damage to vehicles covered by car insurance companies (Schoubroeck, 1997). Euro-Lloyd is the only company covering flood damage at high premium covering only 25 % of total damage (Kok, 2005).

Firms continue to raise awareness and build the capacity of their staff to incorporate PCRA information into general business decisions. The sensitization approach ranged from informal unstructured discussions to organized meetings and structured workshops. SAREF for example leverage internal newsletters and organized lunch meetings where presentations are given to create awareness among certain departments such as commercial and residential real estate, acquisition & development and portfolio management. We observed that while the impact of physical climate risk has been an old problem, concerns about the need for PCRA information are at their infancy among the real estate sector and so no specific department is yet assigned the responsibility. However, the need for PCRA information is likely to increase in the future depending on the value addition of the PCRA in monetary terms. Already the interviewed companies have plans to integrate PCRA into the organizational process. Currently, the strategy and research departments of SAREF and international advisory departments of MVGM for example oversee the preparation of PCRA but mostly in partnership with external consultants. For Vesteda, physical climate risk is embedded in their sustainability issues and captured in their quarterly reports.

Given that the interest in PCRA information is on the rise among various real estate companies, we asked about the sources of this information for decision making. Results show that both internal and external sources of information are used. For example, SAREF uses information from the standards of the blue label developed by its mother organization as a protocol for evaluating risk and improving assets. The Dutch Climate Impact Atlas and Task Force on Climate-related Financial Disclosures (TCFD) Knowledge Hub also serve as sources of physical climate risk information.

4.3. Incorporation of PCRA information and impacts on investment decisions

From the interviews, we found that PCRA information is used either in isolation or in combination with other risk factors to develop risk scores or categories that provide insights into complete financial implications. For example, for all properties managed by Vesteda, risk scores are computed using special criteria. These scores are discussed every-three years and are included in budgets and used for the development of company policies on acceptable risk levels.

Also, interview results show that currently, the influence of PCRA information on investment decisions vary from one company to the other; slightly influential at Vesteda, moderately influential at SAREF and highly influential at MVGM. In cases where interviewees consider it slightly influential, they were quick at adding that this may change in the future and PCRA information will play a bigger role depending on the robustness of the information and how quick climate change will develop. Krueger et al., (2020) found that Climate risks are ranked relatively low compared to other risks such as operating and governance and.

social risk in terms of importance though its impact is considered to have significant financial implications for portfolio firms. The respondents agree that PCRA information is helpful in several ways summarized into four main points; first, it supports investors to pinpoint which assets need attention and how much money is required to mitigate the impacts. Second, they serve as a template upon which clients can make purchasing decisions. Third, they serve as a tool for determining the choice of building materials and the structure of properties. Fourth, they assist firms in the development of plausible adaptation strategies.

However, the feedback analysis shows that lots of information delivered to the end-users were unclear. For example, the underlying factors that contribute to the risk information and how these factors may evolve in the future were not indicated. The sources of data and procedure for analysis were also unclear and not detailed enough to allow for proper financial decision making. This seems to be a key problem, the best information available cannot solve. If there is a lack of expertise on the receiving end, then the information cannot be effectively used for decision making.The respondents also identified the usefulness of story maps with metadata presented in excel and accessible 24/7 via email services as an effective mode of communicating results.

5. Discussion and conclusion

The main objective of this paper is to provide recommendations for improving Physical Climate risk Assessment (PCRA) for the financial sector based on case studies of real estate assets and portfolios and literature review.

Quantifying and handling risk for financial decisions may not be new to investors yet the challenges that climate change poses has recently increased the interest in PCRA. Different PCRA methodologies have been proposed for estimating physical climate risk in general (Palutikof et al., 2019; Street et al., 2019; Jones and Preston, 2011) and for the financial sector in particular (Bernstein et al., 2019; Dietz et al., 2016; Bansal et al., 2016). A survey performed by Krueger et al., (2020) shows that only 7 % of organisations adopt no approach to managing climate risk, implying the variety of methodologies existing in the financial sector. However, simply selecting a PCRA methodology does not guarantee uptake of information by end-users, because there is not a single approach that is suitable and appropriate for all contexts. Irrespective of the PCRA methodology selected, individuals and organizations attempting to perform a PCRA will be faced with lots of context related issues that require proactive decisions which affect the final PCRA results. Reflecting on the lessons from the literature and the case studies, we identified five main areas relevant for ensuring that the PCRA process respects the needs of both providers and end-users with particular attention to context issues. They include (i) engagement and co-production, (ii) need identification, (iii) data availability and quality, (iv) internal integration, and (v) communication. For each of these areas, we present a set of recommendations that incorporates scenarios and critical decision points to help with deciding on what best suits end-users context. These recommendations are not by themselves static but depend on the context pivotal to the implementation of PCRA.

5.1. Engagement and co-production

Generally, we found different types of engagement in the PCRA process; (i) between PCRA providers and financial actors; (ii) within the financial organization itself; (iii) between financial actors and their clients such as investors or tenants; and (iv) between PCRA providers and the clients or investors or tenants. Different actors are involved for two main reasons; first, because of the knowledge they possess and their willingness to make this knowledge available. For instance, the engagement of financial actors and/or their clients is aimed at gathering information that otherwise is beyond the reach of the PCRA providers. These actors have site-specific information that is relevant to the PCRA process. For example data on the exposure and vulnerability components of risk are mostly unavailable and therefore most PCRA focus on the hazard analyses. However, engaging important stakeholders can help to gather relevant data and information for a robust risk assessment. The second reason for engagement is to create awareness and build the capacity and skills of individuals within the organizations.

Ultimately, engagement results in the co-production of PCRA information that is relevant for the appropriate needs (see also Lemos and Morehouse, 2005). Actors can be involved in the PCRA process through several approaches and at different times depending on the suitability of each situation. Just as the cases implemented in the water and agriculture sector (Butterfield and Osano, 2020; Nyadzi, 2020), the cases in this study used workshops as the primary method of engaging stakeholders. The workshops were relevant for gathering local and organizational level data for validating and refining the PCRA information. In cases when providers have ample data to perform the PCRA, it is still useful to involve actors in the process because it results in the actionability of PCRA information with a high potential for uptake. The degree of involvement may also differ as actors may just be contributors, collaborators or co-creators. In the case of actors as contributors, the PCRA is performed by providers and actors contribute data. In a collaborative process, the actors go to the extent of assisting in data analysis and or dissemination approach. In the co-creation process, actors participation is very active in most or all steps of the PCRA process (see also Brudney and England, 1983; Brandsen and Honingh, 2016).

Both the case studies and reviewed literature point at the importance of having an extensive process of engagement and co-production with the target user (see Lemos and Morehouse, 2005; Cash et al., 2003). reflecting on the case studies, we found that it is important to first reach an agreement on what ‘risk’ actually entails, which mechanisms drive risk and how to define threshold needs of the end users which change over time. For example, the companies in the case studies initially asked for aggregated risk scores for each asset in the portfolio. As the PCRA progressed, however, the aggregated risk score raised new questions for example what do red, orange and green mean? which mechanisms determine the risk? what are the uncertainties in the data? how can we mitigate the risks? In the case study of the hotel in Rotterdam it turned out that in the end, the client wanted to know the flood probability/return periods to be able to obtain flood insurance. Therefore case specific information is needed to reduce risks and obtain insurance.

From the case studies, we observed that co-production helped address uncertainties in three mainways;characterizing, estimating, and communicating uncertainties which is consistent with the findings of Barnhart et al., (2018). In the initial stage of the case study (primarily problem definition and needs assessment stage) participants and researchers identified potential uncerntainties and agreed upon acceptable levels of these uncertainties. We found that most of the uncertainty concerns of the stakeholders were due to inadequate understanding of the climate risk assessment process itself. For example, uncertaintiess associated with quantifying the harzards with impact models. As a results researchers help explained these uncerntainties and their causes as well as provided scientific insight into setting thresholds of uncertainties to curb unrealistic expectations. On the other hand, researchers improved their understanding on uncertainties related to exposure and vulnerability due to participants inputs. In addition, how uncertainties should be presented and communicated were explored with participants.

5.2. Needs identification

Different types of financial institutions have different problems and therefore needs that must be met. To provide useable and actionable PCRA information, needs must be identified and prioritised. Proper needs assessment refines and directs the outputs of PCRA. An initial needs assessment may establish the boundaries of operation, guiding data collection, analysis and presentation. However, the needs assessment process is not a one-time event, but should rather be continuous and flexible because the demands of end-users may change over time (Gallo and Lepousez, 2020). For example, before the Vesteda case was performed we did not anticipate heat stress as an important issue for the hotel in Rotterdam, whereas at the needs assessment stage, Vesteda regarded it as a very important risk component for which they would like to obtain risk information. There is no one-size-fits-all risk assessment approach, and the various components of risk have to be identified, weighted and interpreted for and with each client. Also, in the portfolio risk assessment cases (case study 3), impact chain diagrams were generated during workshops with the client. By jointly developing the impact chain diagrams, the client gained a deeper understanding of the concept of climate risks and the components that determine risk. During the process, both the provider and user gained a better understanding of the relevant damage mechanism for the different types of assets and the possible related climate risks. Brokers, for example, require site specific information while insurers need information for calculating insurance premiums for buildings. Tenants are also interested in the risk associated with their wellbeing before deciding to purchase a property. Engagement and co-production as discussed earlier offer an opportunity to achieve meaningful needs identification.

It is, however, important to acknowledge that, in most cases, the initial end-users demands may not be realistic because the data are not available and/or the future climate change risks are too uncertain. Therefore to improve indicators and metrics to help investors better manage their climate risks, some critical initial questions needs to be answered during needs assessment; (i) which climate-related risks require immediate attention from investors, and what scientific information or data is available? (ii) How can investors better secure the value of their portfolios against physical impacts from climate change? (De Bruin et al., 2019).

5.3. Data availability and quality

An essential component of PCRA is data requirements. Typically, physical PCRA requires data on hazard, exposure and vulnerability. In many cases hazard data are derived from rainfall, temperature and windspeed which is either modelled and/or based on observational records. While modelled data may contain biases (Bakker, 2015), observational records are often unavailable or not representative of the future due to climate change (Sobel and Tippett, 2018). The exposure and vulnerability component, however, require information that can be obtained mostly at the asset level. These data, however, are not readily available to providers (Gallo and Lepousez, 2020). Usually, it is not possible to gather all data at the asset level. Therefore risk assessment will often have to be done based on imperfect and uncertain data.

To better capture aspects of the vulnerability of individual assets or buildings the inclusion of building standards (e.g. energy labels) could be an interesting way forward. The case studies used a classification method that accounts for factors driving the vulnerability of the assets. The classification method gives scores for certain elements of the building that determine its vulnerability, wherefore example, having a green roof, shading or green near the building will reduce the level of vulnerability.

A forward looking PCRA, especially for a large portfolio of assets, is not a simple task. In general, available data on climate change impacts have not been developed for use at the asset level. The data is often at much coarser spatial resolution and may be insufficient for an effective PCRA at a local scale (Carter et al., 2015). Climate models have inherent systemic errors that affect their application in impact studies. While downscaling data may improve the physical understanding and offer more geographical detail of the data, downscaling also introduce new biases and uncertainties due to mismatches between GCM and RCM in terms of parameterizations (Jacob et al., 2020). The problem with downscaling however is the over or underestimation of anomaly in climate variables (e.g. precipitation and temperature) which impede hazards analysis of the climate risk assesement. The purpose of the Dutch Climate Impact Atlas is meant to raise a general sense of urgency and provide a first order assessment of which areas are potentially exposed to relatively high risk. Because damage mechanisms are often local, results of asset level PCRA cannot be based on national scale data (let alone data at a global scale). Therefore, localized tailor made approaches are needed for a meaningful assessment. Reflecting on the case study performed, we recommend the following three-step approach to develop PCRAs at the scale of individual assets;

1. Perform a quick scan of the portfolio using an approach that captures the key hazards and preferably also includes sensitivity/adaptive capacity indicators. This would identify possible hotspot areas and raise general awareness of climate risk in the portfolio.
2. In the second step, identify regions where a relatively high number of assets are exposed (hotspots). The assessment under the first step can serve as a basis for selecting regions with a relatively high number of assets at risk. For these hotspot regions, a tailor-made approach can be applied using local data and available hazard maps from local sources.
3. Within the geographical hotspots, work with asset managers to identify local vulnerability characteristics (location of critical equipment, adaptation measures in place, policy context) on the asset level. This assessment can for instance be done through a questionnaire or interview with the asset owners.

The question that remains vital throughout the PCRA process is how the identified needs can be met using the available data? Limited data availability has consequences for the quality of information generated and to a larger extent increases the uncertainties related to the information. Case studies results showed that companies were not surprised about the coarseness of the information provided, perhaps because financial institutions have long term experience in dealing with data uncertainties. However, they expect that providers update them on the data types and the mechanism of analysis behind the physical climate risk information. User engagement is also important here, by engaging the user throughout the risk assessment process the user better understand the data limitations and related uncertainties.

Data from multiple sources are helpful in obtaining better insight into climate risk concerns, however, this can also pose challenges to both the process and the outcome of climate risk assessment. Data merging may seem simple yet a process that is often complicated because of inconsistencies in different data frames and duplications that could increase inaccuracies. For example, observational rainfall data could be available as point data from one source and grid in others, also they could be written and stored in different file formats that require substantive processing which could increase error in resultant data and subsequently affect the results of the climate risk assessment. Nonetheless combining data from different sources into a single point of reference is important though this should be treated with caution to avoid data loss and damage to the structure of the individual data involve. This can be achieved through proper data filing, cleansing, standardization, and transformation. A critical aspect of data integration is combining qualitative and quantitative data in climate risk assessment. For example, one might want to explore stakeholders' perspectives (using qualitative methods:e.g. interviews) on the occurrence of climate hazards or level of exposure or vulnerability and at the same time investigate these with climate data and spatial analysis (using statistical and dynamic modeling). Combing these datasets in an analysis may validate the results when both results point in the same direction but the challenge arises when the results point in different directions. In this situation, both results should be communicated for stakeholders to to make their own decisions.

5.4. Internal integration

The ultimate aim of conducting a PCRA is to be able to link information generated to adaptation action and find solutions to the anticipated impacts. Proper PCRA information informs financial institutions and property owners to make decisions about the exposure of their assets to the risk (de Bruin et al., 2020; Morel et al. 2015). Also, results from PCRA served as input for reporting on physical climate risk to regulating bodies. Financial institutions are encouraged by external regulating bodies to report on physical climate risks. Therefore we suggest the need to check the TCFD guidelines, EU Taxonomy annual reporting requirements for example as a guide.

While improving the PCRA process is important, it is the effectiveness of translating this information into evidence-based decision making that is challenging. The process requires a system thinking approach where all factors that may influence the acceptance of risk levels are considered (see also Krebs, 2011). Financial institutions may already have the capacity to incorporate other forms of risk into their decision making, yet there is a need to improve the capacity to understand the mechanism of climate risk and their uncertainties, as this could create a dilemma for investment decision making. In the case studies, we learned that jointly developing impact chains was an effective way to develop such capacities.

Generally integrating risk management into core business processes, decision making and the overall culture of the organisation is no small task (Sidorenko and Demidenko, 2016). According to McDermott and Surminski, (2018), existing approaches for integrating risk into decision making offer little insights on the interplay of PCRA and present fundamental challenges that appear to hamper the translation of PCRA information into action during the decision making process. The authors argue that the success of PCRA integration into decision making is only possible if certain issues that arise during the decision making process are properly presented in the PCRA. These relate to, that; (i) the PCRA should handle critical normative choices such as a social appetite for risk (acceptable level of risk), target of the risk and distributional issues and discounting the future (including costs and/or benefits of risk). (ii) The PCRA must be able to handle economic, social and political realities. While the PCRA process and evaluation of adaptation options may be devoid of economic, social and political considerations, the ultimate decision to implement the preferred option may be affected. For example, flooding is a sensitive issue with emerging social controversies over the selection of flood relief options including flood insurance that is influenced by economic feasibility and political decisions. (iii) Framing climate risk uncertainty. The way scenarios are presented to investors will either facilitate smooth decision making or complicate the process. Decision makers are comfortable when they are presented with one scenario than with multiple possible scenarios of uncertainty. Moreover, it is very likely for people to analyse climate risk with an emotional rather than a logical lens. Therefore framing uncertainty around climate risk should be done cautiously and logically.

Given that these concerns are essential to the effective integration of PCRA investment decisions, the authors argue for a broader stakeholder engagement and transparency in performing and communicating PCRA information.

5.5. Communication

How PCRA information is disseminated to end-users in the financial sector is very important. The role of service providers is to help end-users understand the content of the PCRA (the current risk and how they will evolve in the future) and possible limitations (Krebs, 2011). The quality of the PCRA is vital, yet it is the interpretation and the application for a financial decision making process that determines if and what action is taken. Presenting PCRA information in a manner that hampers correct interpretation during decision making can lead to maladaptation which may result in extra and unnecessary costs (McDermott and Surminski, 2018). This highlights the important role communication plays in the PCRA process. To ensure successful delivery, the information has to be provided at the right time and in the appropriate format understood by the end-users. Achieving this requires effective communication tools and methods and frequent interaction with the user. Additionally, careful considerations must be given to the language and the use of technical and specialist terminologies as these may pose difficulties for usage. In cases where replacing technical terminologies may distort the information, thorough explanations of the terms used should be provided. Proper communication of future changes and their related uncertainties will be useful for financial decision making.

We acknowledge that the relatively low number of case studies limits the possibility to generalize are our results. It is possible that the cases are not always representative of the situation in the Netherlands. However, there were clear similarities between the cases and insight obtained from the cases provide an important basis for the future development of PCRA in the financial sector.

PCRA is an important point of departure for making climate-sensitive investment decisions. Yet the assessment is often performed by experts outside financial organisations and sectors due to lack of capacity by the internal staff and the limited number of people having both financial and climate expertise (Dessai et al., 2005; Measham et al., 2011). This in itself contributes to the challenge of improper alignment of PCRA information with company needs. Therefore, engagement and co-production remain essential approaches to developing a PCRA that is useful for financial decision making. The interaction between providers, users and other stakeholders must occur throughout the PCRA process and be structured in a way that captures the opinions and ideas as well as questions of all parties involved. While the degree of involvement may differ co-production remains the vital choice of generating reliable and acceptable PCRA information tailored to meet needs (Lemos and Morehouse, 2005).

Finally, this paper provides a valuable reference for both service providers and users willing to conduct PCRA for the finance sector. By following the recommendations, there is an opportunity to increase the value of PCRA information leading to informed investment decisions and the development of robust adaptation options. This is especially important for the real estate sector.

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

Data will be made available on request.

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